# Thermal-neutron capture by $^{58}$Ni, $^{59}$Ni, and $^{60}$Ni

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We have studied the primary and secondary $\gamma$ rays (414 in $^{59}$Ni, 390 in $^{60}$Ni, and 240 in $^{61}$Ni) following thermal-neutron capture by the stable $^{58}$Ni, radioactive $^{59}$Ni, and stable $^{60}$Ni isotopes. Most of these $\gamma$ rays have been incorporated into the corresponding level schemes consisting of 65 levels in $^{59}$Ni, 88 levels in $^{60}$Ni, and 40 levels in $^{61}$Ni. The measured neutron separation energies ($S_n$ in keV) for $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni are, respectively, $8999.28\pm0.05$, $11\,387.73\pm0.05$, and $7820.11\pm0.05$. The measured thermal-neutron capture cross sections (in barns) for $^{58}$Ni, $^{59}$Ni, and $^{60}$Ni are, respectively, $4.13\pm0.05$, $73.7\pm1.8$, and $2.34\pm0.05$. In all three cases, primary electric-dipole ($E1$) transitions account for the bulk of the total capture cross section. We have calculated these $E1$ partial cross sections (in $^{59}$Ni and $^{61}$Ni) using direct-capture theory and models of compound-nuclear capture. The agreement between theory and experiment is good. The experimental level schemes have been compared with the results from a large-basis shell-model calculation. The agreement was also found to be quite good.

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## I. INTRODUCTION

In a series of papers [1–16] we have examined off-resonance slow-neutron capture by light nuclides ($A\leqslant 50$) and have shown that the direct-capture mechanism as originally formulated by Lane and Lynn [17,18] and further developed in Refs. [1–3] provides a sound description of the partial cross sections of the electric-dipole ($E1$) primary transitions in these nuclides. In this paper, we study the primary and secondary $\gamma$ rays following thermal-neutron capture by $^{58}$Ni, $^{59}$Ni, and $^{60}$Ni. In all three cases, $E1$ primary transitions account for the bulk of the total capture cross section. We calculate the $E1$ partial cross sections using direct-capture theory employing the same methods as developed in the earlier papers. In particular, we use a global optical model plus a valence correction. We find again that direct capture accounts for a major fraction of the cross sections of primary $E1$ transitions and that the differences between theory and experiment can be explained by admixtures of compound-nuclear amplitudes into the direct-capture amplitudes. The resulting average compound-nuclear cross sections are reasonably consistent with theoretical expectations.

From a variety of studies [19–83] discussed in greater detail in later sections, ~200 bound levels are known below 7.6 MeV in $^{59}$Ni, ~150 levels below 10.0 MeV in $^{60}$Ni, and ~170 levels below 5.5 MeV in $^{61}$Ni. In each nucleus, about a third of all known levels are populated significantly in the current (thermal $n,\gamma$) study. For each final nucleus, we have provided a conspectus of bound levels and their spin and parity ($J^{\pi}$) assignments. We have also compared the experimentally known levels in $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni with those calculated with a large-basis shell-model interaction.

## II. EXPERIMENTAL PROCEDURES

The $(n,\gamma)$ measurements were carried out with enriched targets obtained from the research materials collection maintained by the Oak Ridge National Laboratory. Measurements were also made with natural nickel. Each target was studied in the thermal column of the internal target facility at the Los Alamos Omega West Reactor. The target was placed in a graphite holder, which was inside an evacuated bismuth channel. The target position was 1.5 m from the edge of the reactor core. At this position, the thermal-neutron flux was $\sim 6\times10^{11}$n cm$^{-2}$ s$^{-1}$ . The Los Alamos facility and the data analysis procedures have been described in detail in Ref. [1]. Gamma-ray spectra were obtained with a 30-cm$^3$ coaxial intrinsic Ge detector positioned inside a 20-cm-diameter by 30-cm-long NaI(Tl) annulus. This Ge detector was located 6.3 m from the target and was operated either in the Compton-suppressed mode (0.454 keV/channel) or in the pair-spectrometer mode (0.629 keV/channel). The latter mode utilizes the lengthwise optical division of the annulus so that only double-escape peaks appear in the pulse-height spectrum. At lower energies the two annulus halves are connected together electrically to operate in the conventional

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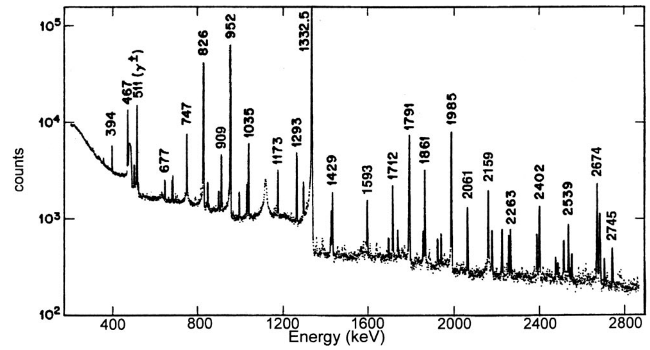


FIG. 1. Gamma-ray spectra from thermal-neutron capture by $^{59}$Ni. The Ge detector was operated in the Compton-suppression mode. All energies are in keV.

Compton-suppressed mode. The pulse-height analyzer had 16 384 channels. In the Compton-suppressed mode, the full width at half maximum (FWHM) values for our system were 1.5, 1.8, 2.3, and 2.9 keV, respectively, for $\gamma$-ray energies of 0.5, 1.0, 2.0, and 3.0 MeV. Figure 1 shows a sample spectrum obtained with the $^{59}$Ni target in this mode. In the pair-spectrometer mode, the FWHM values were 2.5, 3.3, 4.0, and 4.7 keV, respectively, for $\gamma$-ray energies of 3, 5, 7, and 9 MeV. Figure 2 shows a sample spectrum obtained with the $^{59}$Ni target in the latter mode.

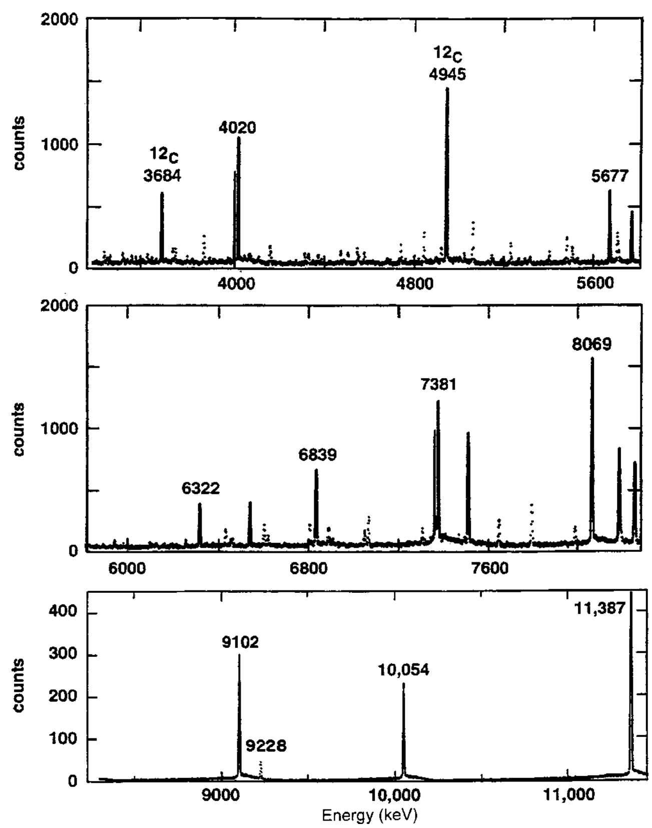


FIG. 2. Gamma-ray spectra from thermal-neutron capture by $^{59}$Ni. The Ge detector was operated in the pair-spectrometer mode. All energies are in keV.

Energy calibrations in the pair-spectrometer mode were performed with the prompt $\gamma$-ray spectrum from neutron capture in melamine ($C_3H_6N_6$). In the Compton-suppressed mode, the prompt $\gamma$ ray from the $^1$H$(n,\gamma)$ reaction plus the annihilation radiation were employed for this purpose. In both modes, nonlinearity corrections to the measured energies were made (see Fig. 2 of Ref. [15]), using precisely known $\gamma$ rays appropriate to the range of energies of interest. The primary calibration energies were those recommended by Wapstra and his co-worker [84,85]: $510.999 \pm 0.001$ keV for the annihilation radiation, $2223.255 \pm 0.003$ keV for the $\gamma$ ray from the $^1$H$(n,\gamma)$ reaction, and $4945.302 \pm 0.003$ keV for the ground-state transition in the $^{12}$C$(n,\gamma)$ reaction. Secondary calibration energies were provided by the $\gamma$ rays in the $^{14}$N$(n,\gamma)$ reaction [15].

Intensity calibrations (see Fig. 3 of Ref. [15]) were determined in the Compton-suppressed mode with a set of standard radioisotopic sources with precalibrated $\gamma$-ray intensities. The efficiency curve in the pair-spectrometer mode was derived from the relative intensities of $\gamma$ rays from the $^{14}$N$(n,\gamma)$ reaction [15,86]. The effect of possible variations in neutron flux was taken into account by normalizing the data to the neutron fluence for each run measured with a small fission counter located near the target position in the thermal column. The capture cross sections reported in the current work for $^{58}$Ni and $^{60}$Ni are based on measurements in which each target was studied together with a 100.0-mg $CH_2$ standard. The cross sections are normalized to the recommended value of $\sigma_\gamma(2200\ \mathrm{m/s}) = 332.6 \pm 0.7$ mb [87] for $^1$H present in the standard. The $^{59}$Ni capture cross section is based on the $^{58}$Ni and $^{60}$Ni capture cross sections and the isotopic composition of the sample. The thermal-neutron flux at the target position approximates a Maxwellian distribution corresponding to a temperature of 350 K, for which the most probable neutron velocity is 2400 m/s. To determine the cross sections at 2200 m/s, we have assumed a $1/v$ dependence of the capture cross section for $^1$H and for all target isotopes.

## III. PRESENTATION OF RESULTS

This paper contains a large body of data on three nickel isotopes. There are common threads among the tables presented in this paper. We discuss our overall philosophy and methods of presentation in this section.

### A. Previous measurements

Because almost all the reactions that are likely to give useful information on the energy levels in $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni have already been studied—some several times—and because of the lessened activity in conventional nuclear spectroscopy expected in future years, significant new information on these levels will likely appear with greatly reduced frequency. Thus we feel a review of the currently available information is timely. We start with a list of references to previous measurements. When several references are avail-

TABLE I. Partial list of references to previous measurements on $^{59}$Ni levels. See Ref. [89] for additional references.

| Measurement | Author(s) | Year | Facility$^a$ | Reference |
|---|---|---|---|---|
| $^{50}$Cr($^{12}$C,$2pn\gamma$) reaction | Pichevar *et al.* | 1976 | Saclay | [19] |
| $^{56}$Fe($\alpha,n\gamma$) reaction | Hutton *et al.* | 1973 | TUNL | [20] |
| | Monseu, Forssten, and Sawa | 1974 | Stockholm | [21] |
| | Pichevar *et al.* | 1976 | Saclay | [19] |
| $^{58}$Ni($\alpha$,$^3$He) reaction | Roussel *et al.* | 1970 | Saclay | [22] |
| $^{58}$Ni($^3$He,$2p\gamma$) reaction | Juutinen *et al.* | 1989 | U. Jyväskylä | [23] |
| $^{59}$Co($p,n$) reaction | Stelson | 1967 | Oak Ridge | [24] |
| $^{59}$Co($p,n\gamma$) reaction | Stelson, Dickens, and Perey | 1967 | Oak Ridge | [25] |
| | Mittal, Avasthi, and Govil | 1983 | Panjab U. | [26] |
| $^{58}$Ni(thermal $n,\gamma$) reaction | Hofmeyr | 1975 | Pelindaba | [27] |
| | Ishaq *et al.* | 1977 | McMaster U. | [28] |
| | Harder | 1992 | Grenoble | [29] |
| | Harder *et al.* | 1993 | Grenoble | [30] |
| $^{58}$Ni(polarized $n,\gamma$) reaction | Stecher-Rasmussen *et al.* | 1972 | Petten | [31] |
| $^{58}$Ni($d,p$) reaction | Fulmer *et al.* | 1964 | Aldermaston | [32] |
| | Cosman *et al.* | 1966 | MIT | [33] |
| | Litvin *et al.* | 1972 | Leningrad | [34] |
| | Chowdhury and Sen Gupta | 1973 | Aldermaston | [35] |
| $^{58}$Ni(polarized $d,p$) reaction | Aymar *et al.* | 1973 | U. Notre Dame | [36] |
| | Taylor and Cameron | 1980 | McMaster U. | [37] |
| $^{59}$Cu($\beta^+ + \varepsilon$) decay | Van Patter, Rauch, and Stein | 1973 | U. Frankfurt | [38] |
| | Sen, Sen, and Basu | 1977 | SUNY | [39] |
| $^{60}$Ni($p,d$) reaction | Sherr *et al.* | 1965 | U. Colorado | [40] |
| $^{60}$Ni(polarized $p,d$) reaction | Nann *et al.* | 1983 | Indiana U. | [41] |
| $^{60}$Ni($^3$He,$\alpha$) reaction | Zimmerman *et al.* | 1978 | U. Colorado | [42] |
| | Sen Gupta *et al.* | 1990 | U. Birmingham | [43] |

$^a$Facility where the actual measurements were done. The symbol U stands for a university.

able for a given reaction, we list only those that we feel give definitive results.

### B. Known energy levels

From the list of references to previous measurements, we select those that give information leading to a skeleton level scheme. We specifically exclude previous $(n,\gamma)$ studies. The construction of this skeleton level scheme is nontrivial because it is necessary to establish a one-to-one correspondence between the levels reported in different experiments. In this paper, we have provided critically evaluated lists of the bound states in $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni and their spin and parity ($J^\pi$) assignments. Our summaries are independent of similar summaries appearing in Refs. [88–96].

### C. Observed $\gamma$ rays

The energies and intensities of $\gamma$ rays observed in this work from the respective $(n,\gamma)$ reactions are given in separate tables. Unplaced and multiply placed $\gamma$ rays are noted and, for each placed $\gamma$ ray, the preferred placement is indicated in the table. Alternate placements are given at the end of the table.

### D. Level schemes

The construction of a level scheme based on $(n,\gamma)$ data is somewhat akin to solving a jigsaw puzzle. The problem is rendered easier to the extent to which the energy levels and their branching ratios are known from other experiments. Each and every known level that could reasonably be expected to receive population in the $(n,\gamma)$ reaction was checked against the $\gamma$-ray data. In this paper, the level schemes of $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni based on our $(n,\gamma)$ studies are presented in tabular form. The level energies listed in these tables were obtained through an overall least-squares fit involving all placed transitions except those noted as multiply placed. In deducing these level energies, nuclear recoil was taken into account. Also presented in these tables are the summed cross section for populating each level, the summed cross section for deexciting each level, and the intensity imbalance. The level scheme based on our $(n,\gamma)$ work is then carried over to an earlier table for comparison with the previous best $(n,\gamma)$ level scheme and with all previously known levels.

Multiple placements of $\gamma$ rays are inevitable in a complex level scheme. In this work, we initially placed $\gamma$ rays in all

TABLE II. Known energy levels in $^{59}$Ni.

| Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) | Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) |
|---|---|---|---|---|---|---|---|
| 0.0 | $\frac{3}{2}^-$ | 0.0 | 0.0 | 3187 *5* | | | |
| 339.36 *7* | $\frac{5}{2}^-$ | 339.419 *22* | 339.399 *16* | 3297.1 *15* | | | |
| 464.97 *7* | $\frac{1}{2}^-$ | 464.971 *22* | 464.935 *16* | 3308.1 *20* | | | |
| 878.04 *8* | $\frac{3}{2}^-$ | 877.941 *21* | 877.961 *15* | 3315 *5* | | | |
| 1189.08 *9* | $\frac{5}{2}^-$ | 1188.783 *24* | 1188.789 *16* | 3340.0 *14* | | | |
| 1301.48 *7* | $\frac{1}{2}^-$ | 1301.40 *3* | 1301.437 *17* | 3347 *5* | | | 3343.22 *6* |
| 1337.86 *8* | $\frac{7}{2}^-$ | | 1337.89 *3* | 3354 *5* | | | |
| 1679.75 *8* | $\frac{5}{2}^-$ | 1679.69 *3* | 1679.700 *24* | 3363 *5* | | | |
| 1734.74 *7* | $\frac{3}{2}^-$ | 1734.72 *3* | 1734.687 *17* | 3377.00 *15* | $\left(\frac{11}{2}^-\right)$ | | |
| 1739.19 *22* | $\left(\frac{9}{2}^-\right)$ | | | 3377 *5* | | 3377.41 *9* | 3377.22 *6* |
| 1746.1 *7* | $\frac{5}{2}^-, \frac{7}{2}^-$ | | | 3380.7 *19* | | | |
| 1767.42 *9* | $\frac{9}{2}^-$ | | | 3408 *5* | | | |
| 1948.02 *11* | $\frac{7}{2}^-$ | | 1948.32 *17* | 3415 *5* | $\frac{1}{2}^+$ | | 3413.55 *15* |
| 2349.22 *14* | $\left(\frac{11}{2}^-\right)$ | | | 3452 *5* | $\frac{3}{2}^-$ | 3452.41 *11* | 3452.34 *10* |
| 2414.84 *18* | $\frac{3}{2}^-$ | 2414.97 *3* | 2414.892 *17* | 3505 *5* | | | |
| 2422 *5* | | | 2421.95 *6* | 3521 *5* | | | |
| 2526 *5* | | | | 3534 *5* | $\left(\frac{5}{2}^+\right)$ | | |
| 2530.47 *15* | $\left(\frac{9}{2}^-\right)$ | | | 3538.60 *23* | $\left(\frac{9}{2}^-\right)$ | | |
| 2533.0 *21* | | | | | | 3540.05 *12* | 3540.05 *7* |
| 2535.46 *23* | $\left(\frac{13}{2}^-\right)$ | | | 3545.9 *4* | | | |
| 2553.4 *21* | | | | 3559.54 *13* | $\left(\frac{11}{2}^-\right)$ | | |
| 2627.28 *17* | $\frac{7}{2}^-$ | | 2627.05 *8* | 3563 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3563.10 *9* | 3562.98 *3* |
| 2681.1 *7* | $\left(\frac{5}{2}^-\right)$ | | 2679.57 *14* | 3590 *5* | | | |
| 2685 *5* | | | | 3638 *5* | | | |
| 2698 *5* | | | | 3686 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | 3686.20 *10* | 3686.109 *22* |
| 2705.29 *14* | $\frac{11}{2}^-$ | | | 3718 *5* | | | |
| 2713.1 *21* | | | 2715.03 *11* | 3730 *20* | $\frac{7}{2}^-$ | | |
| 2893 *5* | $\frac{3}{2}^{(-)}$ | 2893.61 *4* | 2893.521 *20* | 3735 *5* | | 3730.38 *10* | 3730.24 *5* |
| 3027 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 3025.82 *8* | 3025.769 *25* | 3781 *5* | | | |
| 3038.0 *21* | $\frac{7}{2}^-$ | | | 3796 *5* | | | |
| 3054.52 *14* | $\frac{9}{2}^+$ | | | 3802 *5* | | | |
| 3125.53 *18* | $\left(\frac{7}{2}^-, \frac{9}{2}^-\right)$ | | | 3856 *5* | $\frac{3}{2}^-$ | 3853.71 *11* | 3853.63 *6* |
| 3126.8 *12* | | | 3126.10 *17* | | | 3858.26 *12* | |
| 3177 *5* | $\frac{3}{2}^{(-)}$ | 3181.63 *8* | 3181.564 *18* | 3887 *5* | | 3889.74 *12* | 3889.70 *7* |

possible positions in the level scheme warranted by the spin change and agreement—within twice the energy uncertainty—between the level energy difference and the $\gamma$-ray energy. We then either removed or retained multiple placements, depending on the intensity balance considerations for each level. Multiply placed $\gamma$ rays were excluded in the overall least-squares routine used to determine the best level energies and their uncertainties.

If a level scheme is complete and internal conversion can be neglected, the quantities $\Sigma I_\gamma$ (primary), $\Sigma E_\gamma I_\gamma / S_n$, and $\Sigma I_\gamma$ (to ground state) should all be the same within their stated uncertainties. We have listed these quantities for all three isotopes.

### E. Previous $(n,\gamma)$ measurements

For all three nickel isotopes, the current spectroscopic data are more extensive and definitive than previous $(n,\gamma)$ studies. The detection limit (for a $\gamma$ ray in the 0.1–10.0 MeV region), enrichment of the sample, and sample purity were all better than in previous measurements. This improvement, in turn, has resulted in a significant increase in the number of $\gamma$ rays identified in this work as belonging to a particular isotope. This increasing complexity is quantified in respective tables for the three nickel isotopes. A limiting factor in the current measurements was the presence of trace impurities in the enriched targets. In separate experiments, we have

TABLE II. (*Continued.*)

| Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) | Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) |
|---|---|---|---|---|---|---|---|
| 3899 *5* | | | | 4668 *5* | | | |
| 3933 *5* | | | | 4682 *7* | | | |
| 3994 *5* | | | | 4690 *20* | $\frac{7}{2}^-$ | | |
| 4004 *5* | | | | 4697 *5* | | | |
| 4025 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 4021.90 *11* | 4021.87 *5* | 4709 *10* | | | |
| 4076 *5* | | | | 4716 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 4715.33 *13* | 4715.34 *4* |
| 4103.11 *16* | $(\frac{11}{2}^+)$ | | | 4756 *7* | | | |
| 4109 *5* | | | | 4787 *5* | $\frac{3}{2}^+$, $\frac{5}{2}^+$ | | 4782.91 *17* |
| 4122 *5* | | | | 4810 *5* | | | |
| 4141.13 *16* | $(\frac{13}{2}^-)$ | | | 4844 *5* | | | |
| 4143 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 4140.31 *11* | 4140.242 *25* | 4857 *5* | | | |
| 4160 *20* | $\frac{7}{2}^-$ | | | 4875 *5* | | | |
| 4166 *5* | | | | 4908 *5* | | | |
| 4202 *5* | | | | 4927 *5* | | | |
| 4230 *20* | $\frac{7}{2}^-$ | | | 4947.20 *22* | $(\frac{15}{2}^-)$ | | |
| 4253 *5* | $(\frac{1}{2}^-, \frac{3}{2}^-)$ | 4253.01 *11* | 4252.74 *6* | 4948 *5* | $(\frac{1}{2}^-, \frac{3}{2}^-)$ | | 4949.17 *5* |
| 4282 *5* | | | | 4968 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 4968.87 *13* | 4968.89 *4* |
| 4317 *5* | | | | 5015 *7* | | | |
| 4345 *5* | | | | 5024 *5* | | | |
| | | 4352.45 *12* | 4352.46 *8* | 5049 *7* | | | |
| 4384 *5* | | | | 5068 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 5068.98 *13* | 5069.10 *5* |
| 4396 *5* | | | | 5098.27 *23* | $(\frac{13}{2}^-)$ | | |
| 4408 *5* | | | | 5106 *7* | | | |
| 4418.84 *24* | $(\frac{13}{2}^-)$ | | | 5137 *5* | $\frac{1}{2}^+$ | | 5131.94 *18* |
| 4455.28 *17* | $(\frac{13}{2}^+)$ | | | 5201 *5* | $\frac{3}{2}^+$, $\frac{5}{2}^+$ | | |
| 4458 *5* | | | | 5246 *5* | | | |
| 4494 *5* | $\frac{5}{2}^+$ | | 4494.18 *12* | 5251.3 *3* | $(\frac{17}{2}^+)$ | | |
| 4531 *5* | | | 4532.8 *3* | 5256 *7* | | | |
| 4545 *5* | | | | 5280 *5* | | | |
| 4560 *20* | $\frac{7}{2}^-$ | | | 5293.04 *25* | $(\frac{15}{2}^-)$ | | |
| 4613 *10* | | | | 5360 *5* | | | |
| 4615.95 *24* | $(\frac{9}{2}^+)$ | | | 5381.38 *29* | $(\frac{15}{2}^+)$ | | |
| 4634 *5* | | | | 5383 *5* | $\frac{3}{2}^+$, $\frac{5}{2}^+$ | 5384.69 *14* | 5384.76 *7* |
| 4651 *7* | | | | 5417 *5* | $(\frac{7}{2}^+, \frac{9}{2}^+)$ | | |

obtained spectra under similar conditions from several commonly occurring elements to aid in the identification of peaks resulting from impurities and to correct for them in case of interference. We have also made use of existing compilations of $\gamma$ rays from neutron capture by natural elements [97,98].

### F. Comparison of capture data with calculations

In most, if not all, light nuclei, the direct-capture mechanism accounts for the major part of the thermal-neutron capture cross section in which the primary transition is electric dipole. In simple terms, direct capture can be described as the transition from the orbit of a neutron being scattered by a smooth potential field representing the target nucleus to the single-particle component of the bound final state. Because the major part of the integrand in the radial matrix element lies beyond the nuclear potential radius (this part is "channel capture" [17,18]), the direct-capture cross section to a given final state can be calculated quite accurately if the $s$-wave neutron scattering length and the $p$-wave single-neutron spectroscopic factor of the final state are known. It has been shown [1,2] that the direct-capture cross section can be constructed from a potential-capture amplitude calculated from

TABLE II. (*Continued.*)

| Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) | Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) |
|---|---|---|---|---|---|---|---|
| 5446 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | 5443.87 *13* | 6236 *5* | | | |
| 5496 *5* | | | 5494.23 *11* | 6260 *5* | | | |
| 5516 *5* | | | | 6275 *5* | | | 6279.86 *7* |
| 5558 *5* | $\frac{1}{2}^+$ | | | 6296 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 5597 *5* | | | | 6330 *5* | | | |
| 5618 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 5617.20 *15* | 5617.33 *6* | 6345 *5* | | | |
| 5637 *5* | | 5632.06 *15* | 5632.17 *6* | 6371 *5* | $\frac{1}{2}^+$ | | |
| 5681 *5* | $\frac{1}{2}^+$ | | 5676.87 *18* | 6425 *5* | | | 6431.34 *9* |
| | | 5702.34 *16* | 5702.11 *18* | 6446 *5* | $(\frac{3}{2}^+, \frac{5}{2}^+)$ | | |
| 5736 *5* | | | | 6473 *5* | | | |
| 5746 *7* | | | | 6499 *5* | | | 6498.21 *17* |
| 5751 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 5754.54 *16* | 5754.67 *9* | 6502.43 *25* | $(\frac{19}{2}^-)$ | | |
| 5772 *5* | | | | 6513 *5* | | | |
| 5794 *5* | | | | 6527 *5* | | | |
| 5810 *5* | | | 5808.80 *8* | 6559 *5* | | | 6562.16 *6* |
| 5833 *5* | $(\frac{3}{2}^+, \frac{5}{2}^+)$ | | | 6575 *5* | | | |
| 5861 *5* | | | | 6597 *5* | | 6598.19 *18* | 6598.48 *5* |
| 5883 *5* | $(\frac{3}{2}^+, \frac{5}{2}^+)$ | | | 6641 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 5913 *5* | | | | 6672 *5* | | | |
| 5936 *5* | | | | 6683 *5* | | | |
| 5957 *5* | | 5957.25 *16* | 5957.56 *7* | 6702 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 5978 *5* | $(\frac{1}{2}^-, \frac{3}{2}^-)$ | | | 6719 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 5989.2 *3* | | | | 6742 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| | | 5994.17 *15* | | 6764 *5* | | | |
| 6003 *5* | | | | 6781 *5* | | | |
| 6024 *5* | $(\frac{1}{2}^-, \frac{3}{2}^-)$ | 6030.54 *16* | 6030.59 *14* | 6800 *5* | | | |
| 6061 *5* | | | | 6828 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 6076.13 *22* | $(\frac{15}{2}^-, \frac{17}{2}^-)$ | | | 6853 *5* | | | |
| | | 6101.39 *16* | 6101.73 *9* | 6874 *5* | | | 6873.64 *7* |
| 6104 *5* | | | 6106.73 *12* | 6913 *5* | $\frac{1}{2}^+$ | | |
| 6139 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 6141.52 *16* | 6141.79 *9* | 6950 *5* | $\frac{1}{2}^+$ | | 6948.41 *15* |
| 6179 *5* | | | 6183.68 *14* | 6969 *5* | | | |
| 6196 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | | 6989 *5* | | | |
| 6216 *5* | $(\frac{3}{2}^+, \frac{5}{2}^+)$ | | | 7018 *5* | | | |

the real part of the scattering wave function in a global optical potential model and a valence amplitude resulting from the neutron width amplitude of one or more local resonance levels that account for the difference between the global potential scattering length and the actual thermal-neutron scattering length. The direct-capture cross sections of the $E1$ transitions observed in the $^{58}$Ni and $^{60}$Ni neutron capture reactions have been calculated in this way; the results are given in this paper. The direct-capture cross sections of transitions in the $^{59}$Ni capture reaction cannot be estimated because there are no spectroscopic factors available from the $(d,p)$ reaction.

The differences between the calculated direct-capture cross sections $\sigma_{\mathrm{dir},\gamma}$ and the experimental values $\sigma_{\mathrm{expt},\gamma}$ are attributed to the admixture of a true compound-nuclear component $\sigma_{\mathrm{CN},\gamma}$ whose value is found from the formula

$$\sigma_{\mathrm{expt},\gamma}{}^{1/2} = \sigma_{\mathrm{CN},\gamma}{}^{1/2} + \sigma_{\mathrm{dir},\gamma}{}^{1/2}. \tag{1}$$

The signs of $\sigma_{\mathrm{expt},\gamma}{}^{1/2}$ and $\sigma_{\mathrm{dir},\gamma}{}^{1/2}$ are unknown, of course. This uncertainty implies that there are two possible values of the compound-nuclear capture cross section for each transition. In many of our previous studies of capture by light nuclei [4,11,16], the values of the measured cross section and

TABLE II. (*Continued.*)

| Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) | Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) |
|---|---|---|---|---|---|---|---|
| 7037 *5* | | | | 7279 *5* | | | |
| 7068 *5* | | | | 7301 *5* | | | |
| 7088 *5* | | | | 7322 *5* | | | |
| 7107 *5* | | | | 7351 *5* | | | |
| 7120 *5* | | | | 7382 *5* | | | |
| 7137 *5* | | | | 7406 *5* | | | |
| 7156 *5* | $\frac{1}{2}^+$ | | | 7432 *5* | | | |
| 7163.9 *3* | $\left(\frac{19}{2}^-, \frac{21}{2}^-\right)$ | | | 7454 *5* | | | |
| 7183 *5* | | | 7187.22 *14* | 7477 *5* | | | |
| 7200 *5* | | | | 7490 *5* | | | |
| 7234 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | | 7503 *5* | | | |
| 7260 *5* | | | | 7520 *5* | | | |
| | | 7270.35 *20* | 7270.54 *7* | 7538 *5* | | | |

$^a$In our notation, 339.36 *7* $\equiv$ 339.36 $\pm$ 0.07, 3187 *5* $\equiv$ 3187 $\pm$ 5, etc.

the calculated direct capture were similar, implying that direct capture was the predominant component and that it could therefore be assumed that the lower value of the pair of compound-nuclear cross-section values was the correct one. In capture by the nickel isotopes, it appears that the direct and compound-nuclear amplitudes are of similar magnitude and therefore we cannot select *a priori* the correct compound-nuclear cross section. We have therefore devised a statistical method to extract the magnitude of the average compound-nuclear capture cross section for each isotope. We compare these averages with theoretical models of the capture mechanism.

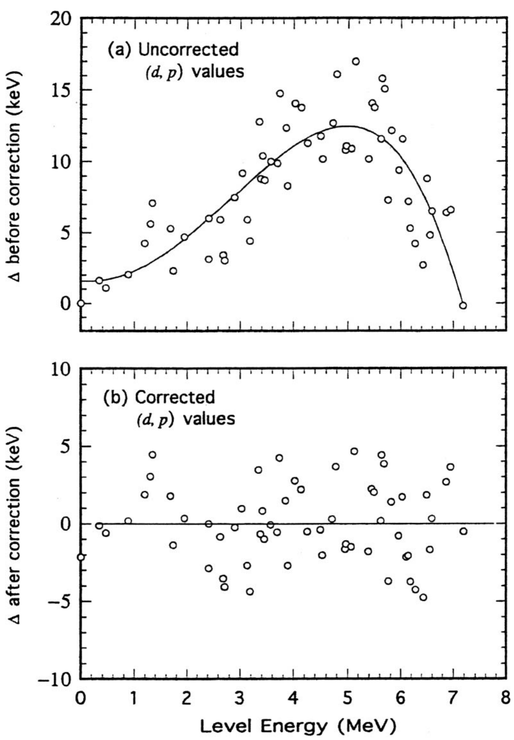


FIG. 3. Deviation $\Delta$ of the $^{59}$Ni level energies measured in the $(d,p)$ reaction [33] from the current $(n,\gamma)$ values. Applying the correction given by the solid line in (a) removes the systematic differences as shown in (b). The corrected values are given in Table II.

Briefly, in this method, we examine certain statistical properties of sequences of $\sigma_{\mathrm{CN},\gamma}$ values drawn from the pairs of values of all measured transitions and thus determine a range of mean $\sigma_{\mathrm{CN},\gamma}$ that is consistent with the Porter-Thomas [99] distribution for individual transitions. In principle, it is possible to do this for all possible sequences, but since there are $2^{26}(\approx 67\times 10^6)$ sequences that can be formed, for example, from the 26 primary $E1$ transitions measured in the $^{58}$Ni capture reaction, we believe that random sampling from the pairs of values should give a sufficiently accurate picture of the statistical properties of the sequences.

We first assume that the expectation value of the compound-nuclear cross section for a transition with energy $\varepsilon_\gamma$ is given by

$$\langle \sigma_{\mathrm{CN},\gamma} \rangle = a(\varepsilon_\gamma)^b. \tag{2}$$

The values of $a$ and $b$ are to be compared with the predictions of various theories. The value of $b$ is expected to lie between 3 (the Weisskopf model [100] and variants) and 5 (Brink-Axel model [101,102]). We use the maximum likelihood method to determine the mean values of $a$ and $b$ for a given sequence ($n$ in number) of $\sigma_{\mathrm{CN},\gamma}$ values (which are labeled $y_i$ with transition energies $\varepsilon_i$). For an assumed Porter-Thomas distribution of $\sigma_{\mathrm{CN},\gamma}/(\varepsilon_\gamma)^b$, the estimates of $a$ and $b$ are given by the simultaneous equations

TABLE III. Energies ($E_\gamma$) and intensities ($I_\gamma$) of $\gamma$ rays from the $^{58}$Ni$(n,\gamma)^{59}$Ni reaction.

| $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 310.78 4 | 3.02 7 | 1188 → 877 | 1256.49 18 | 0.55 7 | unplaced | 1725.33[g] 21 | 4.0 8 | 4140 → 2414 |
| 339.37 3 | 221 5 | 339 → 0 | 1264.18 20 | 0.82 9 | 3686 → 2421 | 1728.71 7 | 3.78 13 | C → 7270 |
| 412.96 9 | 0.64 6 | 877 → 464 | 1269.74 3 | 4.16 8 | 1734 → 464 | 1734.70 3 | 24.0 3 | 1734 → 0 |
| 423.46 3 | 13.7 14 | 1301 → 877 | 1274.5 7 | 0.28 9 | unplaced | 1778.92 20 | 0.81 8 | 4494 → 2715 |
| 450.0 3 | 0.28 5 | 3343 → 2893 | 1275.9 4 | 0.52 13 | 5808 → 4532 | 1782.97 10 | 1.95 10 | unplaced |
| 451.58 14 | 0.34 5 | unplaced | 1301.44 3 | 76.6 8 | 1301 → 0 | 1800.02 17 | 1.37 12 | unplaced |
| 454.77 10 | 0.40 4 | unplaced | 1337.87 5 | 1.68 12 | 1337 → 0 | 1802.0 3 | 0.95 13 | 2679 → 877 |
| 464.94 3 | 1126 28 | 464 → 0 | 1340.28 3 | 27.3 3 | 1679 → 339 | 1812.05 14 | 0.93 7 | C → 7187 |
| 538.54 4 | 4.47 6 | 877 → 339 | 1379.40 19 | 0.50 5 | 5632 → 4252 | 1818.7 6 | 0.32 10 | unplaced |
| 545.87 3 | 4.47 7 | 1734 → 1188 | 1382.1 3 | 0.32 6 | unplaced | 1820.6 3 | 0.72 9 | unplaced |
| 609.2 3 | 0.16 4 | unplaced | 1386.8 3 | 0.31 6 | 6102 → 4715 | 1827.8 5 | 0.23 6 | 3562 → 1734 |
| 723.93 7 | 1.02 6 | 1188 → 464 | 1395.27 3 | 6.68 10 | 1734 → 339 | 1833.3 6 | 0.22 7 | unplaced |
| 731.85 20 | 0.31 5 | unplaced | 1405.7[d] 8 | 0.17 7 | 4968 → 3562 | 1836.97 12 | 1.04 9 | 2715 → 877 |
| 735.2 4 | 0.15 5 | 2414 → 1679 | 1414.2 6 | 0.19 7 | unplaced | 1851.12 17 | 1.05 9 | unplaced |
| 759.3 3 | 0.23 5 | 1948 → 1188 | 1434.12 16 | 0.76 7 | unplaced | 1864.9 4 | 0.50 9 | 5754 → 3889 |
| 766.65 4 | 3.58 8 | 3181 → 2414 | 1438.58 10 | 2.03 8 | 3853 → 2414 | 1872.2 3 | 0.58 9 | unplaced |
| 797.03 6 | 0.97 5 | 4140 → 3343 | 1446.85 4 | 14.86 16 | 3181 → 1734 | 1880.12 5 | 5.61 13 | 3181 → 1301 |
| 801.78 15 | 0.34 4 | 1679 → 877 | 1449.0 4 | 0.48 9 | unplaced | 1889.13 17 | 1.88 16 | 6141 → 4252 |
| 816.3 3 | 0.29 5 | 5069 → 4252 | 1474.81 9 | 1.38 7 | 3889 → 2414 | 1891.0 7 | 0.40 14 | unplaced |
| 818.1 7 | 0.12 5 | unplaced | 1490.6 3 | 0.67 11 | 2679 → 1188 | 1901.9 3 | 0.75 14 | 5632 →3730 |
| 822.6 3 | 0.21 5 | unplaced | 1492.3 4 | 0.48 11 | 5632 → 4140 | 1917.0 9 | 0.19 8 | unplaced |
| 827.9 5 | 0.16 5 | 3853 → 3025 | 1496.2 4 | 0.27 6 | unplaced | 1923.4 4 | 0.74 13 | 4949 → 3025 |
| 836.48 3 | 12.0 13 | 1301 → 464 | 1501.84 3 | 21.23 22 | 3181 → 1679 | 1937.7 3 | 0.93 13 | 4352 → 2414 |
| 840.6 3 | 0.35 6 | 4021 → 3181 | 1513.0 4 | 0.31 6 | 4140 → 2627 | 1943.3 4 | 0.73 13 | 4968 → 3025 |
| 849.36 4 | 3.4 8 | 1188 → 339 | 1536.90 3 | 27.3 4 | 2414 → 877 | 1948.3 4 | 1.3 2 | 1948 → 0 |
| 877.94 3 | 325 3 | 877 → 0 | 1539.5 3 | 0.58 8 | unplaced | 1949.92 3 | 67.6 14 | 2414 → 464 |
| 962.00 19 | 0.34 5 | 1301 → 339 | 1545.54 11 | 0.96 6 | unplaced | 1992.76 4 | 21.21 22 | 3181 → 1188 |
| 998.50 3 | 3.65 8 | 1337 → 339 | 1555.8[e] 3 | 0.59 9 | 2893 → 1337 | 2001.93 10 | 2.34 12 | unplaced |
| 1006.3 4 | 0.22 5 | 3686 → 2679 | 1557.7 7 | 0.21 8 | unplaced | 2015.53 3 | 16.94 19 | 2893 → 877 |
| 1008.9 4 | 0.22 5 | 4352 → 3343 | 1567.5 6 | 0.18 6 | unplaced | 2042.0[h] 7 | 1.0 3 | 5384 → 3343 |
| 1031.5 3 | 0.34 6 | unplaced | 1572.1 5 | 0.23 7 | 4949 → 3377 | 2050.78 15 | 1.35 11 | C → 6948 |
| 1045.76 18 | 0.59 6 | unplaced | 1592.06 8 | 1.58 8 | 2893 → 1301 | 2075.37 6 | 3.44 12 | 4968 → 2893 |
| 1048.8 3 | 0.38 6 | unplaced | 1599.8 6 | 0.22 6 | 4021 → 2421 | 2094.05 16 | 1.21 9 | unplaced |
| 1051.0 6 | 0.18 6 | 3730 → 2679 | 1607.07 16 | 1.21 10 | 4021 → 2414 | 2112.0 3 | 0.74 9 | 3413 → 1301 |
| 1078.27 10 | 0.87 6 | unplaced | 1609.0[f] 3 | 0.89 11 | 1948 → 339 | 2125.60 7 | 2.50 12 | C → 6873 |
| 1103.2 4 | 0.22 5 | 3730 → 2627 | 1613.8 4 | 0.35 6 | unplaced | 2147.77 3 | 17.31 20 | 3025 → 877 |
| 1113.38 6 | 2.25 7 | 2414 → 1301 | 1617.0 5 | 0.29 7 | 5069 → 3452 | 2154.3 4 | 0.57 11 | 3343 → 1188 |
| 1147.98 10 | 0.64 5 | 3562 → 2414 | 1623.49 13 | 0.93 7 | unplaced | 2174.55 21 | 1.13 11 | unplaced |
| 1156.1 5 | 0.16 4 | unplaced | 1663.7 8 | 0.22 9 | 3343 → 1679 | 2177.3 9 | 0.26 9 | 6030 → 3853 |
| 1158.6 3 | 0.26 5 | 2893 → 1734 | 1665.8 3 | 0.55 9 | unplaced | 2242.9 5 | 0.32 8 | unplaced |
| 1163.5 3 | 0.38 8 | unplaced | 1679.73 14 | 4.3 4 | 1679 → 0 | 2248.2[i] 3 | 0.51 8 | 3126 → 877 |
| 1188.77 3 | 76.9 8 | 1188 → 0 | 1688.00 14 | 1.08 9 | 3025 → 1337 | 2254.68 17 | 0.99 8 | 5632 → 3377 |
| 1210.5 4 | 0.37 8 | 3889 → 2679 | 1695.64 25 | 0.78 11 | unplaced | 2258.03 13 | 1.38 9 | 6279 → 4021 |
| 1213.81 9 | 2.95 18 | 2893 → 1679 | 1704.67 6 | 4.30 13 | 2893 → 1188 | 2261.44 15 | 2.42 15 | 3562 → 1301 |
| 1214.7 4 | 0.42 15 | 1679 → 464 | 1717.65 21 | 0.95 11 | 3452 → 1734 | 2263.35[j] 25 | 1.14 17 | 3452 → 1188 |
| 1226.08 3 | 17.9 3 | 2414 → 1188 | 1724.17 12 | 7.43 9 | 3025 → 1301 | 2267.96 11 | 1.46 8 | unplaced |

$$a = \left[\sum_i y_i/(\varepsilon_i)^b\right] \Big/ n \tag{3}$$

and

$$a\sum_i \ln \varepsilon_i - \sum_i y_i(\varepsilon_i)^{-b} \ln \varepsilon_i = 0. \tag{4}$$

In practice, we assume a value for $b$, calculate $a$, and the left-hand side of Eq. (4) which we call $Mb$. We also calculate the maximum likelihood estimator for the $\chi$-squared family of statistical distributions with characterizing parameter $\nu$ (known as the "number of degrees of freedom"). The Porter-Thomas distribution is a member of this family with $\nu=1$. The expression for this maximum likelihood estimator is

TABLE III. (*Continued.*)

| $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 2287.61 *17* | 1.25 *14* | 2627 → 339 | 2723.2 *5* | 0.37 *9* | 5617 → 2893 | 3184.56[s] *25* | 1.64 *13* | 6598 → 3413 |
| 2297.0 *4* | 0.42 *10* | unplaced | 2727.6 *3* | 0.76 *12* | unplaced | 3190.39 *8* | 2.84 *10* | C → 5808 |
| 2303.53 *5* | 5.94 *14* | 3181 → 877 | 2739.0 *4* | 0.61 *9* | 5632 → 2893 | 3200.54 *7* | 4.87 *12* | 3540 → 339 |
| 2323.5 *3* | 0.54 *9* | unplaced | 2757.59 *9* | 2.55 *12* | 5384 → 2627 | 3214.7 *4* | 0.55 *11* | 4949 → 1734 |
| 2328.7 *5* | 0.87 *25* | unplaced | 2763.7 *4* | 0.58 *9* | 6106 → 3343 | 3221.04 *5* | 21.5 *3* | 3686 → 464 |
| 2330.8 *4* | 1.55 *20* | unplaced | 2771.07 *24* | 0.82 *9* | unplaced | 3234.2 *4* | 0.59 *11* | 4968 → 1734 |
| 2345.2 *4* | 0.45 *9* | unplaced | 2786.5 *3* | 0.69 *9* | 3126 → 339 | 3244.50 *9* | 3.11 *13* | C → 5754 |
| 2380.4 *5* | 0.44 *8* | unplaced | 2808.09[n] *5* | 12.25 *20* | 3686 → 877 | 3250.0 *4* | 0.70 *10* | 6431 → 3181 |
| 2384.64 *4* | 9.97 *14* | 3686 → 1301 | 2815.52 *14* | 2.14 *12* | C → 6183 | 3256.63 *15* | 1.60 *10* | unplaced |
| 2400.75 *5* | 7.97 *11* | C → 6598 | 2823.1 *4* | 0.74 *11* | unplaced | 3262.01[t] 18 | 1.59 *16* | 4140 → 877 |
| t 2414.86 *4* | 18.0 *3* | 2414 → 0 | 2833.18 *11* | 2.74 *13* | 4021 → 1188 | 3265.23 *7* | 7.75 *16* | 3730 → 464 |
| 2421.89[k] *6* | 4.02 *10* | 2421 → 0 | 2838.67 *11* | 4.03 *17* | 4140 → 1301 | 3268.8 *4* | 0.89 *12* | 4949 → 1679 |
| 2425.06 *19* | 1.06 *8* | unplaced | 2842.07 *6* | 67.3 *7* | 3181 → 339 | 3289.3 *4* | 0.67 *11* | 4968 → 1679 |
| 2428.53 *4* | 9.7 *12* | 2893 → 464 | 2852.2 *4* | 0.76 *12* | 3730 → 877 | 3295.57 *20* | 2.35 *25* | unplaced |
| 2437.06 *6* | 3.54 *9* | C → 6562 | 2857.40 *12* | 4.67 *15* | C → 6141 | 3297.0 *3* | 4.9 *6* | C → 5702 |
| 2450.9 *9* | 0.23 *6* | 5632 → 3181 | 2878.22 *18* | 1.53 *18* | 3343 → 464 | 3303.20 *16* | 1.66 *11* | unplaced |
| 2460.2 *4* | 0.44 *4* | 4140 → 1679 | 2892.3 *5* | 5.1 *7* | C → 6106 | 3317.58 *23* | 1.09 *11* | unplaced |
| 2465.5[l] *4* | 0.39 *8* | 5808 → 3343 | 2893.3 *3* | 11.7 *12* | 2893 → 0 | 3322.7 *5* | 0.53 *11* | C → 5676 |
| 2483.16 *12* | 1.41 *8* | unplaced | 2897.50 *9* | 4.72 *17* | C → 6101 | 3334.2 *6* | 0.39 *12* | 5069 → 1734 |
| 2491.3[m] *4* | 0.50 *8* | 5617 → 3126 | 2911.7[o] *8* | 0.82 *25* | 3377 → 464 | 3339.2 *5* | 0.46 *11* | 5754 → 2414 |
| 2497.33 *6* | 8.35 *15* | 3686 → 1188 | 2927.0 *4* | 0.54 *9* | unplaced | 3346.62 *5* | 9.34 *14* | 3686 → 339 |
| 2499.18 *11* | 2.54 *24* | 3377 → 877 | 2948.3 *3* | 1.29 *11* | 3413 → 464 | 3367.02 *6* | 10.65 *16* | C → 5632 |
| 2500.6 *3* | 1.23 *15* | C → 6498 | 2951.06 *15* | 2.19 *12* | 4252 → 1301 | 3374.9 *7* | 0.60 *17* | 4252 → 877 |
| 2505.1 *5* | 0.36 *9* | 5957 → 3452 | 2963.28 *17* | 1.21 *9* | unplaced | 3377.34 *17* | 2.72 *18* | 4715 → 1337 |
| 2535.3 *4* | 0.76 *12* | 3413 → 877 | 2968.5 *7* | 12.6 *3* | C → 6030 | 3381.83 *6* | 8.95 *15* | C → 5617 |
| 2541.30 *22* | 1.19 *12* | 3730 → 1188 | 2976.5 *9* | 0.18 *8* | unplaced | 3388.4 *5* | 0.97 *21* | 3853 → 464 |
| 2545.7 *4* | 0.69 *12* | 4494 → 1948 | 2980.2[p] *4* | 0.60 *10* | 6106 → 3126 | 3390.6 *4* | 1.56 *20* | 3730 → 339 |
| 2554.06 *4* | 62.6 *8* | 2893 → 339 | 2987.5[q] *5* | 0.41 *10* | 3452 → 464 | 3393.8 *5* | 0.61 *12* | 5808 → 2414 |
| 2567.89 *9* | 3.20 *14* | C → 6431 | 3003.9 *9* | 1.9 *5* | 3343 → 339 | 3437.7 *6* | 0.44 *10* | unplaced |
| 2574.29 *21* | 1.24 *13* | 3452 → 877 | 3005.2 *5* | 3.0 *5* | 6030 → 3025 | 3452.08[u] *17* | 1.33 *13* | 3452 → 0 |
| 2616.2 *3* | 0.97 *13* | unplaced | 3025.63 *5* | 17.65 *20* | 3025 → 0 | 3496.9 *6* | 0.52 *12* | 6873 → 3377 |
| 2618.6 *3* | 1.03 *13* | unplaced | 3029.17 *20* | 1.69 *12* | 5443 → 2414 | 3504.94 *12* | 3.28 *20* | C → 5494 |
| 2626.70 *19* | 1.48 *16* | 2627 → 0 | 3037.73 *6* | 6.53 *15* | 3377 → 339 | 3514.05 *18* | 2.16 *18* | 3853 → 339 |
| 2629.21 *16* | 1.76 *12* | unplaced | 3041.60 *7* | 6.68 *14* | C → 5957 | 3525.8 *8* | 0.38 *12* | 4715 → 1188 |
| 2633.38 *22* | 1.02 *11* | unplaced | 3045.66 *17* | 1.79 *12* | 6498 → 3452 | 3545.2 *3* | 1.38 *17* | unplaced |
| 2636.61 *22* | 1.00 *11* | unplaced | 3051.5 *3* | 0.83 *16* | 4352 → 1301 | 3555.47 *16* | 2.74 *20* | C → 5443 |
| 2645.94 *19* | 1.51 *10* | unplaced | 3063.85[r] *11* | 2.86 *13* | 4252 → 1188 | 3562.82 *7* | 9.1 *3* | 3562 → 0 |
| 2653.90 *18* | 1.57 *12* | 5069 → 2414 | 3072.2 *4* | 0.64 *12* | 5494 → 2421 | 3614.38 *7* | 7.4 *3* | C → 5384 |
| 2662.0 *3* | 0.40 *13* | 3540 → 877 | 3111.0 *3* | 1.06 *12* | unplaced | 3635.2 *5* | 0.69 *15* | unplaced |
| 2664.80 *19* | 1.19 *11* | 3853 → 1188 | 3113.0 *8* | 0.50 *16* | 3452 → 339 | 3667.53 *18* | 1.80 *14* | 4968 → 1301 |
| 2679.6 *3* | 0.90 *12* | 2679 → 0 | 3125.6 *6* | 0.52 *12* | 3126 → 0 | 3675.23 *4* | 39.4 *5* | 4140 → 464 |
| 2684.97 *5* | 16.0 *3* | 3562 → 877 | 3136.6 *3* | 0.99 *13* | 6030 → 2893 | 3679.2 *5* | 1.08 *16* | 6101 → 2421 |
| 2689.0 *4* | 0.86 *12* | 6141 → 3452 | 3143.78 *14* | 3.03 *15* | 4021 → 877 | 3685.98 *15* | 16.8 *9* | 3686 → 0 |
| 2703.78 *14* | 1.71 *11* | unplaced | 3156.28 *16* | 1.38 *11* | 4494 → 1337 | 3705.3 *5* | 0.55 *12* | 5384 → 1679 |
| 2716.57 *10* | 3.55 *14* | 3181 → 464 | 3163.5 *4* | 1.12 *20* | 4352 → 1188 | 3712.07 *18* | 2.44 *20* | unplaced |
| 2719.38 *7* | 4.89 *15* | C → 6279 | 3181.45 *6* | 15.50 *17* | 3181 → 0 | 3719.1 *6* | 0.75 *18* | 6141 → 2421 |

$$M\nu = \left[ \sum_i (\ln y_i - b \ln \varepsilon_i) \right] \bigg/ n - \ln a. \qquad (5)$$

The expectation value of $M\nu$ is $-1.24$ for $\nu=1$ with a standard deviation depending on $n$. For $n=26$ ($^{58}$Ni) the standard deviation is $\pm 0.28$, while that for $Mb$ is $\pm 1.25$. For $n=16$ ($^{60}$Ni), it is $\pm 0.34$ for $M\nu$ and $\pm 1.5$ for $Mb$. Sequences of $\sigma_{\mathrm{CN},\gamma}$ values that lie within these ranges of the maximum likelihood estimators are considered statistically acceptable and thus give us an estimate of the mean value of $a$ and its error range for a given value of $b$. More detail on the application of this method can be found in Secs. IV C and VI C.

### G. Shell-model calculations of energy levels

We have carried out large-scale shell-model calculations for the three nickel isotopes $^{59,60,51}$Ni using the shell-model

TABLE III. (*Continued.*)

| $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 3730.11[v] 5 | 2.0[w] 3 | 3730 → 0 | 4507.9 5 | 0.80 25 | 7187 → 2679 | 5617.12 18 | 3.10 17 | 5617 → 0 |
| 3730.35[v] 10 | 2.7[x] 3 | 7270 → 3540 | 4604.1 7 | 0.44 13 | 5069 → 464 | 5621.6 14 | 5.29 20 | C → 3377 |
| 3734.0 9 | 0.27 13 | 7187 → 3452 | 4609.3 4 | 0.66 14 | 4949 → 339 | 5632.4 9 | 0.47 15 | 5632 → 0 |
| 3767.3 5 | 0.80 16 | 5069 → 1301 | 4629.7 6 | 0.61 14 | 4968 → 339 | 5641.65 25 | 2.16 20 | 6106 → 464 |
| 3779.94 7 | 10.4 3 | 4968 → 1188 | 4646.69 9 | 5.67 25 | C → 4352 | 5655.5 5 | 1.18 18 | C → 3343 |
| 3787.5 4 | 1.12 18 | 4252 → 464 | 4715.16 6 | 12.0 4 | 4715 → 0 | 5682.5 7 | 0.67 16 | unplaced |
| 3800.69 15 | 3.05 24 | 4140 → 339 | 4729.8 5 | 0.83 15 | 5069 → 339 | 5701.5 4 | 1.38 17 | 5702 → 0 |
| 3838.1 5 | 0.71 16 | unplaced | 4746.19 10 | 5.84 25 | C → 4252 | 5754.6 7 | 0.86 22 | 5754 → 0 |
| 3853.71 16 | 2.37 18 | 3853 → 0 | 4805.03 16 | 2.96 19 | 6106 → 1301 | 5817.35 5 | 151.9 20 | C → 3181 |
| 3857.8 3 | 1.36 17 | 6279 → 2421 | 4824.1 5 | 1.10 18 | 5702 → 877 | 5843.7 7 | 1.05 25 | 6183 → 339 |
| 3867.15 20 | 2.06 19 | C → 5131 | 4841.4 6 | 0.55 15 | 6030 → 1188 | 5887.1 6 | 0.94 17 | unplaced |
| 3879.8 6 | 0.58 15 | 5069 → 1188 | 4858.84 3 | 64.2 8 | C → 4140 | 5901.6 6 | 0.90 18 | unplaced |
| 3889.47 15 | 3.06 19 | 3889 → 0 | 4912.1 9 | 0.41 15 | 6101 → 1188 | 5935.0 9 | 0.50 17 | unplaced |
| 3897.7 7 | 0.50 15 | 5632 → 1734 | 4919.8 3 | 1.32 21 | 5384 → 464 | 5956.9 3 | 2.5 3 | 5957 → 0 |
| 3905.8 7 | 0.51 15 | unplaced | 4949.02 10 | 11.7 5 | 4949 → 0 | 5973.14 5 | 36.8 8 | C →3025 |
| 3912.7 6 | 0.49 14 | 4252 → 339 | 4968.6 4 | 1.79 23 | 4968 → 0 | 5994.0 4 | 1.24 17 | unplaced |
| 3930.06 5 | 16.7 4 | C → 5069 | 4977.27 8 | 10.6 4 | C → 4021 | 6030.4 3 | 1.73 17 | 6030 → 0 |
| 3937.5 8 | 0.39 9 | 5617 → 1679 | 5029.6 9 | 0.38 18 | 5494 → 464 | 6105.38 6 | 98.0 14 | C → 2893 |
| 3952.6 4 | 1.11 16 | 5632 → 1679 | 5044.9 4 | 1.06 17 | 5384 → 339 | 6111.6 4 | 1.48 23 | unplaced |
| 3972.64 21 | 1.51 17 | unplaced | 5068.97 13 | 4.47 22 | 5069 → 0 | 6141.42 23 | 2.37 19 | 6141 → 0 |
| 3989.9 4 | 0.72 14 | unplaced | 5078.9 5 | 0.94 16 | 5957 → 877 | 6160.0 7 | 0.74 16 | unplaced |
| 4021.69 21 | 1.73 16 | 4021 → 0 | 5109.37 12 | 4.36 21 | C → 3889 | 6258.8 3 | 1.56 16 | 6598 → 339 |
| 4030.26 4 | 20.9 4 | C → 4968 | 5113.8 9 | 0.49 16 | unplaced | 6279.0 9 | 0.38 16 | 6279 → 0 |
| 4049.99 5 | 14.1 3 | C → 4949 | 5130.7 3 | 1.40 15 | unplaced | 6371.2 9 | 0.55 16 | C → 2627 |
| 4056.1 6 | 0.56 14 | unplaced | 5140.3 6 | 0.79 15 | unplaced | 6391.9 5 | 1.10 17 | 7270 → 877 |
| 4067.4 6 | 0.64 15 | 4532 → 464 | 5145.34 10 | 5.91 23 | C → 3853 | 6401.2 7 | 0.77 16 | unplaced |
| 4071.5 4 | 0.90 15 | 4949 → 877 | 5152.37[z] 23 | 1.87 16 | 6030 → 877 | 6408.0 5 | 1.06 17 | 6873 → 464 |
| 4083.0 5 | 0.74 15 | 5384 → 1301 | 5169.2 9 | 0.35 14 | unplaced | 6499.0 8 | 0.65 15 | unplaced |
| 4090.6 5 | 0.67 14 | 4968 → 877 | 5224.0 4 | 0.95 15 | 6562 → 1337 | 6516.2 9 | 0.43 15 | unplaced |
| 4119.4 9 | 0.38 16 | unplaced | 5228.6 7 | 0.40 13 | 6106 → 877 | 6561.7 8 | 0.79 22 | 6562 → 0 |
| 4140.10[y] 8 | 10.0 4 | 4140 → 0 | 5268.79 5 | 12.3 4 | C → 3730 | 6576.8 6 | 1.47 23 | C → 2421 |
| 4191.04 10 | 4.72 19 | 5069 → 877 | 5277.5 5 | 0.85 15 | 5617 → 339 | 6583.98 6 | 109.4 15 | C → 2414 |
| 4216.08 20 | 1.87 20 | C → 4782 | 5287.3 6 | 0.84 18 | unplaced | 6598.15 25 | 3.5 3 | 6598 → 0 |
| 4237.6 5 | 0.76 16 | unplaced | 5292.7 4 | 1.49 19 | 5632 → 339 | 6617.5 9 | 0.60 19 | unplaced |
| 4250.6 5 | 1.6 3 | 4715 → 464 | 5312.95 4 | 75.4 9 | C → 3686 | 6644.2 9 | 0.44 18 | unplaced |
| 4253.6 4 | 2.20 5 | 5131 → 877 | 5362.5 3 | 1.93 21 | 5702 → 339 | 6752.6 8 | 0.58 16 | unplaced |
| 4283.77 5 | 18.5 5 | C → 4715 | 5384.6 7 | 0.78 23 | 5384 → 0 | 6872.8 8 | 0.63 15 | 6873 → 0 |
| 4295.9 4 | 0.89 15 | 6030 → 1734 | 5409.4 6 | 0.88 18 | 6598 → 1188 | 6892.0 9 | 0.46 14 | unplaced |
| 4305.2 3 | 1.42 16 | 5494 → 1188 | 5436.00 4 | 26.3 5 | C → 3562 | 6940.3 8 | 0.53 15 | unplaced |
| 4317.5 3 | 1.17 16 | 4782 → 464 | 5458.79 18 | 3.19 22 | C → 3540 | 6947.6 4 | 1.33 16 | 6948 → 0 |
| 4352.4 3 | 2.22 19 | 4352 → 0 | 5469.4 6 | 0.68 16 | 5808 → 339 | 7050.1 9 | 0.43 16 | C → 1948 |
| 4375.31 19 | 2.44 19 | 5676 → 1301 | 5492.1 6 | 0.68 14 | 5957 → 464 | 7264.18 6 | 9.3 3 | C → 1734 |
| 4428.24 19 | 1.70 17 | 5617 → 1188 | 5546.8 14 | 2.87 17 | C → 3452 | 7697.30 6 | 51.7 7 | C → 1301 |
| 4452.3 9 | 0.30 12 | 6873 → 2421 | 5553.0 4 | 0.98 14 | 6431 → 877 | 8120.75 7 | 177 3 | C → 877 |
| 4466.2 6 | 0.52 13 | C → 4532 | 5566.4 8 | 0.61 16 | unplaced | 8533.71 7 | 996 15 | C → 464 |
| 4504.7 3 | 2.33 18 | C → 4494 | 5585.2 6 | 0.70 14 | C → 3413 | 8998.63 7 | 2082 30 | C → 0 |

code ANTOINE [103]. The full *pf* shell (orbits $0f_{7/2}, 1p_{3/2}, 0f_{5/2}$, and $1p_{1/2}$) was used as valence space with the KB3G effective interaction [104]. Because the number of possible levels is very large, it is necessary to limit the total number of possible configurations using some truncation scheme. The configurations included in the calculations are of the type $(f_{7/2})^{16-t}, (p_{3/2}, f_{5/2}, p_{1/2})^{n+t}$, where $n=3,4$, and 5 for $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni, respectively, and $t$, which is either 0, 1, 2, or 3, is the additional particles excited outside the $f_{7/2}$ shell.

## IV. REACTION $^{58}$Ni$(n,\gamma)$

### A. Skeleton level scheme of $^{59}$Ni

Table I lists the variety of previous measurements that have been carried out concerning the energy levels in $^{59}$Ni.

TABLE III. (*Continued.*)

[a] In our notation, 310.78 *4* ≡ 310.78 ± 0.04, etc.
[b] In our notation, 3.02 *7* ≡ 3.02 ± 0.07, etc. Multiply by 0.0243 to obtain photons per 100 thermal neutron captures.
[c] C denotes the capturing state.
[d] Can also be placed as a 4782 → 3377 transition.
[e] Can also be placed as a 5808 → 4252 transition.
[f] Can also be placed as a 6141 → 4532 transition.
[g] Can also be placed as a 4352 → 2627 transition.
[h] Can also be placed as a 5494 → 3452 transition or as a 3343 → 1301 transition.
[i] Can also be placed as a 6101 → 3853 transition.
[j] Can also be placed as a 5676 → 3413 transition.
[k] Can also be placed as a 6562 → 4140 transition.
[l] Can also be placed as a 3343 → 877 transition.
[m] Can also be placed as a 5384 → 2893 transition.
[n] Can also be placed as a 6948 → 4140 transition.
[o] Can also be placed as a 6598 → 3686 transition.
[p] Can also be placed as a 4715 → 1734 transition.
[q] Can also be placed as a 5702 → 2715 transition.
[r] Can also be placed as a 5957 → 2893 transition.
[s] Can also be placed as a 6562 → 3377 transition.
[t] Can also be placed as a 6948 → 3686 transition.
[u] Can also be placed as a 5131 → 1679 transition.
[v] Deduced for one member of a close doublet from level energies obtained by an overall least-squares fit excluding this transition.
[w] Inferred from the measured intensity of the 3730.11 + 3730.35 doublet.
[x] Inferred from the intensity balance requirement for the 7270 keV level.
[y] Can also be placed as a 6562 → 2421 transition.
[z] Can also be placed as a 5617 → 464 transition.

Based on these measurements, we have assembled a list (see Table II) of ~217 levels below 7.54 MeV. Eleven works [19–21,23,31,33,35–38,41] out of the 25 listed in Table I contain additional information leading to $J^{\pi}$ values for ~90 levels. We have critically evaluated this information and our adopted $J^{\pi}$ values are also listed in Table II.

The $^{58}$Ni$(d,p)^{59}$Ni study by Cosman, Paris, Sperduto, and Enge [33] is the backbone of the skeleton level scheme. Herein lies a problem. These authors have listed 173 levels up to an excitation energy of 7.5 MeV. They estimate the uncertainties in the excitation energies as "±5 keV for the lowest states and ±10 keV for the highest excited states." Quite early in our attempts to construct an $(n,\gamma)$ level scheme, we began to suspect that serious systematic uncertainties are present in the $(d,p)$ excitation energies. This suspicion arose while trying to establish the expected one-to-one correspondence between energy levels populated strongly by primary $\gamma$ rays in the $(n,\gamma)$ reaction and levels with $\ell_n=1$ angular distributions in the $(d,p)$ reaction. The systematic differences that exist between the $(d,p)$ and $(n,\gamma)$ level energies are illustrated in Fig. 3(a). It is then straightforward to apply corrections to the $(d,p)$ energies. These corrected values are used in Table II in constructing a cumulative list of ~217 levels from a variety of experiments. About 30% of these are populated significantly in the current (thermal $n,\gamma$) study.

### B. Thermal-neutron capture $\gamma$-ray data

The $^{58}$Ni$(n,\gamma)$ reaction with thermal neutrons has been studied previously with Ge detectors at the Pelindaba, McMaster, and Grenoble reactors by Hofmeyr [27], Ishaq *et al.* [28], and Harder *et al.* [30], respectively. The study by Harder *et al.* [30] at Grenoble is the most extensive of these three studies. The table of $\gamma$ rays published in Ref. [30] is an abridged version of a more extensive table contained in the unpublished thesis of Harder [29]. (In the published paper, she chose to omit the unplaced $\gamma$ rays and those that were very weak and therefore questionable.) The thesis [29] was made available to us and this report was of considerable help in our analysis of the $\gamma$-ray spectra.

The current (thermal $n,\gamma$) measurements were made with a 120.5-mg, 99.93%-enriched $^{58}$NiO target. The results are given in Table III. In most measurements made at the Los Alamos Omega West reactor, the detection limit for a $\gamma$ ray in the 0.1–10.0 MeV region is typically 2–4 photons per $10^4$ thermal-neutron captures, which is a factor of 2–5 better than in measurements at other facilities also using Ge detectors. (The weakest $\gamma$ ray that we have detected is the 7120-keV, primary transition from the neutron-capturing state to the 696-keV, first-excited state in $^{144}$Nd with an intensity of only ~3 photons per $10^5$ captures [105], but this was a case requiring special efforts.) The limitations on sensitivity arise as a result of the Compton tails of higher energy $\gamma$ rays and room background. In the case of the $^{58}$Ni$(n,\gamma)$ reaction, however, the sensitivity was much better than usual. We have detected nearly 50 $\gamma$ rays with intensities smaller than one photon per $10^4$ captures, including ten $\gamma$ rays below 2 MeV with intensities less than five photons per $10^5$ captures. There is a reason for this apparent improvement in the sensitivity. In the $^{58}$Ni(thermal $n,\gamma$) reaction, the two highest-energy $\gamma$ rays at 8534 and 8999 keV account for nearly 75% of the capture cross section of ~4 b. The Compton backgrounds from these two $\gamma$ rays are either eliminated by the pair-spectrometer requirement or reduced by Compton suppression. The ability to detect other $\gamma$ rays remains largely unaffected except that when the sensitivity is expressed in units of photons per $10^4$ neutron captures, there is now an apparent gain by a factor of ~4.

The level scheme resulting from this work is presented in Table IV. Nearly three-fourths of the observed $\gamma$ rays, totalling 414 in number, have been incorporated into this scheme consisting of 65 bound levels. According to Harder *et al.* [30], 41 levels in $^{59}$Ni are populated significantly in the (thermal $n,\gamma$) reaction. We confirm this conclusion for all except the levels at 3858.26 and 5994.17 keV. The 3858.26-keV level was introduced in Ref. [30] to accommodate a primary $\gamma$ ray of energy 5140.76 keV and secondary $\gamma$ rays of energies 2178.63, 2980.59, and 3858.04 keV. The strongest of the secondary $\gamma$ rays at 2178.63 keV has a reported intensity of eight photons per $10^4$ neutron captures. The relevant portion of the $\gamma$-ray spectrum from 2140 to 2190 keV is shown in Fig. 4. We do see a very weak shoulder at 2177.3 keV but the intensity of a peak at this energy is only ~6 photons per

TABLE IV. Level scheme of $^{59}$Ni from this work in tabular form.

| $E$(level)[a] (keV) | $J^\pi$ | Deexciting $\gamma$ rays[b] | $I_\gamma$ (in)[a] (mb) | $I_\gamma$ (out)[a] (mb) | $I_\gamma$ (in − out)[a] (mb) |
|---|---|---|---|---|---|
| 0.0 | $\frac{3}{2}^-$ | | 4110 *50* | | 4110 *50* |
| 339.399 *16* | $\frac{3}{2}^-$ | 339.37 | 219.7 *17* | 221 *5* | −1 *6* |
| 464.935 *16* | $\frac{1}{2}^-$ | 464.94 | 1179 *16* | 1130 *30* | 50 *40* |
| 877.961 *15* | $\frac{3}{2}^-$ | 877.94, 538.54, 412.96 | 318 *4* | 330 *3* | −12 *5* |
| 1188.789 *16* | $\frac{5}{2}^-$ | 1188.77, 849.36, 723.93, 310.78 | 84.3 *8* | 84.3 *12* | −0.1 *14* |
| 1301.437 *17* | $\frac{1}{2}^-$ | 1301.44, 962.00, 836.48, 423.46 | 97.5 *9* | 102.6 *21* | −5.1 *23* |
| 1337.89 *3* | $\frac{7}{2}^-$ | 1337.87, 998.50 | 6.7 *3* | 5.33 *15* | 1.4 *4* |
| 1679.700 *24* | $\frac{5}{2}^-$ | 1679.73, 1340.28, 1214.7, 801.78 | 28.6 *4* | 32.4 *6* | −3.8 *7* |
| 1734.687 *17* | $\frac{3}{2}^-$ | 1734.70, 1395.27, 1269.74, 545.87 | 28.5 *5* | 39.3 *4* | −10.8 *6* |
| 1948.32 *17* | $\frac{7}{2}^-$ | 1948.3, 1609.0, 759.3 | 1.12 *20* | 2.42 *24* | −1.3 *3* |
| 2414.892 *17* | $\frac{3}{2}^-$ | 2414.86, 1949.92, 1536.90, 1226.08, 1113.38, 735.2 | 127.5 *18* | 133.2 *16* | −5.7 *23* |
| 2421.95 *6* | | 2421.89 | 6.6 *5* | 4.02 *10* | 2.6 *5* |
| 2627.05 *8* | $\frac{7}{2}^-$ | 2626.70, 2287.61 | 3.63 *22* | 2.73 *22* | 0.9 *3* |
| 2679.57 *14* | $\left(\frac{5}{2}^-\right)$ | 2679.6, 1802.0, 1490.6 | 1.6 *3* | 2.52 *21* | −1.0 *4* |
| 2715.03 *11* | | 1836.97 | 0.81 *8* | 1.04 *9* | −0.23 *12* |
| 2893.521 *20* | $\frac{3}{2}^{(-)}$ | 2893.3, 2554.06, 2428.53, 2015.53, 1704.67, 1592.06, 1555.8, 1213.81, 1158.6 | 103.7 *15* | 110.6 *19* | −6.9 *24* |
| 3025.769 *25* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 3025.63, 2147.77, 1724.17, 1688.00 | 41.4 *10* | 43.5 *4* | −2.0 *11* |
| 3126.10 *17* | | 3125.6, 2786.5, 2248.2 | 1.10 *13* | 1.72 *17* | −0.62 *22* |
| 3181.564 *18* | $\frac{3}{2}^{(-)}$ | 3181.45, 2842.07, 2716.57, 2303.53, 1992.76, 1880.12, 1501.84, 1446.85, 766.65 | 153.2 *20* | 158.8 *9* | −5.6 *22* |
| 3343.22 *6* | | 3003.9, 2878.22, 2154.3, 1663.7, 450.0 | 4.3 *4* | 4.5 *6* | −0.2 *7* |
| 3377.22 *6* | | 3037.73, 2911.7, 2499.18, | 7.0 *3* | 9.9 *4* | −2.9 *5* |
| 3413.55 *15* | $\frac{1}{2}^+$ | 2948.3, 2535.3, 2112.0, | 2.34 *20* | 2.79 *19* | −0.5 *3* |
| 3452.34 *9* | $\frac{3}{2}^-$ | 3452.08, 3113.0, 2987.5, 2574.29, 2263.35, 1717.65 | 6.4 *3* | 5.6 *4* | 0.9 *5* |
| 3540.06 *6* | | 3200.54, 2662.0 | 5.9 *4* | 5.27 *18* | 0.6 *5* |
| 3562.98 *3* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3562.82, 2684.97, 2261.44, 1827.8, 1147.98 | 26.5 *5* | 28.4 *5* | −1.9 *7* |
| 3686.110 *22* | $\left(\frac{3}{2}\right)^+$ | 3685.98, 3346.62, 3221.04, 2808.09, 2497.33, 2384.64, 1264.18, 1006.3 | 75.4 *9* | 79.3 *10* | −3.8 *14* |
| 3730.25 *5* | $\left(\frac{3}{2}\right)^-$ | 3730.20, 3390.6, 3265.23, 2852.2, 2541.30, 1103.2, 1051.0 | 13.1 *5* | 13.7 *5* | 0.6 *6* |
| 3853.63 *6* | $\frac{3}{2}^-$ | 3853.71, 3514.05, 3388.4, 2664.80, 1438.58, 827.9 | 6.17 *25* | 8.9 *4* | −2.7 *5* |
| 3889.70 *7* | | 3889.47, 1474.81, 1210.5 | 4.86 *23* | 4.81 *22* | 0.1 *4* |
| 4021.87 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 4021.69, 3143.78, 2833.18, 1607.07, 1599.8, 840.6 | 12.0 *5* | 9.3 *3* | 2.7 *5* |
| 4140.242 *25* | $\frac{3}{2}^-$ | 4140.10, 3800.69, 3675.23, 3262.01, 2838.67, 2460.2, 1725.33, 1513.0, 797.03 | 64.7 *8* | 63.8 *11* | 0.9 *14* |
| 4252.75 *6* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 3912.7, 3787.5, 3374.9, 3063.85, 2951.06 | 8.5 *3* | 7.3 *4* | 1.3 *5* |
| 4352.46 *8* | | 4352.4, 3163.5, 3051.5, 1937.7, 1008.9 | 5.67 *25* | 5.3 *4* | 0.4 *5* |
| 4494.18 *12* | $\frac{5}{2}^+$ | 3156.28, 2545.7, 1778.92 | 2.33 *18* | 2.88 *19* | −0.5 *3* |
| 4532.8 *3* | | 4067.4 | 1.04 *19* | 0.64 *15* | 0.40 *24* |
| 4715.34 *4* | $\left(\frac{3}{2}\right)^-$ | 4715.16, 4250.6, 3525.8, 3377.34 | 18.8 *5* | 16.7 *6* | 2.1 *8* |
| 4782.91 *17* | $\left(\frac{3}{2}\right)^+$ | 4317.5 | 1.87 *20* | 1.17 *16* | 0.7 *3* |
| 4949.17 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 4949.02, 4609.3, 4071.5, 3268.8, 3214.7, 1923.4, 1572.1 | 14.1 *3* | 15.7 *6* | −1.6 *7* |

TABLE IV. (*Continued.*)

| $E$(level)[a] (keV) | $J^\pi$ | Deexciting $\gamma$ rays[b] | $I_\gamma$ (in)[a] (mb) | $I_\gamma$ (out)[a] (mb) | $I_\gamma$ (in − out)[a] (mb) |
|---|---|---|---|---|---|
| 4968.89 *4* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 4968.6, 4629.7, 4090.6, 3779.94, 3667.53, 3289.3, 3234.2, 2075.37, 1943.3, 1405.7 | 20.9 *4* | 20.9 *6* | 0.0 *7* |
| 5069.10 *5* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 5068.97, 4729.8, 4604.1, 4191.04, 3879.8, 3767.3, 3334.2, 2653.90, 1617.0, 816.3 | 16.7 *4* | 14.4 *5* | 2.3 *6* |
| 5131.94 *18* | $\frac{1}{2}^+$ | 4253.6 | 2.06 *19* | 2.20 *5* | −0.14 20 |
| 5384.76 *7* | $\frac{3}{2}^+$ | 5384.6, 5044.9, 4919.8, 4083.0, 3705.3, 2757.59, 2042.0 | 7.4 *3* | 8.0 *6* | −0.6 *6* |
| 5443.87 *13* | $\frac{3}{2}^+$, $\frac{5}{2}^+$ | 3029.17 | 2.74 *20* | 1.69 *12* | 1.05 *24* |
| 5494.23 *11* | | 5029.6, 4305.2, 3072.2 | 3.28 *20* | 2.4 *3* | 0.8 *4* |
| 5617.33 *6* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 5617.12, 5277.5, 4428.24, 3937.5, 2723.2 2491.3 | 8.95 *15* | 6.9 *4* | 2.0 *4* |
| 5632.17 *6* | | 5632.4, 5292.7, 3952.6, 3897.7, 2739.0, 2450.9, 2254.68, 1901.9, 1492.3, 1379.40 | 10.65 *16* | 7.1 *4* | 3.5 *5* |
| 5676.87 *18* | $\frac{1}{2}^+$ | 4375.31 | 0.53 *11* | 2.44 *19* | −1.91 *22* |
| 5702.11 *18* | | 5701.5, 5362.5, 4824.1 | 4.9 *6* | 4.4 *4* | 0.5 *7* |
| 5754.67 *9* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 5754.6, 3339.2, 1864.9 | 3.11 *13* | 1.8 *3* | 1.3 *3* |
| 5808.80 *8* | | 5469.4, 3393.8, 2465.5, 1275.9 | 2.84 *10* | 2.2 *3* | 0.6 *3* |
| 5957.56 *7* | | 5956.9, 5492.1, 5078.9, 2505.1 | 6.68 *14* | 4.5 *4* | 2.2 *4* |
| 6030.59 *14* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 6030.4, 5152.37, 4841.4, 4295.9, 3136.6 3005.2, 2177.3 | 12.6 *3* | 9.3 *7* | 3.3 *7* |
| 6101.72 *9* | | 4912.1, 3679.2, 1386.8 | 4.72 *17* | 1.80 *23* | 2.9 *3* |
| 6106.74 *12* | | 5641.65, 5228.6, 4805.03, 2980.2, 2763.7 | 5.1 *7* | 6.7 *4* | −1.6 *8* |
| 6141.79 *9* | $\frac{1}{2}^-$, $\frac{3}{2}^-$ | 6141.42, 3719.1, 2689.0, 1889.13 | 4.67 *15* | 5.9 *4* | −1.2 *4* |
| 6183.68 *14* | | 5843.7 | 2.14 12 | 1.05 *25* | 1.1 *3* |
| 6279.86 *7* | | 6279.0, 3857.8, 2258.03 | 4.89 *15* | 3.1 *3* | 1.8 *3* |
| 6431.34 *9* | | 5553.0, 3250.0 | 3.20 *14* | 1.68 *18* | 1.52 *23* |
| 6498.21 *17* | | 3045.66 | 1.23 *15* | 1.79 *12* | −0.56 *20* |
| 6562.16 *6* | | 6561.7, 5224.0 | 3.54 *9* | 1.7 *3* | 1.8 *3* |
| 6598.48 *5* | | 6598.15, 6258.8, 5409.4, 3184.56 | 7.97 *11* | 7.6 *4* | 0.4 *5* |
| 6873.64 *7* | | 6872.8, 6408.0, 4452.3, 3496.9 | 2.50 *12* | 2.5 *3* | 0.0 *3* |
| 6948.41 *15* | $\frac{1}{2}^+$ | 6947.6 | 1.35 *11* | 1.33 *16* | 0.02 *20* |
| 7187.22 *14* | | 4507.9, 3734.0 | 0.93 *7* | 1.1 *3* | −0.1 *3* |
| 7270.54 *7* | | 6391.9, 3730.20 | 3.78 *13* | 3.8 *4* | 0.0 *4* |
| 8999.28[c] *3* | $\frac{1}{2}^+$ | 8998.63, 8533.71, 8120.75, 7697.30, 7264.18, 7050.1, 6583.98, 6576.8, 6371.2, 6105.38, 5973.14, 5817.35, 5655.5, 5621.6, 5585.2, 5546.8, 5458.79, 5436.00, 5312.95, 5268.79, 5145.34, 5109.37, 4977.27, 4858.84, 4746.19, 4646.69, 4504.7, 4466.2, 4283.77, 4216.08, 4049.99, 4030.26, 3930.06, 3867.15, 3614.38, 3555.47, 3504.94, 3381.83, 3367.02, 3322.7, 3297.0, 3244.50, 3190.39, 3041.60, 2968.5, 2897.50, 2892.3, 2857.40, 2815.52, 2719.38, 2567.89, 2500.6, 2437.06, 2400.75, 2125.60, 2050.78, 1812.05, 1728.71 | | 4130 *40* | −4130 *40* |

[a]In our notation, 339.399 *16* ≡ 339.399 ± 0.016, 4110 *50* ≡ 4110 ± 50, etc.
[b]See also Table III.
[c]Capturing state.

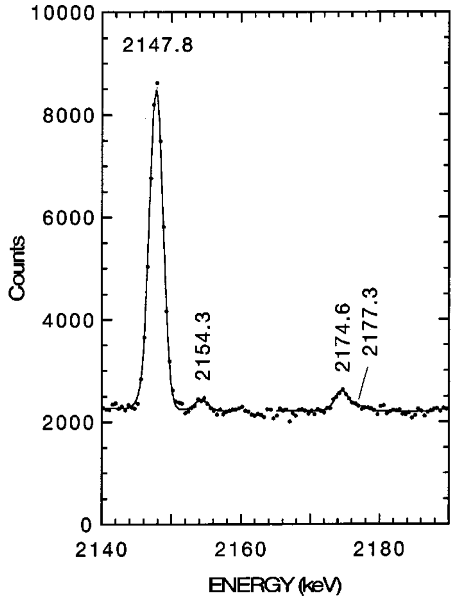


FIG. 4. Selected portion of the $\gamma$-ray spectrum from the $^{58}$Ni$(n,\gamma)^{59}$Ni reaction with thermal neutrons. See Sec. IV B for related discussion concerning a possible $\gamma$ ray at 2178 keV.

$10^5$ captures. Therefore, the strongest argument in favor of a level at 3858.26 keV is invalid. The level at 5994.17 keV was introduced in Ref. [30] to accommodate eight $\gamma$ rays. These $\gamma$ rays are (i) not seen in the current more sensitive study, (ii) seen but remain unplaced, or (iii) are placed elsewhere in the level scheme.

In our level scheme (see Table IV), there is an $(n,\gamma)$ level at 4949.16±0.05 keV corresponding to a $(d,p),\ell_n=1$ level (see Table II) at 4948±5 keV. This level is fed by a primary $\gamma$ ray of energy 4049.99±0.05 keV and deexcites by emitting seven $\gamma$ rays (see Table III). Out of the eight $\gamma$ rays connected with this level, six were observed by Harder and listed in Table A3 of Ref. [29]. However, she carried only the strongest two out of these six to Table VI of the published paper [30]. Her primary $\gamma$-ray energy, 4049.94±0.07 keV, is in excellent agreement with our value, but her secondary $\gamma$-ray energy, 4949.68±0.09 keV, is drastically different from our value of 4949.02±0.10 keV. We have no explanation for this discrepancy.

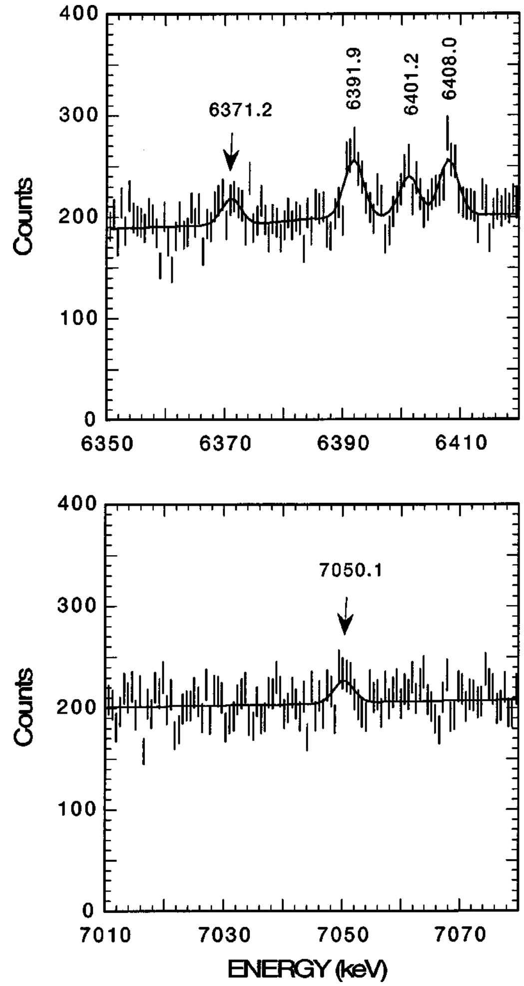


FIG. 5. Selected portions of the $\gamma$-ray spectrum from the $^{58}$Ni$(n,\gamma)^{59}$Ni reaction with thermal neutrons. See Sec. IV B for related discussion concerning the $\gamma$ rays at 6371.2 and 7050.1 keV which are possible primary $E3$ transitions.

In addition to the 39 levels common to this work and the earlier work by Harder *et al.* [30], 26 levels are populated

TABLE V. Increasing complexity in the study of the $^{58}$Ni$(n,\gamma)^{59}$Ni reaction.

| Number of | Ishaq *et al.* [28] McMaster (1977) | Harder [29] unpublished Grenoble (1992) | Harder *et al.* [30] Grenoble (1993) | This work LANL/ORNL |
|---|---|---|---|---|
| $\gamma$ rays | 59[d] | 576 | 243 | 414 |
| spurious $\gamma$ rays[a] | 4 | 241 | 39 | |
| placed $\gamma$ rays[b] | 40 | 233 | 232 | 315 |
| primary $\gamma$ rays | 19 | 37 | 37 | 58 |
| secondary $\gamma$ rays | 21 | 196 | 195 | 257 |
| unplaced $\gamma$ rays[c] | 19 | 343 | 11 | 99 |
| bound levels | 20 | 41 | 41 | 65 |

[a]Gamma rays sought but not observed in this more sensitive work and, therefore, considered spurious.
[b]Some of the placed $\gamma$ rays may be spurious.
[c]Some of the unplaced $\gamma$ rays may be genuine.
[d]Measurements limited to $E_\gamma > 1.9$ MeV using a Ge(Li)–NaI(Tl) pair spectrometer.

TABLE VI. Direct-capture cross sections for primary E1 transitions in the $^{58}$Ni$(n,\gamma)^{59}$Ni reaction. Columns 1, 2, and 3 give the energy, $J^{\pi}$ value, and the $l=1$ $(d,p)$, spectroscopic factor multiplied by $(2J+1)$ for the final state, respectively. Column 4 is the primary transition energy. Column 5 is the average valency capture width and column 6 the potential-capture cross section, both calculated using a global optical potential (see Eqs. (4)–(7) of Ref. [3]). The entries in column 5 do not include the spin-coupling factor and the spectroscopic factor; those in column 6 do. Column 7 is the calculated cross section using the global plus valence $(G+V)$ procedure [11]. The measured cross sections are given in column 8. Column 9 gives the hypothesized compound-nuclear contributions deduced from the differences between column 7 and column 8 via Eq. (8) of Ref. [3]. In the table subheading a(X) refers to the experimental scattering length, while a(G) and $\overline{\Gamma_n^0}/D$ refer to the scattering length and the neutron strength function, respectively, both calculated using the global optical potential.

| $E_f$ (keV) | $J^{\pi}$ | $(d,p)$ $(2J+1)\,S^a$ | $E_{\gamma}$ (keV) | $\Gamma_{\gamma,\mathrm{val}}/DE_{\gamma}^3$ $(10^{-7}\ \mathrm{MeV}^{-3})$ | $\sigma_{\mathrm{pot},\gamma}$ (mb) | $\sigma(G+V)$ (mb) | $\sigma_{\gamma}(X)$ $^b$ (mb) | $\sigma_{\mathrm{CN},\gamma}$ (mb) |
|---|---|---|---|---|---|---|---|---|
| | | Reaction $^{58}$Ni$(n,\gamma)^{59}$Ni; $a(X)=14.2$ fm; $a(G)=6.93$ fm; $\bar{\Gamma}_n^0/D=4.4\times10^{-4}$ | | | | | | |
| 0 | $\frac{3}{2}^-$ | 3.263 | 8999 | 0.64 | 0.30 | 4389 | 2082 30 | 420 or 12500 |
| 465 | $\frac{1}{2}^-$ | 1.240 | 8534 | 0.21 | 0.053 | 1213 | 996 15 | 11 or 4410 |
| 878 | $\frac{3}{2}^-$ | 0.286 | 8121 | 0.064 | 0.28 | 312 | 177 3 | 19 or 960 |
| 1301 | $\frac{1}{2}^-$ | 0.572 | 7697 | 0.11 | 0.39 | 456 | 51.7 7 | 200 or 814 |
| 1735 | $\frac{3}{2}^-$ | 0.034 | 7264 | 0.0089 | 0.090 | 29 | 9.3 3 | 5.6 or 72 |
| 2415 | $\frac{3}{2}^-$ | 0.032 | 6584 | 0.0095 | 0.14 | 23 | 109 2 | 32 or 230 |
| 2894 | if $\frac{1}{2}^-$ | 0.009 | 6105 | 0.0024 | 0.032 | 4.5 | 98.0 14 | 61 or 140 |
| 2894 | if $\frac{3}{2}^-$ | 0.009 | 6105 | 0.0030 | 0.051 | 5.4 | 98.0 14 | 58 or 150 |
| 3026 | if $\frac{1}{2}^-$ | 0.032 | 5973 | 0.0089 | 0.126 | 15 | 36.8 8 | 4.7 or 99 |
| 3026 | if $\frac{3}{2}^-$ | 0.032 | 5973 | 0.011 | 0.19 | 18 | 36.8 8 | 3.2 or 107 |
| 3126 | if $\frac{1}{2}^-$ | 0.006 | 5873 | 0.0017 | 0.025 | 2.8 | < 3 | 0.006 or 12[c] |
| 3126 | if $\frac{3}{2}^-$ | 0.006 | 5873 | 0.0021 | 0.038 | 3.3 | < 3 | 0.007 or 13[c] |
| 3182 | if $\frac{1}{2}^-$ | 0.032 | 5817 | 0.009 | 0.14 | 14 | 152 2 | 73 or 260 |
| 3182 | if $\frac{3}{2}^-$ | 0.032 | 5817 | 0.011 | 0.21 | 17 | 152 2 | 67 or 270 |
| 3452 | $\frac{3}{2}^-$ | 0.135 | 5547 | 0.050 | 0.99 | 65 | 2.9 2 | 41 or 96 |
| 3563 | if $\frac{1}{2}^-$ | 0.093 | 5436 | 0.029 | 0.49 | 36 | 26.3 5 | 0.78 or 124 |
| 3563 | if $\frac{1}{2}^-$ | 0.093 | 5436 | 0.035 | 0.71 | 62 | 26.3 5 | 7.6 or 169 |
| 3854 | $\frac{3}{2}^-$ | 0.100 | 5145 | 0.041 | 0.85 | 41 | 5.9 3 | 16 or 78 |
| 4022 | if $\frac{1}{2}^-$ | 0.048 | 4977 | 0.017 | 0.31 | 15 | 10.6 4 | 0.45 or 52 |
| 4022 | if $\frac{3}{2}^-$ | 0.048 | 4977 | 0.020 | 0.43 | 18 | 10.6 4 | 1.0 or 56 |
| 4140 | $\frac{3}{2}^-$ | 0.068 | 4859 | 0.030 | 0.63 | 24 | 64.2 8 | 9.5 or 168 |
| 4166 | if $\frac{1}{2}^-$ | 0.012 | 4836 | 0.0044 | 0.082 | 3.6 | < 3 | 0.03 or 13[c] |
| 4166 | if $\frac{3}{2}^-$ | 0.012 | 4836 | 0.0053 | 0.11 | 4.3 | < 3 | 0.11 or 14[c] |
| 4253 | if $\frac{1}{2}^-$ | 0.110 | 4746 | 0.041 | 0.78 | 32 | 5.8 3 | 11 or 65 |
| 4253 | if $\frac{3}{2}^-$ | 0.110 | 4746 | 0.050 | 1.06 | 37 | 5.8 3 | 14 or 73 |
| 4715 | if $\frac{1}{2}^-$ | 0.090 | 4284 | 0.039 | 0.74 | 21 | 18.5 5 | 0.06 or 78 |
| 4715 | if $\frac{3}{2}^-$ | 0.090 | 4284 | 0.046 | 0.98 | 24 | 18.5 5 | 0.37 or 85 |
| 4949 | if $\frac{1}{2}^-$ | 0.054 | 4050 | 0.025 | 0.48 | 11 | 14.1 3 | 0.21 or 50 |
| 4949 | if $\frac{3}{2}^-$ | 0.054 | 4050 | 0.030 | 0.62 | 13 | 14.1 3 | 0.04 or 53 |
| 4969 | if $\frac{1}{2}^-$ | 0.050 | 4030 | 0.023 | 0.44 | 10 | 20.9 4 | 2.0 or 60 |
| 4969 | if $\frac{3}{2}^-$ | 0.050 | 4030 | 0.027 | 0.57 | 12 | 20.9 4 | 1.4 or 64 |
| 5069 | if $\frac{1}{2}^-$ | 0.033 | 3930 | 0.016 | 0.30 | 6.2 | 16.7 4 | 2.5 or 43 |
| 5069 | if $\frac{3}{2}^-$ | 0.033 | 3930 | 0.019 | 0.39 | 7.2 | 16.7 4 | 2.0 or 46 |
| 5617 | if $\frac{1}{2}^-$ | 0.033 | 3382 | 0.019 | 0.34 | 4.3 | 8.9 2 | 0.81 or 26 |
| 5617 | if $\frac{3}{2}^-$ | 0.033 | 3382 | 0.022 | 0.42 | 5.0 | 8.9 2 | 0.58 or 27 |
| 5755 | if $\frac{1}{2}^-$ | 0.058 | 3244 | 0.036 | 0.61 | 6.9 | 3.1 2 | 0.74 or 19 |
| 5755 | if $\frac{3}{2}^-$ | 0.058 | 3244 | 0.041 | 0.75 | 7.8 | 3.1 2 | 1.1 or 21 |
| 5978 | if $\frac{1}{2}^-$ | 0.024 | 3022 | 0.016 | 0.26 | 2.4 | < 3 | 0.04 or 11[c] |
| 5978 | if $\frac{3}{2}^-$ | 0.024 | 3022 | 0.018 | 0.32 | 2.7 | < 3 | 0.008 or 11[c] |
| 6031 | if $\frac{1}{2}^-$ | 0.047 | 2969 | 0.032 | 0.51 | 4.5 | 12.6 3 | 2.1 or 32 |
| 6031 | if $\frac{1}{2}^-$ | 0.047 | 2969 | 0.037 | 0.62 | 5.0 | 12.6 3 | 1.7 or 34 |
| 6142 | if $\frac{1}{2}^-$ | 0.084 | 2857 | 0.060 | 0.92 | 7.2 | 4.7 2 | 0.27 or 24 |
| 6142 | if $\frac{3}{2}^-$ | 0.084 | 2857 | 0.068 | 1.1 | 8.1 | 4.7 2 | 0.47 or 25 |

[a]From Ref. [35].
[b]From Table III.
[c]Assuming the upper limit for $\sigma_{\gamma}(X)$.

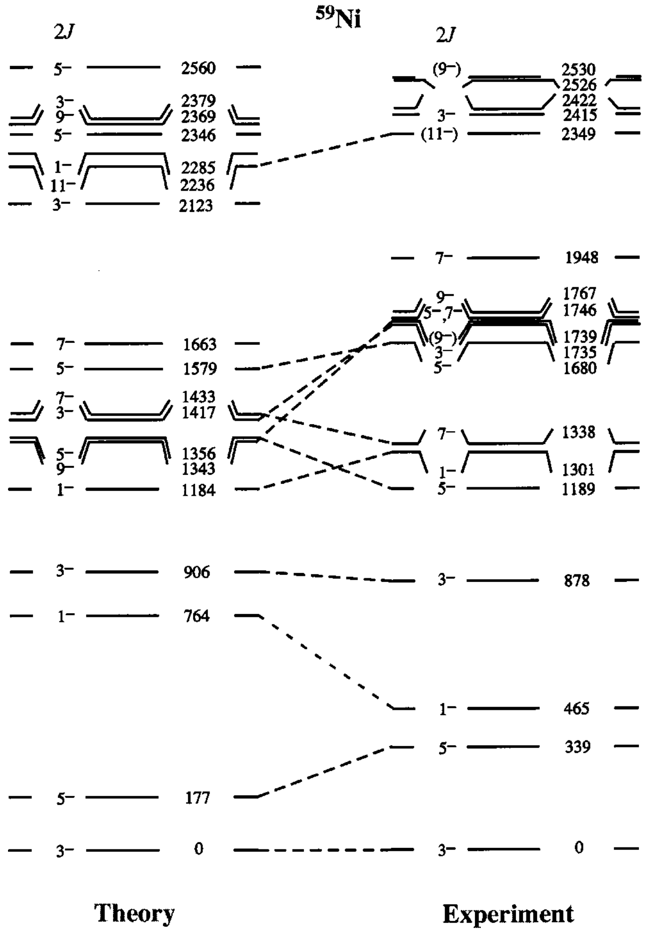


FIG. 6. Comparison between the shell-model predictions and the experimental level scheme of $^{59}$Ni. The levels are labeled by $2J^{\pi}$ on the left and by level energies (in keV) on the right.

significantly in the $^{58}$Ni(thermal $n,\gamma$) reaction, bringing the total to 65 levels (see Table V). Of these, 60 levels correspond well with known levels in $^{59}$Ni. The remaining five levels (at 3540.05, 4352.45, 5702.11, 6101.73, and 7270.54 keV) are common to both this work and Ref. [30].

The $J^{\pi}$ assignments for the levels populated in the $^{58}$Ni(thermal $n,\gamma$) reaction were initially assumed to be the same as the known assignments (see Table II). In Table IV, we have further narrowed the $J^{\pi}$ choices for the levels at 3686, 3730, 4140, 4715, 4783, and 5385 keV by considering the decay properties of these levels. For common levels, our branching ratios are in reasonable agreement with those reported in the $^{58}$Ni($^3$He,$2p\gamma$) [23], $^{59}$Co($p,n\gamma$) [25,26], and $^{58}$Ni($n,\gamma$) [30] reactions. For the 1680-keV level, our branching ratios agree with ($p,n\gamma$) and not with ($^3$He,$2p\gamma$); the reverse holds true for the 2627-keV level.

In the ($n,\gamma$) reaction, the observed primary $\gamma$ rays (those originating from the capturing state) are predominantly $E1$ or $M1$. Of these two, primary $E1$ transitions are generally stronger than primary $M1$ transitions. Primary $E2$ transitions are extremely rare in the ($n,\gamma$) reaction [106–109]. In $^{59}$Ni, we observed a weak primary $E2$ transition with an intensity of $\sim$6 photons per $10^4$ captures to the known $\frac{5}{2}^+$ state [36,37] at 4494 keV. (There are no other definite $\frac{5}{2}^+$ states known in this nucleus.) Primary $M2$ transitions are rarer than primary $E2$ transitions and only one viable candidate (in $^{20}$F) has been reported [14] till date. In this work, we sought but did not observe primary $M2$ transitions to the known $\frac{5}{2}^-$ levels at 339, 1189, and 1680 keV.

As shown in Fig. 5, we have detected very weak peaks at 6371.2 and 7050.1 keV with intensities of $\sim$13 and $\sim$10 photons per $10^5$ captures, respectively. The energies of these $\gamma$ rays and the purity of the $^{58}$Ni target virtually guarantee that these $\gamma$ rays do not originate from an impurity [97]. The most logical placements for these $\gamma$ rays are between the capturing state $(J^{\pi}=\frac{1}{2}^+)$ and the levels at 2627 and 1948 keV, respectively. These two levels have definite $J^{\pi}=\frac{7}{2}^-$ assignments from (polarized $p,d$) measurements [41]. If these placements and the $J^{\pi}$ assignments are correct, these $\gamma$ rays would represent the first examples of primary $E3$ transitions in the ($n,\gamma$) reaction. According to the Weisskopf estimates, an $E3$ transition of energy $\sim$6.7 MeV should be weaker than an $E1$ transition of similar energy by a factor of $\sim 10^7$. However, it is known that the strengths of the (primary) $E1$ transitions are themselves reduced by a factor of $\sim 10^3$ as a result of the drawing away of the $E1$ strength by the giant dipole resonance. The net result is that the weakness factor is only $\sim 10^4$ instead of $10^7$ and the current measurement is sensitive enough to detect such weak transitions.

The neutron separation energy determined in this work is $S_n(^{60}\mathrm{Ni}) = 8999.28 \pm 0.05$ keV, where the uncertainty includes the uncertainties in the primary calibration energies and in the nonlinearity curve. The value obtained by Harder *et al.* [30], $S_n = 8999.15 \pm 0.23$ keV, is consistent with our value, but the value obtained by Ishaq *et al.* [28], $S_n = 8999.91 \pm 0.20$ keV, is not. Harder *et al.* [30] have pointed out that the uncertainty in the latter value is probably underestimated.

### C. Capture cross sections of $^{58}$Ni

The measured values $\Sigma I_{\gamma}$ (primary) $= 4.110 \pm 0.050$ b, $\Sigma E_{\gamma} I_{\gamma}/S_n = 4.145 \pm 0.020$ b, and $\Sigma I_{\gamma}$ (to ground state) $= 4.130 \pm 0.030$ b agree within their stated uncertainties. Our recommended cross-section value of $4.13 \pm 0.05$ b for the $^{58}$Ni($n,\gamma$) reaction is significantly more precise than the currently accepted value of $4.6 \pm 0.4$ b [110].

Strictly speaking, the three measured values for $\Sigma I_{\gamma}$ (primary), $\Sigma E_{\gamma} I_{\gamma}/S_n$, and $\Sigma I_{\gamma}$ (to ground state) are lower limits because we cannot claim that we have either detected all possible $\gamma$ rays from the $^{58}$Ni($n,\gamma$) reaction or placed all $\gamma$ rays correctly in the level scheme. The total intensity of the observed but unplaced $\gamma$ rays is $\sim$1.9%. We estimate that any systematic uncertainty in our measured cross-section values is unlikely to exceed $\sim$2%. This uncertainty is not included in our recommended cross-section value.

The lowest $s$-wave resonance in the neutron cross section is at 15.35 keV neutron energy. From its resonance param-

TABLE VII. Partial list of references to previous measurements on $^{60}$Ni levels. See Ref. [93] for additional references.

| Measurement | Author(s) | Year | Facility[a] | Reference |
|---|---|---|---|---|
| $^{46}$Ti ($^{16}$O, $2p\gamma$) reaction | Kim *et al.* | 1975 | Saclay | [44] |
| $^{50}$Cr ($^{12}$C, $2p\gamma$) reaction | Kim *et al.* | 1975 | Saclay | [44] |
| $^{51}$V ($^{12}$C, $p2n\gamma$) reaction | Ivanov *et al.* | 1975 | Leningrad | [45] |
| $^{56}$Fe ($^{7}$Li, $p2n\gamma$) reaction | Kearns *et al.* | 1980 | U. Liverpool | [46] |
| $^{56}$Fe ($^{6}$Li, $d$) reaction | Stein, Sunier, and Woods | 1977 | Los Alamos | [47] |
| | Fulbright *et al.* | 1977 | U. Rochester | [48] |
| $^{58}$Ni ($^{14}$C, $^{12}$C) reaction | Videbaek *et al.* | 1985 | Los Alamos | [49] |
| $^{58}$Ni ($\alpha$, $2p\gamma$) reaction | Kim *et al.* | 1975 | Saclay | [44] |
| | Tsan Ung Chan *et al.* | 1984 | Grenoble | [50] |
| $^{58}$Ni ($t,p$) reaction | Darcey, Chapman, and Hinds | 1971 | Aldermaston | [51] |
| $^{59}$Co ($^{3}$He, $d\gamma$) reaction | Ronsin *et al.* | 1973 | Saclay | [52] |
| $^{59}$Co ($p,\gamma$) reaction | Demeter *et al.* | 1971 | Budapest | [53] |
| | Erlandsson, Lyttkens, and Marcinkowski | 1975 | U. Lund | [54] |
| $^{59}$Co ($\alpha,t$) reaction | Peterson *et al.* | 1987 | Indiana U. | [55] |
| $^{60}$Co $\beta^-$ decay | Hansen and Spernol | 1968 | Geel | [56] |
| | Raman | 1969 | Oak Ridge | [57] |
| | Camp and Van Hise | 1976 | Livermore | [58] |
| $^{59}$Ni (thermal $n,\gamma$) reaction | Wilson, Thomas, and Jackson | 1975 | Argonne | [59] |
| | Raman and Jurney | 1979 | Los Alamos | [60] |
| $^{60}$Ni ($\gamma,\gamma'$) reaction | Metzger | 1970 | Bartol | [61] |
| $^{60}$Ni ($e,e'$) reaction | Lindgren *et al.* | 1981 | MIT | [62] |
| $^{60}$Ni ($\pi,\pi'$) reaction | Clausen *et al.* | 1990 | Los Alamos | [63] |
| $^{60}$Ni ($p,p'$) reaction | Tee and Aspinall | 1967 | Aldermaston | [64] |
| $^{60}$Ni ($p,p'\gamma$) reaction | Mohindra and Van Patter | 1965 | U. Pennsylvania | [65] |
| | Moazed *et al.* | 1971 | U. Pennsylvania | [66] |
| | Ronsin *et al.* | 1973 | Saclay | [52] |
| | Passoja *et al.* | 1981 | U. Jyväskylä | [67] |
| $^{60}$Cu ($\beta^+ + \varepsilon$) decay | Van Patter and Rauch | 1972 | Bartol | [68] |
| $^{61}$Ni ($p,d$) reaction | Koang, Chien, and Rossner | 1976 | Michigan State U. | [69] |
| $^{62}$Ni ($p,t$) reaction | Kong-A-Siou *et al.* | 1974 | Grenoble | [70] |

[a]Facility where the actual measurements were done. The symbol U stands for a university.

eters, we compute that its contribution to the thermal capture cross section is about 0.4 b. Resonances at higher neutron energy contribute less than 0.04 b. Most of the capture cross section ($\approx$3.7 b) can therefore be attributed to one or more bound levels. The large thermal-neutron scattering length $a_{J=1/2}=14.2$ fm indicates that the most important bound level either lies very close to the neutron separation energy or has a very large reduced neutron width. If we assume that only one level affects the scattering length, we can obtain an estimate for its ratio of reduced width to binding energy; it is about 2. From the capture cross section that we estimate as arising from the bound level ($\approx$3.7 b), we can then obtain the ratio of its radiation width to binding energy; this is about $2.2\times10^{-4}$. The measured radiation widths of the $s$-wave neutron resonances range from about 1 eV to 3 eV. We conclude therefore that the energy of the first bound level is about $-10$ keV.

The cross sections for the individual primary $E1$ transitions are given in Table VI along with their $\gamma$-ray energies and $(d,p)$ spectroscopic factors of the final states. From these and the thermal-neutron scattering length, the direct-capture cross sections are calculated. These are also presented in Table VI. In general, there are significant differences between the direct-capture cross section and the experimental value. These differences are attributed to the admixture of compound-nuclear capture resulting from the nearest resonance levels (bound and unbound). The two possible magnitudes of the compound-nuclear cross section, extracted using Eq. (1), for each transition are listed in the final column of Table VI.

The method for determining combinations of these compound-nuclear cross sections is described in Sec. III F. Before applying this method to the $^{58}$Ni data, we note that the higher value for the ground-state transition seems to be excessively large compared with nearly all other values. Quantitatively this conclusion is confirmed by our findings that this value, combined with the lower values for all other transitions, gives $M\nu=-3.2$, $Mb=6.9$ for $b=3$ and $M\nu=-2.2$, $Mb=5.6$ for $b=5$. If the value for the ground-state transition is fixed at the higher of the two possible values and the values for the rest of the transitions are chosen randomly, we find that, for $b=3$, none of the randomly chosen sequences have an acceptable value of $M\nu$ (in the range $-1.52$

TABLE VIII. Known energy levels in $^{60}$Ni.

| Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) | Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) |
|---|---|---|---|---|---|---|---|
| 0.0 | $0^+$ | 0.0 | 0.0 | 4319.0 *5* | $1^+$, $2^+$ | 4318.3 *11* | 4318.58 *5* |
| 1332.51 *3* | $2^+$ | 1333.4 *3* | 1332.536 *16* | 4334.7 *10* | | 4335.1 *11* | 4335.56 *4* |
| 2158.61 *4* | $2^+$ | 2159.6 *5* | 2158.671 *18* | 4341 5 | $(0^+)$ | | |
| 2284.86 *14* | $0^+$ | 2284.9 *5* | 2284.828 *24* | 4355.7 *5* | | | 4355.57 *12* |
| 2505.71 *3* | $4^+$ | | 2505.79 *3* | 4407.40 *14* | | | |
| 2625.99 *8* | $3^+$ | | 2625.98 *3* | 4493.43 *25* | $2^+$ | | 4493.18 *5* |
| 3119.66 *9* | $4^+$ | | 3119.45 *18* | 4535.7 *10* | | | 4534.13 *14* |
| 3123.98 *13* | $2^+$ | 3124.1 *7* | 3123.750 *21* | 4548.8 *4* | $1^+$, $2^+$ | | 4547.99 *3* |
| 3185.99 *8* | $3^+$ | 3186.8 *9* | 3186.23 *4* | 4579.1 *7* | $2^+$ | | 4577.46 *6* |
| 3194.01 *13* | $1^+$ | 3194.6 *7* | 3193.892 *19* | 4613 *7* | | | |
| 3269.34 *16* | $2^+$ | | 3268.97 *4* | 4760.5 *7* | | | 4760.25 *9* |
| 3316 *7* | $0^+$ | 3318.0 *8* | 3317.85 *3* | 4768 *5* | | | |
| 3381 *5* | | | | 4781 *7* | | | 4779.16 *6* |
| 3393.4 *3* | $2^+$ | 3393.8 *8* | 3393.16 *3* | 4799.9 *5* | | | |
| 3589 *7* | $0^+$ | 3587.9 *9* | 3587.75 *3* | 4844.2 *13* | | | 4843.94 *8* |
| 3619.45 *13* | $(3)^+$ | | 3619.47 *4* | 4850.6 *20* | | | |
| | | 3622.9 *10* | | 4859 *5* | | | |
| 3670.66 *9* | $4^+$ | | | 4891 *7* | | | |
| 3730.64 *6* | | | | 4932 *7* | | | 4929.00 *14* |
| 3735.8 *6* | $2^+$ | 3735.2 *9* | 3734.42 *3* | 4958 *5* | | | 4953.38 *7* |
| 3872.1 *9* | $1^+$, $2^+$ | 3870.8 *9* | 3871.080 *23* | 4970 *5* | | | |
| 3887.8 *4* | | | 3887.38 *7* | 4985.69 *9* | $(6^+)$ | | |
| 3895 *5* | | | | 5015.0 *6* | | | |
| 3924.71 *10* | $2^+$, $3^+$ | | 3925.22 *9* | 5048.3 *7* | | | |
| 4007.9 *7* | $1^+$, $2^+$ | | 4006.46 *3* | 5069 *10* | $(1^-)$ | | 5065.03 *6* |
| 4020.44 *21* | $1^+$, $2^+$ | | 4019.914 *25* | 5106 *5* | | | |
| 4035 *5* | | | | 5110 *20* | $8^-$ | | |
| 4039.66 *15* | $3^-$ | | 4039.92 *6* | 5132 *5* | | | 5127.18 *17* |
| 4078.53 *21* | $1^+$, $2^+$ | | 4078.01 *5* | 5148.6 *6* | | | |
| 4111.7 *4* | | | 4111.97 *9* | 5174 *5* | | | |
| 4165.35 *10* | $5^+$ | | | 5188 *10* | | | |
| 4191 *5* | | | | 5205 *5* | | | |
| 4265.05 *10* | $6^+$ | | | 5244 *5* | $4^+$ | | |
| 4294.5 *3* | | | | 5264 *10* | | | |

to −0.96) and $Mb$ (in the range −1.25 to +1.25). For $b=4$ about 1% have acceptable $M\nu$ and $Mb$ values. For $b=5$, 29% have acceptable values of both $M\nu$ and $Mb$. The value of $a$ in this acceptable range is $(3.5\pm1.4)\times10^{-5}$ b MeV$^{-5}$. This result is to be compared with the result from Lone's formula [111] from the Brink-Axel photonuclear model [101,102] for the neutron capture mechanism which would give for this bound level (and the observed average $s$-wave resonance spacing of $\approx$20 keV) a value of $a=10^{-4}$ b MeV$^{-5}$. Conversely, if we fix the compound-nuclear cross section of the ground-state transition at the lower of the two possible values, we find that 30% of sequences are statistically acceptable for $b=3$ with $a=(4.3\pm0.8)\times10^{-4}$ b MeV$^{-3}$; about 40% satisfy $b=4$ with $a=(1.1\pm0.3)\times10^{-4}$ b MeV$^{-4}$; and 22% are acceptable for $b=5$, giving $a=(2.0\pm0.5)\times10^{-5}$ b MeV$^{-5}$.

Brink's theory (unadapted by Axel) [101] for the radiation width gives $b=4$, $a=7\times10^{-5}$ b MeV$^{-4}$. Cameron's semi-empirical estimate [112] for the radiation width gives $b=3$, $a=1.7\times10^{-4}$ b MeV$^{-4}$. The Weisskopf model [100] gives $b=3$, $a=10^{-3}$ b MeV$^{-4}$ while a generalized valence model assessment [113] gives $b=3$, $a=6\times10^{-4}$ b MeV$^{-4}$. All these theoretical estimates have at least a ±50% uncertainty, because of the uncertainty in the energy of the bound state, placing all, except possibly the Brink-Axel-Lone [111] and Cameron models [112], into agreement with the data. It is clear that the differences between the calculated direct-capture cross sections and the experimental data may be fully attributed to the admixture of a compound-nuclear mecha-

TABLE VIII. (*Continued.*)

| Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) | Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) |
|---|---|---|---|---|---|---|---|
| 5293 *10* | | | 5288.57 *14* | 6142 *10* | | | |
| 5307 *7* | | | | 6181 *10* | | | |
| 5318 *5* | | | | 6192 *10* | | | |
| 5348.9 *5* | $7^-$ | | | 6239 *10* | | | 6239.2 *3* |
| 5379 *5* | | | | 6275 *10* | | | |
| 5396 *10* | $3^-$ | | | 6292 *10* | | | |
| 5428 *10* | | | | 6331 *10* | | | 6327.23 *15* |
| 5444.6 *10* | $2^+$ | | | 6362 *10* | | | 6362.06 *17* |
| | | | 5446.99 *10* | 6380 *10* | | | 6382.4 *4* |
| 5474 *10* | | | 5476.06 *21* | 6403 *10* | | | |
| 5531.6 *10* | $(0^+)$ | | | 6431 *10* | | | |
| 5615 *10* | | | 5612.44 *4* | 6460.7 *12* | | | |
| 5642 *10* | | | | 6468 *10* | | | 6465.27 *16* |
| 5662.7 *6* | | | | 6492 *10* | | | 6489.17 *23* |
| 5675 *10* | | | 5672.39 *7* | 6516 *10* | | | 6516.73 *23* |
| 5713 *10* | | | 5710.82 *4* | 6551 *10* | | | |
| 5741 *10* | | | | 6568 *10* | | | 6567.35 *20* |
| 5780.4 *5* | | | | 6584 *10* | | | |
| 5785.1 *4* | $(7^+)$ | | | 6610 *10* | | | |
| 5799 *5* | $2^+$ | | | 6623 *10* | | | |
| 5824 *5* | | | | 6652 *10* | | | 6647.19 *9* |
| 5848 *10* | | | | 6658 *10* | | | |
| 5863 *10* | | | 5860.0 *5* | 6687 *10* | | | |
| | | | 5878.08 *8* | 6708 *10* | | | |
| 5900 *10* | | | 5902.45 *7* | 6728 *10* | | | |
| 5921 *10* | | | 5918.56 *21* | 6753 *10* | | | 6756.3 *3* |
| 5946 *10* | | | | 6765 *10* | | | |
| | | | 5967.8 *3* | 6791 *10* | | | |
| 5973 *10* | $(5^-)$ | | | 6810.4 *6* | | | |
| 5992 *10* | | | | 6832 *10* | | | 6834.95 *19* |
| 6028 *10* | | | | 6836.6 *10* | | | |
| 6054 *10* | | | | 6859 *10* | | | |
| 6071 *10* | | | 6066.71 *11* | 6892 *10* | | | |
| 6121 *10* | | | | | | | 6911.95 *9* |

nism, but the present results cannot distinguish between a photonuclear giant resonance model and a Weisskopf-type model for that mechanism.

### D. Shell-model calculations of $^{59}$Ni levels

The calculated spectrum is compared with experiment in Fig. 6. There is good agreement between theory and experiment for the first ten states. It is pleasing that the two gaps at 465–878 keV and 1948–2349 keV, where no level is found experimentally, are reproduced by the theoretical spectrum. However, the doublet of $\frac{9}{2}^-$ states at 1739 and 1767 keV [19,21] is not reproduced by our calculations.

## V. REACTION $^{59}$Ni$(n,\gamma)$

### A. Skeleton level scheme of $^{60}$Ni

In Table VII we have listed the previous measurements that have been carried out concerning the energy levels in $^{60}$Ni. From this list, we considered a subset of measurements and results given in Refs. [46,50,52,54,58,64,68,69] which led to the skeleton level scheme of 136 levels given under columns 1 and 5 in Table VIII. The backbone of this scheme

TABLE VIII. (Continued.)

| Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) | Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) |
|---|---|---|---|---|---|---|---|
| | | | 6996.86 *20* | | | | 7950.95 *24* |
| | | | 7056.29 14 | 8043.8 *9* | | | |
| | | | 7207.7 *3* | | | | 8286.3 *3* |
| | | | 7222.81 *11* | | | | 8504.7 *3* |
| | | | 7316.15 *16* | 8520.5 *10* | | | |
| | | | 7339.71 *25* | | | | 8565.63 *18* |
| | | | 7414.18 *23* | | | | 8638.57 *25* |
| | | | 7473.50 *24* | | | | 8666.23 *22* |
| | | | 7495.3 *4* | | | | 9045.23 *24* |
| | | | 7552.0 *3* | | | | 9076.68 *17* |
| | | | 7684.1 *4* | 9132.1 *14* | | | |
| | | | 7690.1 *3* | | | | 9346.84 *18* |
| | | | 7761.7 *3* | | | | 9953.7 *3* |
| | | | 7798.88 *25* | 9989.4 *17* | | | |
| | | | 7818.04 *13* | | | | 10029.04 *17* |

[a]In our notation, 1332.51 *3* ≡ 1332.51 ± 0.03, 4319.0 *5* ≡ 4319.0 ± 0.5, etc.

is the Aldermaston spectrograph $(p,p')$ measurements made by Tee and Aspinall [64]. These authors quote ±7 keV for the energies of levels below 5 MeV and ±10 keV above. More significantly, unlike in the $^{59}$Ni case, we found no systematic errors in the level energies quoted by Tee and Aspinall [64].

The $J^\pi$ assignments for $^{60}$Ni levels arise from a variety of measurements. A convenient way to trace the evolution of these assignments is to follow the reasonings presented in Ref. [90].

### B. Thermal-neutron capture $\gamma$-ray data

The enriched $^{59}$Ni material used in this work was prepared about three decades ago. Five grams of 99.9% enriched $^{58}$Ni were irradiated with neutrons for over 1 yr as part of the Savannah River High Flux Demonstration [114]. After return to Oak Ridge National Laboratory (ORNL), the target material, which had originally been loaded in 12 aluminum cans, was stored to allow short-lived activities to decay. Early in 1971, the nickel target material was reclaimed, and a chemical separation using anion-exchange techniques was made to remove the $^{60}$Co impurity. After further chemical treatment (hydroxide precipitation, electrolysis, etc.) to remove other minor radioactivities, the nickel sample was recovered as NiO and loaned to Knolls Atomic Power Laboratory (KAPL) for a preliminary cross-section measurement. The $^{59}$Ni content at this point was 4.3%. Upon return from KAPL, the 4.16-g nickel sample was again chemically processed, converted to low-fired oxide (600 °C), and used as charge material by passing carbon tetrachloride over the oxide positioned directly in the ion source. The technique of introducing $NiCl_2$ into the ionization region by chlorination with carbon tetrachloride was established on an experimental basis using normal nickel oxide. The isotopic separation, which was performed in a calutron outside the contained area, resulted in a recovery of 30 mg of nickel that was assayed to be 95.35% $^{59}$Ni. A portion of this material (7.0 mg) was available for our measurements. Subsequently, we diluted the sample with natural nickel such that the $^{59}$Ni enrichment dropped to (44.3±0.4)%. We used 6.9 mg of the diluted material in a second set of measurements. Sample spectra obtained with the 7.0-mg metal sample of 95.35% enriched $^{59}$Ni are shown in Figs. 1 and 2.

The energies and intensities of 390 $\gamma$ rays assigned to $^{60}$Ni are given in Table IX. The 11 386.5-keV transition from the capturing state to the ground state is exceptionally strong (∼30% of all captures). Since the early 1970s, the Negev group has been using this transition for photon scattering studies [115,116]. Because the ground state of $^{59}$Ni has $J^\pi = \frac{3}{2}^-$, thermal-neutron capture leads to a $1^-$ or $2^-$ capturing state. The strength of the 11 386.5-keV transition to the $0^+$ ground state of $^{60}$Ni indicates that the capturing state is predominantly a $1^-$ state. The nearest neutron resonance at 203 eV is known to be a $1^-$ resonance [117] and thermal-neutron capture in $^{59}$Ni is believed to result primarily from the tail of this resonance. Even though there are no known $2^-$ neutron resonances below 5 keV, there is some indication that the capturing state is partly $2^-$ from the presence of a primary transition to the 3186.1-keV, $3^+$ state, which is probably an $E1$ and not an $M2$ transition.

The level scheme resulting from this work is presented in Table X. Of the 132 known levels below 6.9 MeV, 59 levels are populated significantly in the $(n,\gamma)$ reaction. The two

TABLE IX. Energies ($E_\gamma$) and intensities ($I_\gamma$) of $\gamma$ rays from the $^{59}$Ni$(n,\gamma)^{60}$Ni reaction.

| $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 119.9 *3* | 0.033 *4* | 2625 → 2505 | 913.63 *14* | 0.047 *4* | 4953 → 4039 | 1568.0 *5* | 0.014 *3* | 6327 → 4760 |
| 123.65 *20* | 0.011 *2* | unplaced | 952.26 *3* | 11.2 *3* | 2284 → 1332 | 1575.84 *13* | 0.071 *5* | 5447 → 3871 |
| 139.11 *17* | 0.013 *3* | unplaced | 964.8 *3* | 0.022 *3* | 3123 → 2158 | 1585.33 *13* | 0.067 *5* | 4779 → 3193 |
| 158.34 *12* | 0.016 *2* | unplaced | 983.9 *4* | 0.011 *3* | 3268 → 2284 | 1592.53 *4* | 0.440 *11* | 5612 → 4019 |
| 215.16 *18* | 0.015 *3* | unplaced | 993.48 *3* | 0.161 *5* | 3619 → 2626 | 1606.10 *14* | 0.059 *5* | 4111 → 2505 |
| 216.95 *25* | 0.014 *3* | unplaced | 1005.83 *10* | 0.054 *4* | unplaced | 1621.2 *5* | 0.017 *5* | 6465 → 4843 |
| 229.62 *10* | 0.027 *3* | unplaced | 1027.56 *4* | 0.228 *5* | 3186 → 2158 | 1628.9 *4* | 0.022 *4* | 7339 → 5710 |
| 277.38 *14* | 0.024 *3* | unplaced | 1035.23 *3* | 1.03 *3* | 3193 → 2158 | 1632.99 *18* | 0.053 *5* | 5710 → 4078 |
| 305.7 *3* | 0.016 *3* | 3925 → 3619 | 1064.2 *4* | 0.021 *4* | 5612 → 4548 | 1636.42 *13* | 0.082 *5* | 4760 → 3123 |
| 355.67 *11* | 0.026 *4* | unplaced | 1091.42 *9* | 0.067 *3* | 5447 → 4355 | 1643.6 *4* | 0.026 *5* | 7316 → 5672 |
| 393.76 *6* | 0.162 *4* | 3587 → 3193 | 1110.31 *9* | 0.081 *6* | 3268 → 2158 | 1684.4 *3* | 0.031 *5* | 4953 → 3268 |
| 431.9 *4* | 0.009 *3* | 4019 → 3587 | 1113.9 *3* | 0.053 *6* | 3619 → 2505 | 1692.45 *8* | 0.119 *7* | 4318 → 2625 |
| 467.28 *3* | 0.71 *3* | 2625 → 2158 | 1154.82 *12* | 0.046 *4* | 4548 → 3393 | 1712.30 *9* | 0.741 *15* | 3871 → 2158 |
| 493.3 *4* | 0.008 *3* | 3119 → 2625 | 1159.09 *13* | 0.043 *4* | 3317 → 2158 | 1734.98 *11* | 0.157 *8* | 4019 → 2284 |
| 497.76 *4* | 0.115 *4* | 3123 → 2625 | 1173.24 *3* | 0.47 *4* | 2505 → 1332 | 1741.3 *5* | 0.013 *4* | 5612 → 3871 |
| 521.24 *8* | 0.118 *8* | unplaced | 1194.4 *5* | 0.015 *5* | 4929 → 3734 | 1766.5 *3* | 0.029 *4* | 3925 → 2158 |
| 541.0 *3* | 0.014 *3* | unplaced | 1234.51 *7* | 0.072 *4* | 3393 → 2158 | 1786.9 *3* | 0.049 *8* | 3119 → 1332 |
| 555.81 *19* | 0.020 *3* | unplaced | 1244.93 *22* | 0.021 *4* | 3871 → 2626 | 1791.19 *3* | 3.07 *3* | 3123 → 1332 |
| 569.5 *4* | 0.009 *3* | 3887 → 3317 | 1248.86 *15* | 0.036 *4* | 5288 → 4039 | 1813.5 *5* | 0.066 *7* | 4318 → 2505 |
| 604.62 *23* | 0.014 *3* | unplaced | 1293.2 *9* | 0.37 *5* | 2625 → 1332 | 1816.1 *5* | 0.016 *4* | unplaced |
| 642.96 *5* | 0.088 *3* | 3268 → 2625 | 1296.3 *4* | 0.028 *5* | unplaced | 1829.9 *4* | 0.018 *5* | 4335 → 2505 |
| 660.27 *16* | 0.019 *3* | unplaced | 1306.5 *5* | 0.019 *5* | 4493 → 3186 | 1853.67 *7* | 0.173 *6* | 3186 → 1332 |
| 667.4 *5* | 0.007 *3* | 4779 → 4111 | 1308.16 *25* | 0.044 *5* | 4577 → 3268 | 1861.33 *3* | 1.34 *3* | 3193 → 1332 |
| 672.90 *6* | 0.073 *3* | unplaced | 1332.54 *3* | 44.6 *9* | 1332 → 0 | 1878.0 *4* | 0.022 *5* | 5612 → 3734 |
| 677.17 *5* | 0.137 *3* | 3871 → 3193 | 1354.08 *9* | 0.065 *5* | 4548 → 3193 | 1881.15 *12* | 0.074 *5* | 4039 → 2158 |
| 680.42 *4* | 0.144 *3* | 3186 → 2505 | 1358.67 *18* | 0.027 *4* | C → 10029 | 1888.4 *3* | 0.031 *4* | 5476 → 3587 |
| 693.57 *11* | 0.037 *3* | 3887 → 3193 | 1380.4 *3* | 0.045 *6* | 4006 → 2625 | 1919.28 *7* | 0.132 *6* | 4078 → 2158 |
| 702.11 *14* | 0.025 *3* | 4019 → 3317 | 1381.8 *3* | 0.035 *6* | 3887 → 2505 | 1936.41 *6* | 0.186 *5* | 3268 → 1332 |
| 727.07 *18* | 0.020 *3* | unplaced | 1385.97 *14* | 0.035 *5* | 4779 → 3393 | 1985.27 *3* | 3.65 *7* | 3317 → 1332 |
| 739.2 *3* | 0.030 *5* | 3925 → 3186 | 1392.3 *5* | 0.009 *3* | 5127 → 3734 | 2028.5 *5* | 0.019 *5* | 4534 → 2505 |
| 747.33 *3* | 0.818 *15* | 3871 → 3123 | 1399.4 *4* | 0.010 *3* | 7761 → 6362 | 2040.85 *19* | 0.048 *5* | C → 9346 |
| 749.7 *3* | 0.050 *6* | 6362 → 5612 | 1404.4 *3* | 0.017 *4* | unplaced | 2060.58 *3* | 0.571 *13* | 3393 → 1332 |
| 751.9 *4* | 0.026 *5* | 3871 → 3119 | 1419.40 *10* | 0.053 *4* | 3925 → 2505 | 2152.6 *3* | 0.035 *5* | 6996 → 4843 |
| 758.5 *4* | 0.020 *6* | 4493 → 3734 | 1424.24 *4* | 0.251 *7* | 4548 → 3123 | 2158.63 *3* | 0.98 *3* | 2158 → 0 |
| 770.3 *3* | 0.011 *3* | unplaced | 1429.07 *3* | 0.496 *10* | 3587 → 2158 | 2176.84 *4* | 0.285 *8* | 4335 → 2158 |
| 805.6 *4* | 0.011 *3* | 3925 → 3119 | 1434.0 *3* | 0.018 *4* | C → 9953 | 2198.1 *4* | 0.027 *5* | 6516 → 4318 |
| 813.48 *7* | 0.068 *3* | 4548 → 3734 | 1451.88 *16* | 0.033 *4* | 4078 → 2625 | 2245.40 *15* | 0.063 *5* | unplaced |
| 826.11 *3* | 6.30 *12* | 2158 → 1332 | 1472.6 *6* | 0.021 *6* | 7799 → 6327 | 2255.18 *5* | 0.230 *7* | 3587 → 1332 |
| 839.08 *19* | 0.023 *3* | 3123 → 2284 | 1474.6 *3* | 0.049 *6* | 5967 → 4493 | 2263.17 *4* | 0.348 *8* | 4548 → 2284 |
| 841.2 *3* | 0.016 *3* | 4953 → 4111 | 1485.94 *19* | 0.039 *4* | 4111 → 2625 | 2282.0 *3* | 0.025 *4* | 5476 → 3193 |
| 851.9 *3* | 0.020 *3* | 5612 → 4760 | 1491.5 *3* | 0.030 *5* | 4760 → 3268 | 2311.00 *18* | 0.048 *5* | C → 9076 |
| 853.8 *4* | 0.015 *3* | 4039 → 3186 | 1497.91 *25* | 0.033 *5* | unplaced | 2317.65 *20* | 0.048 *6* | 5710 → 3393 |
| 868.06 *20* | 0.022 *3* | unplaced | 1510.83 *21* | 0.028 *4* | unplaced | 2320.7 *4* | 0.025 *4* | 6327 → 4006 |
| 883.1 *3* | 0.016 *3* | 4006 → 3123 | 1532.65 *12* | 0.055 *5* | 6066 → 4534 | 2334.4 *3* | 0.031 *5* | 4493 → 2158 |
| 896.23 *6* | 0.119 *5* | 4019 → 3123 | 1562.8 *3* | 0.040 *4* | 5918 → 4355 | 2341.9 *4* | 0.023 *4* | C → 9045 |
| 909.05 *4* | 0.601 *14* | 3193 → 2284 | 1564.6 *7* | 0.015 *5* | unplaced | 2375.6 *3* | 0.030 *4* | 4534 → 2158 |

TABLE IX. (*Continued.*)

| $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 2389.25 *5* | 0.300 *8* | 4548 → 2158 | 3046.7 *7* | 0.017 *4* | 5672 → 2625 | 3703.4 *8* | 0.039 *11* | C → 7684 |
| 2392.6 *3* | 0.040 *5* | 5710 → 3317 | 3058.0 *7* | 0.016 *4* | 6327 → 3268 | 3732.23 *22* | 0.151 *13* | 5065 → 1332 |
| 2401.83 *3* | 0.778 *15* | 3734 → 1332 | 3062.5 *5* | 0.023 *4* | unplaced | 3743.71 *13* | 0.180 *9* | 5902 → 2158 |
| 2418.65 *20* | 0.042 *5* | 4577 → 2158 | 3101.2 *6* | 0.015 *4* | C → 8286 | 3794.8 *4* | 0.049 *6* | 5127 → 1332 |
| 2478.42 *7* | 0.129 *5* | 5672 → 3193 | 3123.70 *5* | 0.34 *2* | 3123 → 0 | 3817.7 *5* | 0.040 *7* | unplaced |
| 2488.73 *10* | 0.088 *4* | 5612 → 3123 | 3129.6 *3* | 0.033 *4* | 7207 → 4078 | 3836.1[h] *5* | 0.033 *6* | C → 7552 |
| 2493.8 *3* | 0.032 *3* | 4779 → 2284 | 3160.60 *6* | 0.260 *8* | 4493 → 1332 | 3870.94 *7* | 0.356 *12* | 3871 → 0 |
| 2496.9 *3* | 0.019 *3* | 6516 → 4019 | 3167.7 *4* | 0.045 *5* | 6362 → 3193 | 3892.4[i] *5* | 0.043 *7* | C → 7494 |
| 2517.00 *9* | 0.246 *8* | 5710 → 3193 | 3193.77 *4* | 0.602 *11* | 3193 → 0 | 3895.4 *5* | 0.045 *7* | unplaced |
| 2525.4 *3* | 0.033 *6* | 5918 → 3393 | 3215.27 *8* | 0.122 *6* | 4548 → 1332 | 3913.7 *3* | 0.042 *6* | C → 7473 |
| 2538.53 *4* | 0.451 *10* | 3871 → 1332 | 3233.0 *3* | 0.030 *5* | unplaced | 3939.5 *4* | 0.042 *6* | unplaced |
| 2547.35 *21* | 0.043 *5* | 6567 → 4019 | 3244.90 *9* | 0.151 *5* | 4577 → 1332 | 3955.2[j] *6* | 0.025 *6* | 5288 → 1332 |
| 2554.69 *10* | 0.124 *5* | 3887 → 1332 | 3264.0 *5* | 0.019 *4* | unplaced | 3973.4 *5* | 0.042 *7* | C → 7414 |
| 2572.2 *4* | 0.017 *4* | 8638 → 6066 | 3268.78 *12* | 0.074 *5* | 3268 → 0 | 3983.6 *4* | 0.050 *6* | 6489 → 2505 |
| 2578.2 *5* | 0.014 *4* | 6465 → 3887 | 3276.32 *20* | 0.044 *5* | 5902 → 2625 | 4006.30 *4* | 1.20 *3* | 4006 → 0 |
| 2586.98 *12* | 0.071 *5* | 5710 → 3123 | 3288.5 *3* | 0.019 *5* | 5447 → 2158 | 4019.74 *5* | 1.68 *4* | 4019 → 0 |
| 2593.3 *4* | 0.015 *4* | 6911 → 4318 | 3296.3 *3* | 0.038 *5* | 7316 → 4019 | 4021.4 *5* | 0.075 *8* | 6647 → 2625 |
| 2601.5 *4* | 0.025 *5* | 4760 → 2158 | 3302.11 *24* | 0.035 *4* | 7414 → 4111 | 4048.2 *4* | 0.048 *6* | C → 7339 |
| 2607.10 *22* | 0.041 *5* | 6647 → 4039 | 3352.8 *4* | 0.025 *6* | unplaced | 4066.3 *3* | 0.062 *8* | unplaced |
| 2613.9 *3* | 0.026 *4* | 8286 → 5672 | 3354.5 *4* | 0.048 *5* | 7690 → 4335 | 4071.49 *22* | 0.073 *8* | C → 7316 |
| 2620.40 *8* | 0.125 *5* | 4779 → 2158 | 3359.5 *4* | 0.027 *5* | unplaced | 4077.6 *9* | 0.022 *5* | 4078 → 0 |
| 2627.4 *3* | 0.029 *4* | 6647 → 4019 | 3369.4 *4* | 0.023 *4* | 6489 → 3119 | 4080.0 *7* | 0.027 *6* | 7950 → 3871 |
| 2633.3 *3* | 0.032 *5* | 5902 → 3268 | 3393.05 *20* | 0.042 *4* | 3393 → 0 | 4111.6 *8* | 0.041 *7* | 4111 → 0 |
| 2673.86 *4* | 1.60 *3* | 4006 → 1332 | 3426.3 *5* | 0.094 *24* | 5710 → 2284 | 4114.4 *6* | 0.070 *8* | 5447 → 1332 |
| 2684.19 *12* | 0.166 *8* | 5878 → 3193 | 3428.0 *4* | 0.096 *25* | 4760 → 1332 | 4164.75 *11* | 0.193 *8* | C → 7222 |
| 2687.33 *4* | 0.712 *16* | 4019 → 1332 | 3436.9 *3* | 0.076 *6* | C → 7950 | 4168.32 *19* | 0.099 *8* | 6327 → 2158 |
| 2707.44 *8* | 0.145 *5* | 4039 → 1332 | 3440.37 *17* | 0.092 *8* | 6066 → 2625 | 4180.5[k] *7* | 0.018 *4* | C → 7207 |
| 2721.59 *25* | 0.038 *5* | C → 8666 | 3446.77 *17* | 0.081 *7* | 4779 → 1332 | 4204.0[l] *7* | 0.021 *6* | 6489 → 2284 |
| 2745.47 *6* | 0.240 *7* | 4078 → 1332 | 3453.67 *11* | 0.131 *5* | 5612 → 2158 | 4255.6 *6* | 0.026 *4* | unplaced |
| 2749.5 *4* | 0.026 *5* | C → 8638 | 3487.1[d] *4* | 0.023 *5* | 6756 → 3268 | 4279.8[m] *4* | 0.034 *6* | 5612 → 1332 |
| 2770.5 *3* | 0.039 *5* | 4929 → 2158 | 3495.12 *16* | 0.108 *5* | unplaced | 4305.2 *6* | 0.019 *5* | unplaced |
| 2779.42 *14* | 0.084 *5* | 4111 → 1332 | 3511.07[e] *18* | 0.174 *8* | 4843 → 1332 | 4318.52 *11* | 0.130 *7* | 4318 → 0 |
| 2785.73 *14* | 0.085 *5* | unplaced | 3513.6 *3* | 0.072 *7* | 5672 → 2158 | 4331.24[n] *15* | 0.113 *6* | C → 7056 |
| 2797.7 *5* | 0.021 *5* | 6066 → 3268 | 3517.3 *3* | 0.042 *5* | 6834 → 3317 | 4335.37 *23* | 0.087 *8* | 4335 → 0 |
| 2822.3 *3* | 0.040 *5* | C → 8565 | 3551.94 *14* | 0.130 *6* | 5710 → 2158 | 4338.3 *3* | 0.064 *7* | unplaced |
| 2831.3 *6* | 0.018 *5* | 6756 → 3925 | 3569.53[f] *13* | 0.088 *5* | C → 7818 | 4348.2 *4* | 0.031 *5* | unplaced |
| 2846.9 *5* | 0.026 *5* | 7339 → 4493 | 3589.0 *3* | 0.051 *8* | C → 7799 | 4356.6 *3* | 0.046 *6* | unplaced |
| 2874.42 *19* | 0.068 *6* | unplaced | 3596.4 *4* | 0.040 *6* | 4929 → 1332 | 4370.7[o] *5* | 0.025 *4* | 6996 → 2625 |
| 2883.0 *4* | 0.037 *5* | C → 8504 | 3603.4[g] *7* | 0.020 *5* | 7222 → 3619 | 4377.65 *13* | 0.120 *6* | unplaced |
| 2907.5 *3* | 0.033 *5* | unplaced | 3620.64 *14* | 0.117 *8* | 4953 → 1332 | 4390.4 *3* | 0.042 *5* | C → 6996 |
| 2938.6 *4* | 0.024 *5* | 7473 → 4534 | 3625.6 *4* | 0.034 *6* | C → 7761 | 4430.3 *4* | 0.040 *5* | 7056 → 2625 |
| 2985.97 *7* | 0.320 *9* | 4318 → 1332 | 3632.4 *6* | 0.024 *6* | 7950 → 4318 | 4475.58 *10* | 0.150 *7* | C → 6911 |
| 3002.5 *4* | 0.025 *5* | 4335 → 1332 | 3641.1 *4* | 0.045 *6* | 6834 → 3193 | 4487.56 *25* | 0.055 *5* | 8565 → 4078 |
| 3022.90 *20* | 0.064 *5* | 4355 → 1332 | 3658.9 *3* | 0.050 *6* | unplaced | 4492.3 *6* | 0.022 *4* | 7761 → 3268 |
| 3027.86 *16* | 0.075 *6* | 6647 → 3619 | 3697.7 *6* | 0.032 *7* | C → 7690 | 4507.04 *18* | 0.163 *10* | unplaced |
| 3040.5 *4* | 0.030 *5* | 6911 → 3871 | 3700.9 *9* | 0.031 *8* | 5860 → 2158 | 4545.9[p] *5* | 0.074 *15* | 5878 → 1332 |

TABLE IX. (*Continued.*)

| $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (b)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 4548.2 *3* | 0.163 *16* | 4548 → 0 | 5306.7 *4* | 0.040 *5* | 9346 → 4039 | 6382.3 *5* | 0.033 *5* | 6382 → 0 |
| 4553.0 *3* | 0.071 *6* | C → 6834 | 5320.69[r] *18* | 0.094 *6* | C → 6066 | 6434.01 *10* | 0.223 *7* | C → 4953 |
| 4577.37 *14* | 0.144 *8* | 4577 → 0 | 5393.3 *3* | 0.062 *5* | 7552 → 2158 | 6458.42 *18* | 0.098 *6* | C → 4929 |
| 4617.2 *4* | 0.048 *6* | 8504 → 3887 | 5407.76 *13* | 0.155 *6* | unplaced | 6464.9 *3* | 0.090 *5* | 6465 → 0 |
| 4631.2 *5* | 0.036 *6* | C → 6756 | 5419.5[s] *6* | 0.025 *5* | C → 5967 | 6543.44 *18* | 0.586 *24* | C → 4843 |
| 4639.1 *6* | 0.030 *6* | unplaced | 5452.1 *5* | 0.028 *5* | 8638 → 3186 | 6608.29 *15* | 0.293 *13* | C → 4779 |
| 4678.3 *5* | 0.050 *5* | 8565 → 3887 | 5468.5 *6* | 0.028 *5* | C → 5918 | 6627.12 *19* | 0.128 *8* | C → 4760 |
| 4683.0 *5* | 0.043 *6* | unplaced | 5472.8 *5* | 0.036 *5* | 8666 → 3193 | 6809.91 *9* | 0.333 *13* | C → 4577 |
| 4693.6 *5* | 0.042 *6* | 7818 → 3123 | 5485.02 *8* | 0.377 *9* | C → 5902 | 6839.38 *12* | 1.21 *7* | C → 4548 |
| 4740.48 *12* | 0.227 *10* | C → 6647 | 5509.46 *11* | 0.223 *8* | C → 5878 | 6894.23 *11* | 0.275 *10* | C → 4493 |
| 4744.7 *5* | 0.047 *7* | unplaced | 5527.4 *5* | 0.035 *5* | C → 5860 | 6911.7 *3* | 0.098 *6* | 6911 → 0 |
| 4760.1 *4* | 0.054 *6* | 4760 → 0 | 5578.7 *6* | 0.022 *5* | 6911 → 1332 | 7032.9 *7* | 0.026 *5* | unplaced |
| 4819.9 *6* | 0.032 *6* | C → 6567 | 5611.8[t] *4* | 0.036 *5* | 5612 → 0 | 7051.67 *12* | 0.220 *9* | C → 4335 |
| 4843.76 *9* | 0.389 *15* | 4843 → 0 | 5640.4 *7* | 0.020 *5* | 7799 → 5152 | 7068.67 *8* | 0.415 *12* | C → 4318 |
| 4871.7 *8* | 0.024 *6* | C → 6516 | 5659.9 *8* | 0.015 *4* | 8286 → 2625 | 7275.9 *9* | 0.019 *5* | C → 4111 |
| 4898.4 *4* | 0.064 *6* | C → 6489 | 5676.64 *4* | 0.935 *18* | C → 5710 | 7309.22 *14* | 0.214 *10* | C → 4078 |
| 4906.1 *5* | 0.043 *6* | 6239 → 1332 | 5710.52 *10* | 0.362 *12* | 5710 → 0 | 7367.31 *5* | 1.95 *5* | C → 4019 |
| 4922.34 *25* | 0.155 *11* | C → 6465 | 5714.96 *18* | 0.159 *9* | C → 5672 | 7380.77 *4* | 2.43 *7* | C → 4006 |
| 4950.1 *5* | 0.101 *15* | unplaced | 5723.0 *5* | 0.035 *5* | 7056 → 1332 | 7473.0 *8* | 0.030 *6* | 7473 → 0 |
| 5005.5[q] *7* | 0.031 *7* | C → 6382 | 5759.1[u] *7* | 0.024 *5* | 9076 → 3317 | 7499.4 *4* | 0.076 *7* | C → 3887 |
| 5025.43 *25* | 0.092 *8* | C → 6362 | 5775.08 *6* | 0.713 *15* | C → 5612 | 7516.17 *4* | 2.04 *5* | C → 3871 |
| 5046.4 *7* | 0.032 *6* | 8666 → 3619 | 5875.2 *7* | 0.017 *4* | 7207 → 1332 | 7652.88 *8* | 0.430 *10* | C → 3734 |
| 5059.8 *6* | 0.040 *7* | C → 6327 | 5886.3 *7* | 0.023 *5* | unplaced | 7689.5 *5* | 0.043 *6* | 7690 → 0 |
| 5064.79 *7* | 0.509 *15* | 5065 → 0 | 5889.9 *5* | 0.033 *5* | 7222 → 1332 | 7761.6 *8* | 0.027 *6* | 7761 → 0 |
| 5097.8 *6* | 0.031 *6* | unplaced | 5911.3 *8* | 0.016 *5* | C → 5476 | 7799.40 *6* | 0.689 *14* | C → 3587 |
| 5132.6 *5* | 0.028 *6* | 6465 → 1332 | 5933.3 *7* | 0.018 *5* | 9953 → 4019 | 7915.1 *9* | 0.022 *6* | unplaced |
| 5148.1 *3* | 0.062 *5* | C → 6239 | 5940.5 *3* | 0.074 *6* | C → 5447 | 7951.4 *8* | 0.025 *6* | 7950 → 0 |
| 5152.61 *25* | 0.070 *5* | unplaced | 5944.3 *5* | 0.039 *5* | unplaced | 7993.95 *10* | 0.310 *11* | C → 3393 |
| 5157.9 *9* | 0.015 *5* | unplaced | 5952.4 *5* | 0.024 *5* | 9076 → 3123 | 8069.26 *4* | 3.18 *6* | C → 3317 |
| 5173.6 *3* | 0.049 *5* | 9045 → 3871 | 5967.5 *8* | 0.014 *5* | 5967 → 0 | 8117.6 *9* | 0.044 *13* | C → 3268 |
| 5184.9 *5* | 0.029 *5* | 10029 → 4843 | 5983.4 *5* | 0.024 *5* | 7316 → 1332 | 8193.24 *4* | 1.90 *5* | C → 3193 |
| 5193.4 *3* | 0.056 *5* | unplaced | 6003.9 *7* | 0.017 *5* | unplaced | 8200.88 *17* | 0.207 *9* | C → 3186 |
| 5234.82 *10* | 0.230 *7* | unplaced | 6067.2 *8* | 0.014 *5* | 6066 → 0 | 8263.35 *5* | 1.59 *5* | C → 3123 |
| 5245.5 *5* | 0.030 *5* | unplaced | 6099.4 *3* | 0.062 *6* | C → 5288 | 8504.2 *9* | 0.020 *4* | 8504 → 0 |
| 5254.46 *14* | 0.146 *6* | unplaced | 6162.5 *6* | 0.032 *5* | 7494 → 1332 | 9102.10 *4* | 8.83 *16* | C → 2284 |
| 5287.8 *7* | 0.022 *5* | 5288 → 0 | 6260.19 *20* | 0.070 *6* | C → 5127 | 9228.19 *9* | 1.14 *4* | C → 2158 |
| 5292.3 *9* | 0.016 *5* | 7793 → 2505 | 6322.29 *11* | 0.557 *14* | C → 5065 | 10054.14 *7* | 8.22 *15* | C → 1332 |
| 5299.1 *5* | 0.074 *16* | unplaced | 6351.2 *4* | 0.032 *5* | 7684 → 1332 | 11386.50 *9* | 21.5 *8* | C → 0 |

[a]In our notation, 119.9 *3* ≡ 119.9 ± 0.3, etc.
[b]In our notation, 3.02 *7* ≡ 3.02 ± 0.07, etc. Multiply by 1.357 to obtain photons per 100 thermal neutron captures.
[c]C denotes the capturing state.
[d]Can also be placed as a 9346 → 5860 transition.
[e]Can also be placed as a 8638 → 5127 transition.
[f]Can also be placed as a 7495 → 3925 transition.
[g]Can also be placed as a 6996 → 3393 transition.
[h]Can also be placed as a 7761 → 3925 transition.
[i]Can also be placed as a 7818 → 3925 transition.
[j]Can also be placed as a 7690 → 3734 transition.
[k]Can also be placed as a 6465 → 2285 transition.
[l]Can also be placed as a 7473 → 3269 transition.
[m]Can also be placed as a 8286 → 4006 transition.
[n]Can also be placed as a 7950 → 3619 transition.
[o]Can also be placed as a 7495 → 3123 transition.
[p]Can also be placed as a 8565 → 4019 transition.
[q]Can also be placed as a 9045 → 4039 transition.
[r]Can also be placed as a 8638 → 3317 transition.
[s]Can also be placed as a 9953 → 4534 transition.
[t]Can also be placed as a 9347 → 3734 transition.
[u]Can also be placed as a 9347 → 3588 transition.

TABLE X. Level scheme of $^{60}$Ni from this work in tabular form.

| $E$(level)$^a$ (keV) | $J^\pi$ | Deexciting $\gamma$ rays$^b$ | $I_\gamma$ (in)$^a$ (b) | $I_\gamma$ (out)$^a$ (b) | $I_\gamma$ (in − out)$^a$ (b) |
|---|---|---|---|---|---|
| 0.0 | $0^+$ | | 73.7 *12* | | 73.7 *12* |
| 1332.536 *16* | $2^+$ | 1332.543 | 42.1 *4* | 44.6 *9* | −2.5 *10* |
| 2158.671 *18* | $2^+$ | 2158.63, 826.11 | 6.42 *7* | 7.28 *13* | −0.86 *14* |
| 2284.828 *24* | $0^+$ | 952.26 | 10.12 *17* | 11.2 *3* | −1.1 *4* |
| 2505.79 *3* | $4^+$ | 1173.24 | 0.546 *18* | 0.47 *4* | 0.08 *5* |
| 2625.98 *3* | $3^+$ | 1293.2, 467.28, 119.9 | 0.937 *21* | 1.11 *6* | −0.18 *7* |
| 3119.45 *18* | $4^+$ | 1786.9, 493.3 | 0.060 *7* | 0.057 *9* | 0.003 *11* |
| 3123.750 *21* | $2^+$ | 3123.70, 1791.19, 964.8, 839.08, 497.76 | 3.10 *6* | 3.57 *5* | −0.47 *7* |
| 3186.23 *4* | $3^+$ | 1853.67, 1027.56, 680.42 | 0.299 *13* | 0.545 *9* | −0.246 *16* |
| 3193.892 *19* | $1^+$ | 3193.77, 1861.33, 1035.23, 909.05 | 3.06 *6* | 3.57 *5* | −0.51 *7* |
| 3268.97 *4* | $2^+$ | 3268.78, 1936.41, 1110.31, 983.9, 642.96 | 0.263 *19* | 0.440 *11* | −0.177 *12* |
| 3317.85 *3* | $0^+$ | 1985.27, 1159.09 | 3.32 *6* | 3.69 *7* | −0.37 *10* |
| 3393.16 *3* | $2^+$ | 3393.05, 2060.58, 1234.51 | 0.472 *16* | 0.685 *15* | −0.213 *21* |
| 3587.75 *3* | $0^+$ | 2255.18, 1429.07, 393.76 | 0.729 *15* | 0.888 *13* | −0.159 *20* |
| 3619.47 *4* | $(3)^+$ | 1113.9, 993.48, | 0.143 *11* | 0.214 *8* | −0.071 *13* |
| 3734.42 *3* | $2^+$ | 2401.83 | 0.564 *15* | 0.778 *15* | −0.214 *21* |
| 3871.080 *23* | $1^+$, $2^+$ | 3870.94, 2538.53, 1712.30, 1244.93, 751.9, 747.33, 677.17 | 2.23 *6* | 2.55 *3* | −0.32 *6* |
| 3887.38 *7* | | 2554.69, 1381.8, 693.57, 569.5 | 0.188 *12* | 0.205 *9* | −0.017 *15* |
| 3925.22 *9* | $2^+$, $3^+$ | 1766.5, 1419.40, 805.6, 739.2, 305.7 | 0.018 *5* | 0.139 *9* | −0.121 *10* |
| 4006.46 *3* | $1^+$, $2^+$ | 4006.30, 2673.86, 1380.4, 883.1 | 2.45 *7* | 2.86 *5* | −0.41 *9* |
| 4019.914 *25* | $1^+$, $2^+$ | 4019.74, 2687.33, 1734.98, 896.23, 702.11, 431.9 | 2.54 *6* | 2.70 *5* | −0.17 *7* |
| 4039.92 *6* | $3^-$ | 2707.44, 1881.15, 853.8 | 0.164 *9* | 0.234 *8* | −0.070 *12* |
| 4078.01 *5* | $1^+$, $2^+$ | 4077.6, 2745.47, 1919.28, 1451.88 | 0.355 *13* | 0.427 *12* | −0.072 *17* |
| 4111.97 *9* | | 4111.6, 2779.42, 1606.10, 1485.94 | 0.077 *8* | 0.223 *11* | −0.146 *14* |
| 4318.58 *5* | $1^+$, $2^+$ | 4318.52, 2985.97, 1813.5, 1692.45 | 0.481 *15* | 0.635 *15* | −0.154 *22* |
| 4335.56 *4* | | 4335.37, 3002.5, 2176.84, 1829.9 | 0.268 *11* | 0.415 *14* | −0.147 *17* |
| 4355.57 *12* | | 3022.90 | 0.107 *5* | 0.064 *5* | 0.043 *7* |
| 4493.18 *6* | $2^+$ | 3160.60, 2334.4, 1306.5, 758.5 | 0.350 *13* | 0.330 *13* | 0.020 *18* |
| 4534.13 *14* | | 2375.6, 2028.5, | 0.079 *7* | 0.049 *7* | 0.030 *10* |
| 4547.99 *3* | $1^+$, $2^+$ | 4548.2, 3215.27, 2389.25, 2263.17, 1424.24, 1354.08, 1154.82, 813.48 | 1.23 *7* | 1.363 *23* | −0.13 *3* |
| 4577.46 *6* | $2^+$ | 4577.37, 3244.90, 2418.65, 1308.16 | 0.333 *13* | 0.381 *12* | −0.048 *18* |
| 4760.25 *9* | | 4760.1, 3428.0, 2601.5, 1636.42, 1491.5 | 0.162 *9* | 0.29 *3* | −0.13 *3* |
| 4779.16 *6* | | 3446.77, 2620.40, 2493.8, 1585.33, 1385.97 , 667.4 | 0.293 *13* | 0.347 *12* | −0.054 *18* |
| 4843.94 *8* | | 4843.76, 3511.07 | 0.67 *3* | 0.563 *17* | 0.10 *3* |
| 4929.00 *14* | | 3596.4, 2770.5, 1194.4 | 0.098 *6* | 0.094 *10* | 0.004 *11* |
| 4953.38 *7* | | 3620.64, 1684.4, 913.63, 841.2 | 0.223 *7* | 0.211 *11* | 0.012 *13* |
| 5065.03 *6* | $(1^-)$ | 5064.79, 3732.23 | 0.557 *14* | 0.660 *20* | −0.103 *25* |
| 5127.18 *17* | | 3794.8, 1392.3 | 0.070 *6* | 0.058 *7* | 0.012 *9* |
| 5288.57 *14* | | 5287.8, 3955.2, 1248.86 | 0.062 *6* | 0.083 *9* | −0.021 *11* |
| 5446.99 *10* | | 3288.5, 1575.84, 1091.42 | 0.074 *6* | 0.227 *11* | −0.153 *13* |
| 5476.06 *21* | | 2282.0, 1888.4 | 0.016 *5* | 0.056 *6* | −0.040 *8* |

levels at 5446.99 and 5967.8 keV and the 27 levels above 6.9 MeV (see Table X) should be viewed with caution, based as they are only on energy fits and not on coincidence data or corroboration in another reaction experiment. The $\gamma$-ray branching ratios determined in this work are reasonably consistent with those adopted in Ref. [93].

The neutron separation energy determined in this work is $S_n(^{60}\mathrm{Ni}) = 11\,387.73 \pm 0.05$ keV. The value obtained by Wilson *et al.* [59], $S_n = 11\,387.5 \pm 0.7$ keV, is consistent with our more accurate value.

The improved sensitivity of the current measurement has resulted in a significant increase (see Table XI) in both the

TABLE X. (*Continued.*)

| $E$(level)$^a$ (keV) | $J^\pi$ | Deexciting $\gamma$ rays$^b$ | $I_\gamma$ (in)$^a$ (b) | $I_\gamma$ (out)$^a$ (b) | $I_\gamma$ (in − out)$^a$ (b) |
|---|---|---|---|---|---|
| 5612.44 *4* | | 5611.8, 4279.8, 3453.67, 2488.73, 1878.0, 1741.3, 1592.53, 1064.2, 851.9 | 0.763 *17* | 0.805 *17* | −0.042 *24* |
| 5672.39 *7* | | 3513.6, 3046.7, 2478.42 | 0.211 *11* | 0.218 *10* | −0.007 *15* |
| 5710.82 *4* | | 5710.52, 3551.94, 3426.3, 2586.98, 2517.00, 2392.6, 2317.65, 1632.99 | 0.957 *19* | 1.04 *3* | −0.09 *4* |
| 5860.0 *5* | | 3700.9 | 0.035 *5* | 0.031 *8* | 0.004 *10* |
| 5878.08 *9* | | 4545.9, 2684.19 | 0.223 *8* | 0.240 *17* | −0.017 *19* |
| 5902.45 *7* | | 3743.71, 3276.32, 2633.3 | 0.377 *9* | 0.256 *12* | 0.121 *15* |
| 5918.56 *21* | | 2525.4, 1562.8 | 0.028 *5* | 0.073 *8* | −0.045 *9* |
| 5967.8 *3* | | 5967.5, 1474.6 | 0.025 *5* | 0.063 *8* | −0.038 *10* |
| 6066.71 *11* | | 3440.37, 2797.7, 1532.65 | 0.111 *8* | 0.182 *12* | −0.071 *14* |
| 6239.2 *3* | | 4906.1 | 0.062 *5* | 0.043 *6* | 0.019 *8* |
| 6327.23 *15* | | 3058.0, 2320.7, 1568.0 | 0.061 *10* | 0.154 *11* | −0.093 *14* |
| 6362.06 *17* | | 3167.7, 749.7 | 0.102 *9* | 0.095 *8* | 0.007 *12* |
| 6382.4 *4* | | 6382.3 | 0.031 *7* | 0.033 *5* | −0.002 *9* |
| 6465.27 *16* | | 6464.9, 5132.6, 2578.2, 1621.2 | 0.155 *11* | 0.149 *10* | 0.006 *15* |
| 6489.17 *23* | | 4204.0, 3369.4 | 0.064 *6* | 0.094 *10* | −0.030 *12* |
| 6516.73 *23* | | 2496.9, 2198.1 | 0.024 *6* | 0.046 *6* | −0.022 *9* |
| 6567.35 *20* | | 2547.35 | 0.032 *6* | 0.043 *5* | −0.011 *8* |
| 6647.19 *9* | | 4021.4, 3027.86, 2627.4, 2607.10 | 0.227 *10* | 0.220 *12* | 0.007 *16* |
| 6756.3 *3* | | 3487.1, 2831.3 | 0.036 *6* | 0.041 *7* | −0.005 *10* |
| 6834.95 *19* | | 3641.1, 3517.3 | 0.071 *6* | 0.087 *8* | −0.016 *10* |
| 6911.95 *9* | | 6911.7, 5578.7, 3040.5, 2593.3 | 0.150 *7* | 0.165 *10* | −0.015 *13* |
| 6996.86 *20* | | 4370.7, 2152.6 | 0.042 *5* | 0.060 *7* | −0.018 *9* |
| 7056.29 *14* | | 5723.0, 4430.3 | 0.113 *6* | 0.075 *7* | 0.038 *10* |
| 7207.7 *3* | | 5875.2, 3129.6 | 0.018 *4* | 0.050 *6* | −0.032 *7* |
| 7222.81 *11* | | 5889.9, 3603.4 | 0.193 *8* | 0.053 *7* | 0.140 *11* |
| 7316.15 *16* | | 5983.4, 3296.3, 1643.6 | 0.073 *8* | 0.088 *9* | −0.015 *12* |
| 7339.71 *25* | | 2846.9, 1628.9 | 0.048 *6* | 0.048 *7* | 0.000 *9* |
| 7414.18 *23* | | 3302.11 | 0.042 *7* | 0.035 *4* | 0.007 *8* |
| 7473.50 *24* | | 7473.0, 2938.6, | 0.042 *6* | 0.054 *8* | −0.012 *10* |
| 7495.3 *4* | | 6162.5, 1005.83, | 0.043 *7* | 0.032 *5* | 0.011 *9* |
| 7552.0 *3* | | 5393.3 | 0.033 *6* | 0.062 *5* | −0.029 *8* |
| 7684.1 *4* | | 6351.2 | 0.039 *11* | 0.032 *5* | 0.007 *12* |
| 7690.1 *3* | | 7689.5, 3354.5 | 0.032 *7* | 0.091 *8* | −0.059 *11* |
| 7761.7 *3* | | 7761.6, 4492.3, 1399.4 | 0.034 *6* | 0.059 *8* | −0.025 *10* |
| 7798.88 *25* | | 5640.4, 1472.6 | 0.051 *8* | 0.057 *10* | −0.006 *13* |
| 7818.04 *13* | | 4693.6 | 0.088 *5* | 0.042 *6* | 0.046 *8* |
| 7950.95 *24* | | 7951.4, 3632.4 | 0.076 *6* | 0.076 *11* | 0.000 *12* |
| 8286.3 *3* | | 5659.9, 2613.9 | 0.015 *4* | 0.041 *6* | −0.026 *7* |
| 8504.7 *3* | | 8504.2, 4617.2 | 0.037 *5* | 0.068 *8* | −0.031 *9* |
| 8565.63 *19* | | 4678.3, 4487.56 | 0.040 *5* | 0.105 *7* | −0.065 *9* |
| 8638.57 *25* | | 5452.1, 2572.2 | 0.026 *5* | 0.045 *7* | −0.019 *9* |

number of detected $\gamma$ rays and the number of bound states found to be populated in the $(n,\gamma)$ reaction.

### C. Thermal-neutron cross sections for $^{59}$Ni

In 1970, Weitman, Dåverhög, and Farvolden [118] reported an anomalously large production of helium gas in nickel samples irradiated with neutrons. Nickel is a constituent of reactor construction materials such as stainless steel. Excessive helium production can cause swelling and embrittlement which, in turn, can limit the useful lifetimes of structures. In a reactor, neutrons are captured by $^{58}$Ni to produce $^{59}$Ni. It is now well established that the $^{59}$Ni$(n,\alpha)$ reaction is a major factor in the helium production. Because of

TABLE X. (Continued.)

| $E$(level)[a] (keV) | $J^\pi$ | Deexciting $\gamma$ rays[b] | $I_\gamma$ (in)[a] (b) | $I_\gamma$ (out)[a] (b) | $I_\gamma$ (in − out)[a] (b) |
|---|---|---|---|---|---|
| 8666.23 *22* | | 5472.8, 5046.4 | 0.038 *5* | 0.068 *8* | −0.030 *10* |
| 9045.23 *24* | | 5173.6 | 0.023 *4* | 0.049 *5* | −0.026 *7* |
| 9076.68 *17* | | 5952.4, 5759.1 | 0.048 *5* | 0.048 *7* | 0.000 *9* |
| 9346.84 *18* | | 5306.7 | 0.048 *5* | 0.040 *5* | 0.008 *5* |
| 9953.7 *3* | | 5933.3 | 0.018 *4* | 0.018 *5* | 0.000 *7* |
| 10029.04 *17* | | 5184.9 | 0.027 *4* | 0.029 *5* | −0.002 *7* |
| 11387.727[c] *19* | | 11386.50, 10054.14, 9228.19, 9102.10, 8263.35, 8200.88, 8193.24, 8117.6, 8069.26, 7993.95, 7799.40, 7652.88, 7516.17, 7499.4, 7380.77, 7367.31, 7309.22, 7275.9, 7068.67, 7051.67, 6894.23, 6839.38, 6809.91, 6627.12, 6608.29, 6543.44, 6458.42, 6434.01, 6322.29, 6260.19, 6099.4, 5940.5, 5911.3, 5775.08, 5714.96, 5676.64, 5527.4, 5509.46, 5485.02, 5468.5, 5419.5, 5320.69, 5148.1, 5059.8, 5025.43, 5005.5, 4922.34, 4898.4, 4871.7, 4819.9, 4740.48, 4631.2, 4553.0, 4475.58, 4390.4, 4331.24, 4180.5, 4164.75, 4071.49, 4048.2, 3973.4, 3913.7, 3892.4, 3836.1, 3703.4, 3697.7, 3625.6, 3589.0, 3569.53, 3436.9, 3101.2, 2883.0, 2822.3, 2749.5, 2721.59, 2341.9, 2311.00, 2040.85, 1434.0, 1358.67 | | 64.2 *9* | −64.2 *9* |

[a]In our notation, 1332.536 *16* ≡ 1332.536 ± 0.016, 73.7 *12* ≡ 73.7 ± 1.2, etc.
[b]See also Table IX.
[c]Capturing state.

TABLE XI. Increasing complexity in the study of the $^{59}$Ni($n,\gamma$)$^{60}$Ni.

| Number of | Wilson, Thomas, and Jackson [59] ANL (1975) | Raman and Jurney [60] unpublished LANL/ORNL (1979) | This work LANL/ORNL |
|---|---|---|---|
| $\gamma$ rays | 17 | 250 | 390 |
| spurious $\gamma$ rays[a] | 1 | 33 | |
| placed $\gamma$ rays[b] | 17 | 210 | 326 |
| primary $\gamma$ rays | 17 | 40 | 80 |
| secondary $\gamma$ rays | 0 | 170 | 246 |
| unplaced $\gamma$ rays[c] | 0 | 40 | 64 |
| bound levels | 17 | 73 | 88 |

[a]Gamma rays sought but not observed in this more sensitive work and, therefore, considered spurious.
[b]Some of the placed $\gamma$ rays may be spurious.
[c]Some of the unplaced $\gamma$ rays may be genuine.

TABLE XII. Thermal-neutron cross sections (in *b*) for $^{59}$Ni. In our notation, 70 *5*≡70±5, 73.7 *18*≡73.7±1.8, etc.

| Reaction | Cross section | Reference | Cross section | Reference | Cross section | Reference | Cross section | Reference |
|---|---|---|---|---|---|---|---|---|
| $^{59}$Ni($n,\gamma$) | 70 *5* | [120, 123] | | | | | | |
| | 73.7 *18* | This work | | | | | | |
| $^{59}$Ni($n,p$) | | | 2.0 *5* | [123] | | | | |
| | | | 4 *1* | [124] | | | | |
| | | | 1.34 *18* | [125] | | | | |
| $^{59}$Ni($n,\alpha$) | | | | | 13.7 *12* | [119] | | |
| | | | | | 18.0 *16* | [121] | | |
| | | | | | 12 *1* | [123] | | |
| | | | | | 22.3 *16* | [124] | | |
| | | | | | 13.3 *12* | [125] | | |
| $^{59}$Ni($n$,abs)[a] | | | | | | | 87 *6* | [120, 123] |
| | | | | | | | 92 *4* | [122] |

[a]Absorption (abs) denotes sum of all interactions except scattering.

their relevance to power reactors, the thermal-neutron cross sections for $^{59}$Ni have been measured at several laboratories [119–125]. The results are summarized in Table XII. There is general agreement concerning the magnitudes of the $(n,p)$, $(n,\alpha)$, and absorption cross sections for $^{59}$Ni (see Table XII) but definitive values are not known at this time and require additional experiments.

The $(n,\gamma)$ cross-section value of $70\pm5$ b reported in Ref. [123] was based on $\gamma$-ray spectrum measurements using a NaI detector and a 7.0-mg nickel-metal target enriched to 95.35% in $^{59}$Ni [120,123]. The cross section in this case was normalized to the value of $\sigma_\gamma(2200\ \mathrm{m/s})=332.6\pm0.7$ mb [87] for $^{1}$H present in a 97-mg, $CH_2$ standard. The current cross-section value of $73.7\pm1.8$ b is based on $\gamma$-ray spectrum measurements using a Ge detector and a 6.9-mg nickel-metal target enriched to $(44.3\pm0.4)\%$ in $^{59}$Ni. The current value agrees with the previous value, but is more accurate. The normalization in the current case was provided by the known value of $(37.9\pm0.4)\%$ for the $^{58}$Ni content in the sample and the value of $\sigma_\gamma(2200\ \mathrm{m/s})=4.13\pm0.05$ b for the $^{58}$Ni$(n,\gamma)$ reaction as determined in this work earlier. The $^{60}$Ni content [$(14.5\pm0.3)\%$ of the sample] and $\sigma_\gamma(2200\ \mathrm{m/s})=2.34\pm0.05$ b for the $^{60}$Ni$(n,\gamma)$ reaction (also determined in this work) provided a cross check of the normalization. The quoted uncertainty of 1.8 b in the $^{59}$Ni cross section includes contributions from all sources including the normalization.

The measured values $\Sigma I_\gamma$ (primary)$=64.2\pm0.9$ b, $\Sigma E_\gamma I_\gamma/S_n=69.9\pm9.9$ b, and $\Sigma I_\gamma$ (to ground state) $=73.7\pm1.2$ b do not agree mainly because we have not detected all primary $\gamma$ rays. In such cases, it is customary to adopt $\Sigma I_\gamma$ (to ground state) as the recommended cross-section value. The 1332.54-keV transition from the first-excited state to the ground state and the 11 386.50-keV transition from the capturing state to the ground state together account for ~90% of this cross section. Holden [110] does not explicitly recommend a value for the capture cross section, but the absorption, $(n,\alpha)$, and $(n,\gamma)$ cross sections listed by him imply a capture cross section of $76\pm5$ b.

Within the direct-capture theory, the two crucial quantities entering the calculation of a partial cross section for a particular $\gamma$ ray are the final-state $(d,p)$ spectroscopic strength and the (normally spin-dependent) neutron scattering length. Because these quantities are unknown for a $^{59}$Ni target, we have not calculated the partial cross sections given by theory.

### D. Shell-model calculations of $^{60}$Ni levels

The calculated spectrum is compared with experiment in Fig. 7. There is a one-to-one correspondence between experiment and theory for the first ten excited states. The theoretical spectrum is compressed in energy compared to the experimental spectrum.

## VI. REACTION $^{60}$Ni$(n,\gamma)$

### A. Skeleton level scheme of $^{61}$Ni

In Table XIII, we have listed the previous measurements that have been carried out concerning the energy levels in

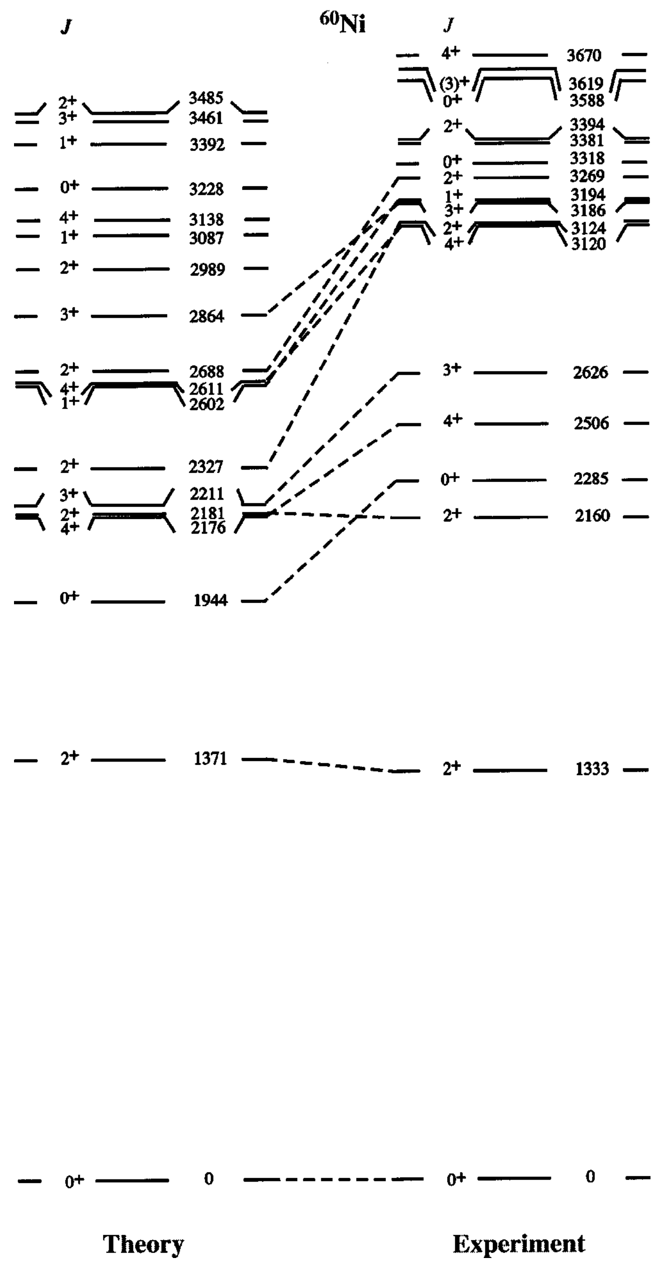


FIG. 7. Comparison between the shell-model predictions and the experimental level scheme of $^{60}$Ni. The levels are labeled by $J^\pi$ on the left and by level energies (in keV) on the right.

$^{61}$Ni. Based on these measurements, we have assembled a list (see Table XIV) of ~168 levels below 5.5 MeV. The backbone of this level scheme is the $^{60}$Ni$(d,p)^{61}$Ni study by Cosman *et al.* [78]. Just as in the $^{59}$Ni case, it was necessary to apply a substantial correction (as large as −12 keV in the 3.2–4.0 keV region and smaller corrections elsewhere) to the level energies reported by Cosman *et al.* [78].

Nine works [69,72–74,76–79,83] out of the 20 listed in Table XIII contain information leading to the $J^\pi$ assignments given in Table XIV for about half of all known levels below 5.5 MeV.

TABLE XIII. Partial list of references to previous measurements on $^{61}$Ni levels. See Ref. [96] for additional references.

| Measurement | Author(s) | Year | Facility[a] | Reference |
|---|---|---|---|---|
| $^{48}$Ca($^{18}$O, $5n$) reaction | Warburton *et al.* | 1978 | Brookhaven | [71] |
| $^{53}$Cr($^{11}$B, $p2n\gamma$) reaction | Wadsworth *et al.* | 1977 | U. Liverpool | [72] |
| $^{58}$Fe($\alpha, n\gamma$) reaction | Wadsworth *et al.* | 1977 | U. Liverpool | [73] |
| $^{58}$Ni(polarized $d, t$) reaction | Huttlin *et al.* | 1976 | U. Notre Dame | [74] |
| $^{59}$Co($^{3}$He, $p$) reaction | Cosman, Schramm, and Enge | 1968 | MIT | [75] |
| $^{59}$Ni($t, p$) reaction | Nann *et al.* | 1978 | Los Alamos | [76] |
| $^{60}$Ni(thermal $n, \gamma$) reaction | Ishaq *et al.* | 1977 | McMaster U. | [28] |
| | Harder *et al.* | 1993 | Grenoble | [30] |
| $^{60}$Ni(polarized $n, \gamma$) reaction | Stecher-Rasmussen *et al.* | 1972 | Petten | [31] |
| | Kopecky *et al.* | 1972 | Petten | [77] |
| $^{60}$Ni($d, p$) reaction | Fulmer *et al.* | 1964 | U. Pittsburgh | [32] |
| | Cosman *et al.* | 1967 | MIT | [78] |
| $^{60}$Ni(polarized $d, p$) reaction | Aymar *et al.* | 1973 | U. Notre Dame | [79] |
| $^{61}$Ni($n, n'\gamma$) reaction | Kosyak, Kaipov, and Chekushina | 1989 | Alma-Ata | [80] |
| $^{61}$Ni($p, p'$) reaction | Cosman *et al.* | 1967 | MIT | [78] |
| | Tee and Aspinall | 1967 | Aldermaston | [64] |
| $^{61}$Ni ($d, d'$) reaction | Cosman *et al.* | 1967 | MIT | [78] |
| $^{61}$Cu($\beta^{+} + \varepsilon$) decay | Meyer *et al.* | 1978 | Livermore | [81] |
| | Satyanarayana *et al.* | 1988 | Calcutta | [82] |
| $^{62}$Ni($p, d$) reaction | Sherr *et al.* | 1965 | U. Colorado | [40] |
| | Koang, Chien, and Rossner | 1976 | Michigan State U. | [69] |
| $^{62}$Ni (polarized $p, d$) reaction | Matoba *et al.* | 1996 | Osaka U. | [83] |

[a]Facility where the actual measurements were done. The symbol U stands for a university.

### B. Thermal-neutron capture $\gamma$-ray data

The $^{60}$Ni($n, \gamma$) reaction with thermal neutrons has been studied previously with Ge detectors at the McMaster and Grenoble reactors by Ishaq *et al.* [28] and Harder *et al.* [30], respectively. The study by Harder *et al.* [30] at Grenoble is the more extensive of these two studies. These authors claim to have observed 312 $\gamma$ rays from the $^{60}$Ni($n, \gamma$) reaction, but the published paper lists only 143 $\gamma$ rays. The unavailability of the complete list has hampered our efforts to fully resolve the differences between our data and the Grenoble data.

The current (thermal $n, \gamma$) measurements were made with a 200.1-mg, 99.83%-enriched $^{60}$NiO target. The results are given in Table XV. The level scheme resulting from this work is presented in Table XVI. Nearly three-fourths of the observed $\gamma$ rays, totaling 240 in number, have been incorporated into this scheme consisting of 40 bound levels.

Gamma rays of energies 3089.7, 3898.5, 6429.5, and 6752.0 keV, reported by Ishaq *et al.* [28], were not observed either by Harder *et al.* [30] or by us. Similarly, the levels at 3590.63, 3968.49, 4290.92, and 4405.16 keV, proposed by Ishaq *et al.* [28], remain unconfirmed by both latter studies.

According to Harder *et al.* [30], 31 levels in $^{61}$Ni are populated significantly in the (thermal $n, \gamma$) reaction. We confirm this conclusion for all levels except those at 4713, 4886, 4963, and 5112 keV. Harder *et al.* [30] list 20 $\gamma$ rays associated with these four levels. We have observed only seven of these $\gamma$ rays. We have placed four of the observed $\gamma$ rays elsewhere in the level scheme and kept the remaining three as unplaced. In addition, we conclude that the published data of Harder *et al.* [30] contain a larger fraction of spurious $\gamma$ rays in $^{61}$Ni($\sim$23%) than in $^{59}$Ni($\sim$16%).

In addition to the 27 levels common to this work and the earlier work by Harder *et al.* [30], we propose that 13 more levels are populated significantly in the $^{60}$Ni($n, \gamma$) reaction, bringing the total to 40 levels (see Table XVII). Of these, all levels except those at 3144.98, 4793.12, and 5036.24 keV correspond well with the known levels in $^{61}$Ni.

The neutron separation energy determined in this work is $S_n(^{61}\mathrm{Ni}) = 7820.11 \pm 0.05$ keV. The values $7820.14 \pm 0.20$ and $7820.07 \pm 0.20$ obtained by Ishaq *et al.* [28] and Harder *et al.* [30], respectively, are consistent with our more accurate value.

### C. Capture cross sections for $^{60}$Ni

The measured values $\Sigma I_\gamma$ (primary) $= 2.308 \pm 0.018$ b, $\Sigma E_\gamma I_\gamma / S_n = 2.330 \pm 0.020$ b, and $\Sigma I_\gamma$ (to ground state) $= 2.390 \pm 0.030$ b agree reasonably well. Our recommended cross-section value of $2.34 \pm 0.05$ b for the $^{60}$Ni($n, \gamma$) reaction is significantly more precise than the currently accepted value of $2.9 \pm 0.3$ b [110]. The total intensity of the observed but unplaced transitions is $\sim$0.03 b. The 2.1% uncertainty quoted for the recommended cross-section value does not include a systematic uncertainty of similar magnitude caused by unplaced and missing transitions.

Unlike $^{58}$Ni, the thermal-neutron capture cross section of $^{60}$Ni is mostly due to the first resonance in the cross section at 12.5 keV. From its resonance parameters, we compute that

TABLE XIV. Known energy levels in $^{61}$Ni.

| Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) | Known $E$(level)$^a$ (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)$^a$ (keV) | This work $(n,\gamma)$ $E$(level)$^a$ (keV) |
|---|---|---|---|---|---|---|---|
| 0.0 | $\frac{3}{2}^-$ | 0.0 | 0.0 | 2902 *10* | $\frac{7}{2}^-$ | | |
| 67.412 *3* | $\frac{5}{2}^-$ | 67.418 *24* | 67.41 *3* | 3040 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | |
| 282.957 *2* | $\frac{1}{2}^-$ | 282.887 *22* | 282.973 *21* | 3062 *5* | $\frac{1}{2}^+$ | 3062.29 *8* | 3062.16 *5* |
| 656.012 *3* | $\frac{1}{2}^-$ | 656.050 *22* | 656.039 *22* | 3105 *5* | $\frac{5}{2}^-, \frac{7}{2}^-$ | | |
| 908.620 *11* | $\frac{5}{2}^-$ | 908.64 *5* | 908.59 *3* | 3130 *5* | $\frac{7}{2}^-$ | | |
| 1015.12 *17* | $\frac{7}{2}^-$ | | 1015.32 *9* | | | 3145.03 *8* | 3144.98 *3* |
| 1099.622 *10* | $\frac{3}{2}^-$ | 1099.67 *3* | 1099.684 *22* | 3153 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | |
| 1132.332 *17* | $\frac{5}{2}^-$ | 1132.40 *3* | 1132.41 *3* | 3188 *7* | | | |
| 1185.236 *11* | $\frac{3}{2}^-$ | 1185.37 *3* | 1185.301 *22* | 3229 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3231.81 *8* | 3231.67 *4* |
| 1454.5 *3* | $\frac{7}{2}^-$ | | 1454.84 *11* | 3256 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | |
| 1609.639 *21* | $\frac{5}{2}^-$ | 1609.88 *5* | 1609.80 *5* | 3259.1 *5* | $\frac{7}{2}^-, \frac{11}{2}^-$ | | |
| 1729.471 *10* | $\frac{3}{2}^-$ | 1729.72 *5* | 1729.63 *3* | 3268 *7* | | | |
| 1807.5 *5* | $\frac{9}{2}^-$ | | | 3286 | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | |
| 1987.6 *3* | $\frac{9}{2}^-$ | | | 3295 *10* | $\frac{7}{2}^-$ | | |
| 1997.5 *3* | $\frac{5}{2}^-$ | | 1998.12 *7* | 3298.7 *8* | $\frac{11}{2}^+$ | | |
| 2018.0 *5* | $\frac{7}{2}^-$ | | | 3306 *10* | $\frac{7}{2}^-$ | | |
| 2121.67 *25* | $\frac{9}{2}^+$ | | | 3358 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | | |
| 2124.0 *7* | $\frac{1}{2}^-$ | 2124.05 *4* | 2123.949 *19* | 3397 *7* | | | |
| 2129.22 *25* | $\frac{11}{2}^-$ | | | 3415 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3415.18 *9* | 3415.14 *4* |
| 2408 *5* | $\left(\frac{3}{2}^-\right)$ | | | 3426.2 *4* | $\frac{13}{2}^-$ | | |
| 2409.7 *3* | $\frac{9}{2}^-$ | | | 3436 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 2465 *5* | $\frac{7}{2}^-$ | | | 3436.5 *6* | $\frac{13}{2}^+$ | | |
| 2527 *5* | $\frac{5}{2}^-, \frac{7}{2}^-$ | | | 3461 *5* | | | |
| 2593 *5* | $\frac{7}{2}^-$ | | | 3480 *5* | $\frac{9}{2}^+$ | | |
| 2638 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 2639.74 *4* | 2639.51 *5* | 3495 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 2697 *5* | $\frac{5}{2}^+$ | | | 3525 *5* | | 3525.57 *11* | 3525.60 *8* |
| 2716 *7* | | | 2707.63 *9* | 3561 *5* | | | |
| 2734 *10* | $\left(\frac{7}{2}^-\right)$ | | | 3570 *7* | | | |
| 2763 *5* | $\frac{3}{2}^-$ | 2765.11 *8* | 2765.03 *9* | 3596 *5* | | | |
| 2794 *5* | $\frac{5}{2}^-, \frac{7}{2}^-$ | | | 3616 *5* | | | |
| 2807 *7* | | | | 3635 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 2860 *10* | $\frac{5}{2}^-, \frac{7}{2}^-$ | | | 3644.6 *8* | | | |
| 2863 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 2863.58 *8* | 2862.94 *9* | 3665.4 *9* | $\frac{7}{2}^-$ | | |
| 2899 *5* | | | | 3671 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3669.01 *10* | 3668.99 *4* |

TABLE XIV. (*Continued.*)

| Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) | Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) |
|---|---|---|---|---|---|---|---|
| 3696 *5* | | | | 4326 *5* | | | |
| 3713 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3711.38 *11* | 3711.49 *6* | 4350 *5* | | | |
| 3741 *5* | $\left(\frac{1}{2}^+\right)$ | 3738.44 *11* | 3738.34 *18* | 4364 *5* | | | |
| 3769 *10* | $\frac{7}{2}^-$ | | | 4376 *5* | $\frac{7}{2}^-$ | | |
| 3779 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 3776.57 *11* | 3776.80 *9* | 4393 *5* | | | |
| 3793 *7* | | | | 4415 *5* | | | |
| 3807 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | | 4438 *5* | | | 4439.88 *13* |
| 3848 *5* | | | | 4457 *7* | | | |
| 3867 *5* | | 3869.92 *11* | 3869.99 *7* | 4467 *5* | | | |
| 3883 *7* | | | | 4487 *10* | $\frac{7}{2}^-$ | | |
| 3930 *5* | $\frac{7}{2}^-$ | | | 4492 *5* | | | |
| 3942 *5* | | | | 4513 *5* | | | 4514.69 *13* |
| 3972 *5* | | | | 4542 *5* | | | |
| 3980 *7* | | | | 4560 *5* | | | |
| 4007 *5* | | | | 4580 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 4019.2 *6* | $\frac{15}{2}^+$ | | | 4586 *10* | $\frac{7}{2}^-$ | | |
| 4024 *7* | $\frac{7}{2}^-$ | | | 4596 *5* | | | |
| 4033 *5* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | | | 4615 *5* | | | |
| 4063 *7* | | | | 4627 *5* | | | |
| 4071 *5* | | | | 4642 *5* | | | |
| 4082 *5* | | | | 4655 *10* | $\frac{7}{2}^-$ | | |
| 4120 *5* | $\left(\frac{1}{2}^+\right)$ | | | 4657 *5* | | | |
| 4143 *7* | $\frac{7}{2}^-$ | | | 4686 *5* | | | |
| 4152 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | | 4708 *5* | | | |
| 4178 *5* | | 4178.67 *14* | 4178.90 *14* | | | 4713.12 *14* | |
| 4189 *5* | | | | 4728 *5* | | | |
| 4204 *5* | | | 4204.3 *4* | 4729 *10* | $\frac{7}{2}^-$ | | |
| 4215 *5* | | | | 4755 *5* | $\frac{3}{2}^+, \frac{5}{2}^+$ | | |
| 4241 *5* | | 4239.73 *11* | 4239.76 *5* | 4788 *5* | | | |
| 4258 *10* | $\frac{7}{2}^-$ | | | 4791 *10* | $\frac{7}{2}^-$ | | |
| 4272 *7* | | | | | | | 4793.12 *16* |
| 4277 *5* | | | | 4811 *5* | | | |
| 4285 *5* | | | | 4818.6 *8* | $\left(\frac{17}{2}^+\right)$ | | |
| 4304 *5* | | | | 4830 *5* | | | |

TABLE XIV. (*Continued.*)

| Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) | Known $E$(level)[a] (keV) | $J^\pi$ | Previous $(n,\gamma)$ $E$(level)[a] (keV) | This work $(n,\gamma)$ $E$(level)[a] (keV) |
|---|---|---|---|---|---|---|---|
| 4850 *5* | | | | 5116 *5* | $\frac{1}{2}^-,\frac{3}{2}^-$ | | 5116.61 *17* |
| 4865 *5* | | | | 5163 *5* | | | |
| 4876 *5* | | | | 5182 *5* | $\frac{1}{2}^+$ | | |
| 4880 *10* | $\frac{7}{2}^-$ | | | 5212 *5* | $\frac{3}{2}^+,\frac{5}{2}^+$ | | |
| | | 4886.09 *13* | | 5232 *10* | $\frac{7}{2}^-$ | | |
| 4910 *5* | | | | 5237 *5* | | | |
| 4948 *5* | | | | 5259 *5* | | | |
| 4956 *10* | $\frac{7}{2}^-$ | | | 5276 *5* | | | |
| 4962 *5* | | 4963.19 *16* | | 5291 *5* | | | |
| 4974 *5* | | | | 5305 *5* | $\frac{1}{2}^+$ | | |
| 4999 *5* | | | | 5316.2 *12* | | | |
| 5014 *5* | | | | 5332 *5* | | | |
| 5028 *5* | | | | 5352 *5* | | | |
| 5031 *10* | $\left(\frac{7}{2}^-\right)$ | | | 5362 *5* | | | |
| | | 5036.12 *14* | 5036.24 *9* | 5391 *5* | | | 5390.85 *14* |
| 5059 *5* | $\frac{1}{2}^+$ | | | 5402 *5* | | | |
| 5079 *10* | $\frac{7}{2}^-$ | | | 5437 *5* | | | |
| 5092 *5* | $\frac{1}{2}^-,\frac{3}{2}^-$ | | | 5463 *5* | | | |
| | | 5112.31 *15* | | 5484[b] *5* | | | |

[a]In our notation, 67.412 *3* ≡ 67.412 ± 0.003, 2902 *10* ≡ 2902 ± 10, etc.
[b]For levels above this energy, see Ref. [96].

TABLE XV. Energies ($E_\gamma$) and intensities ($I_\gamma$) of $\gamma$ rays from the $^{60}Ni(n,\gamma)^{61}Ni$ reaction.

| $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 67.42 *20* | 32.9 *6* | 67 → 0 | 1116.46 *25* | 0.42 *6* | 4178 → 3062 | 1877.1 *4* | 0.39 *8* | 3062 → 1185 |
| 159.46 *20* | 0.18 *3* | unplaced | 1118.39 *99* | 0.69 *7* | 1185 → 67 | 1931.2 *7* | 0.23 *6* | 1998 → 67 |
| 191.16 *8* | 0.64 *5* | 1099 → 908 | 1132.40 *4* | 5.89 *9* | 1132 → 0 | 1943.0 *5* | 0.23 *7* | unplaced |
| 215.51 *9* | 0.38 *3* | 282 → 67 | 1146.69 *16* | 0.69 *7* | 3144 → 1998 | 1959.71 *7* | 1.77 *8* | 3144 → 1185 |
| 277.0 *5* | 0.37 *6* | 1185 → 908 | 1154.9 *3* | 0.41 *6* | 2765 → 1609 | 1998.10 *11* | 1.44 *10* | 1998 → 0 |
| 282.99 *5* | 812 *27* | 282 → 0 | 1185.29 *4* | 52.6 *6* | 1185 → 0 | 2012.47 *22* | 0.81 *12* | 3144 → 1132 |
| 355.85 *14* | 0.29 *3* | unplaced | 1188.18 *12* | 0.47 *7* | unplaced | 2045.32 *5* | 4.76 *13* | 3144 → 1099 |
| 373.07 *5* | 4.27 *5* | 656 → 282 | 1195.3 *4* | 0.24 *6* | unplaced | 2085.7[e] *3* | 0.62 *9* | 4793 → 2707 |
| 394.33 *5* | 1.77 *6* | 2123 → 1729 | 1204.2 *3* | 0.28 *5* | C → 6615 | 2088.26 *25* | 0.79 *10* | unplaced |
| 477.6 *5* | 0.34 *7* | 1609 → 1132 | 1215.35 *5* | 2.00 *6* | 2123 → 908 | 2093.10 *21* | 0.81 *9* | unplaced |
| 514.33 *14* | 0.69 *8* | 2123 → 1609 | 1233.4 *3* | 0.42 *7* | 3231 → 1998 | 2099.27 *7* | 3.34 *10* | 3231 → 1132 |
| 529.27 *3* | 5.37 *6* | 1185 → 656 | 1244.39 *18* | 0.67 *7* | C → 6575 | 2108.99 *18* | 1.12 *10* | 2765 → 656 |
| 546.3 *3* | 0.14 *4* | 1454 → 908 | 1253.23 *20* | 0.57 *7* | 2862 → 1609 | 2111.6 *4* | 0.47 *10* | unplaced |
| 588.59 *5* | 2.33 *5* | 656 → 67 | 1315.2 *4* | 0.20 *5* | unplaced | 2115.2 *3* | 0.49 *11* | 4239 → 2123 |
| 625.60 *17* | 0.30 *5* | 908 → 282 | 1342.3 *4* | 0.26 *6* | 1998 → 656 | 2123.90 *3* | 145.6 *15* | 2123 → 0 |
| 629.86 *25* | 0.20 *4* | 1729 → 1099 | 1377.3[d] *4* | 0.23 *5* | 4439 → 3062 | 2126.9 *3* | 1.19 *16* | unplaced |
| 650.1 *4* | 0.20 *6* | 3415 → 2765 | 1387.6 *4* | 0.21 *5* | 1454 → 67 | 2207.0 *3* | 0.86 *14* | 2862 → 656 |
| 651.14 *25* | 0.50 *11* | unplaced | 1415.43 *10* | 0.90 *7* | 3144 → 1729 | 2229.84 *20* | 0.96 *22* | 3415 → 1185 |
| 656.02 *4* | 20.39 *22* | 656 → 0 | 1434.20 *23* | 0.41 *5* | unplaced | 2282.66 *14* | 0.70 *6* | 3415 → 1132 |
| 701.22 *11* | 0.61 *5* | 1609 → 908 | 1446.71 *6* | 2.08 *7* | 1729 → 282 | 2301.3 *4* | 0.28 *6* | unplaced |
| 780.4 *3* | 0.21 *4* | unplaced | 1454.80 *12* | 0.87 *6* | 1454 → 0 | 2306.3 *5* | 0.24 *6* | unplaced |
| 806.0 *3* | 0.19 *6* | 3668 → 2862 | 1488.0 *3* | 0.34 *6* | unplaced | 2315.35 *16* | 0.82 *7* | 3415 → 1099 |
| 816.70 *4* | 38.7 *4* | 1099 → 282 | 1502.01 *10* | 0.77 *6* | 3231 → 1729 | 2340.56 *22* | 0.46 *6* | 3525 → 1185 |
| 820.90 *10* | 0.87 *6* | 1729 → 908 | 1535.60 *99* | 0.61 *8* | 3144 → 1609 | 2347.5 *4* | 0.28 *6* | unplaced |
| 841.2 *1* | 1.46 *7* | 908 → 67 | 1542.42 *7* | 2.50 *9* | 1609 → 67 | 2351.3 *4* | 0.30 *6* | 5116 → 2765 |
| 848.54 *13* | 0.58 *5* | 3711 → 2862 | 1580.03 *20* | 0.46 *6* | 2765 → 1185 | 2356.6 *3* | 0.37 *6* | 2639 → 282 |
| 888.0 *3* | 0.23 *5* | unplaced | 1587.77 *23* | 0.48 *6* | 3711 → 2123 | 2387.21 *14* | 0.94 *7* | unplaced |
| 900.2 *3* | 0.26 *5* | unplaced | 1601.9 *4* | 0.23 *8* | unplaced | 2406.05 *6* | 3.24 *9* | 3062 → 656 |
| 902.27 *7* | 1.27 *5* | 1185 → 282 | 1610.04 *99* | 2.04 *9* | 1609 → 0 | 2429.15 *14* | 1.11 *8* | C → 5390 |
| 908.59 *4* | 7.66 *9* | 908 → 0 | 1621.86 *8* | 2.02 *9* | 3231 → 1609 | 2432.2 *4* | 0.39 *7* | unplaced |
| 938.62 *4* | 16.28 *17* | 2123 → 1185 | 1633.08 *20* | 0.70 *9* | 2765 → 1132 | 2436.14 *13* | 1.34 *8* | unplaced |
| 947.90 *9* | 0.82 *6* | 1015 → 67 | 1645.0 *3* | 0.35 *6* | unplaced | 2455.5 *6* | 0.21 *6* | unplaced |
| 977.12 *18* | 0.30 *5* | unplaced | 1662.17 *99* | 2.13 *7* | 1729 → 67 | 2460.7 *4* | 0.46 *7* | unplaced |
| 980.81 *25* | 0.24 *5* | unplaced | 1665.18 *99* | 0.92 *6* | 2765 → 1099 | 2463.1 *7* | 0.25 *7* | unplaced |
| 982.6 *4* | 0.14 *5* | 1998 → 1015 | 1685.54 *10* | 1.13 *7* | 3415 → 1729 | 2482.07 *18* | 1.10 *15* | 2765 → 282 |
| 998.0 *4* | 0.14 *5* | unplaced | 1716.46 *25* | 0.63 *8* | unplaced | 2483.6 *7* | 0.32 *14* | 3668 → 1185 |
| 1015.28 *24* | 0.29 *6* | 1015 → 0 | 1721.5 *5* | 0.26 *7* | 5390 → 3668 | 2488.84 *12* | 1.16 *7* | 3144 → 656 |
| 1021.06 *8* | 0.95 *6* | 3144 → 2123 | 1729.74 *8* | 2.03 *9* | 1729 → 0 | 2510.0[f] *3* | 0.53 *7* | 4239 → 1729 |
| 1024.27 *7* | 1.22 *6* | 2123 → 1099 | 1750.9 *6* | 0.21 *6* | 5955 → 4204 | 2575.63 *14* | 0.89 *7* | 3231 → 656 |
| 1032.25 *4* | 6.06 *9* | 1099 → 67 | 1760.2 *4* | 0.35 *6* | unplaced | 2579.84 *15* | 0.91 *7* | 2862 → 282 |
| 1039.8 *3* | 0.26 *5* | unplaced | 1778.83 *12* | 1.09 *7* | 3776 → 1998 | 2611.73 *16* | 1.01 *8* | 3711 → 1099 |
| 1065.01 *5* | 3.29 *6* | 1132 → 67 | 1795.61 *24* | 0.50 *7* | 3525 → 1729 | 2620.7 *5* | 0.35 *8* | unplaced |
| 1073.52 *6* | 1.85 *6* | 1729 → 656 | 1819.7 *6* | 0.25 *7* | unplaced | 2634.0 *4* | 0.38 *7* | unplaced |
| 1089.65 *22* | 0.37 *6* | 1998 → 908 | 1840.94 *5* | 4.78 *12* | 2123 → 282 | 2639.44 *6* | 3.90 *9* | 2639 → 0 |
| 1099.67 *4* | 27.6 *3* | 1099 → 0 | 1843.87 *17* | 1.15 *9* | unplaced | 2644.23 *22* | 0.61 *7* | 3776 → 1132 |
| 1107.71 *9* | 0.68 *6* | 3231 → 2123 | 1864.55 *18* | 0.80 *8* | C → 5955 | 2676.5 *5* | 0.30 *8* | 3776 → 1099 |

TABLE XV. (*Continued.*)

| $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] | $E_\gamma$ (keV)[a] | $I_\gamma$ (mb)[b] | Placement[c] |
|---|---|---|---|---|---|---|---|---|
| 2684.58 *25* | 0.51 *8* | 3869 → 1185 | 3213.9 *3* | 0.64 *9* | 3869 → 656 | 4150.92 *6* | 11.8 *4* | C → 3668 |
| 2698.22 *22* | 0.94 *9* | unplaced | 3231.47 *9* | 2.38 *9* | 3231 → 0 | 4171.7 *6* | 0.45 *12* | 4239 → 67 |
| 2703.38 *19* | 1.25 *9* | C → 5116 | 3242.59 *11* | 1.87 *9* | 3525 → 282 | 4225.9 *8* | 0.59 *18* | 5955 → 1729 |
| 2707.58 *9* | 2.60 *11* | 2707 → 0 | 3254.8 *6* | 0.28 *8* | 4439 → 1185 | 4228.6 *7* | 0.75 *18* | unplaced |
| 2759.38 *19* | 1.37 *8* | 3415 → 656 | 3305.30 *14* | 1.62 *9* | C → 4514 | 4239.66 *9* | 5.43 *24* | 4239 → 0 |
| 2764.69 *16* | 1.60 *9* | 2765 → 0 | 3328.6 *6* | 0.35 *8* | 4514 → 1185 | 4284.0 *6* | 0.25 *9* | unplaced |
| 2771.4 *7* | 0.25 *8* | unplaced | 3347.7 *4* | 0.64 *9* | 3415 → 67 | 4294.44 *15* | 1.99 *13* | C → 3525 |
| 2778.9 *4* | 0.44 *8* | 3062 → 282 | 3359.5 *3* | 0.38 *9* | unplaced | 4404.82 *5* | 16.2 *4* | C → 3415 |
| 2783.80 *9* | 2.41 *10* | C → 5036 | 3369.1 *4* | 0.53 *8* | unplaced | 4439.2 *4* | 0.83 *12* | 4439 → 0 |
| 2795.3[g] *4* | 0.47 *8* | 2862 → 67 | 3380.29 *21* | 2.38 *23* | C → 4439 | 4514.6 *4* | 0.83 *12* | 4514 → 0 |
| 2802.7 *4* | 0.40 *8* | 3711 → 908 | 3382.3 *7* | 0.80 *21* | 4514 → 1132 | 4588.26 *6* | 11.7 *3* | C → 3231 |
| 2816.95 *14* | 1.45 *8* | unplaced | 3385.92 *5* | 9.23 *13* | 3668 → 282 | 4675.05 *5* | 20.3 *3* | C → 3144 |
| 2823.07 *16* | 1.18 *9* | unplaced | 3391.6 *3* | 0.70 *9* | unplaced | 4714.2 *7* | 0.49 *13* | unplaced |
| 2856.48 *13* | 1.33 *7* | unplaced | 3398.6 *3* | 1.16 *15* | unplaced | 4753.0 *6* | 0.72 *15* | 5036 → 282 |
| 2861.95 *4* | 6.59 *11* | 3144 → 282 | 3415.04[h] *6* | 5.05 *11* | 3415 → 0 | 4757.86 *10* | 4.98 *25* | C → 3062 |
| 2903.0 *7* | 0.27 *11* | unplaced | 3525.1 *9* | 0.20 *7* | 3525 → 0 | 4793.2 *7* | 0.51 *13* | 4793 → 0 |
| 2914.5 *7* | 0.25 *8* | unplaced | 3531.51 *20* | 2.00 *18* | 4439 → 908 | 4818.8 *4* | 0.89 *14* | unplaced |
| 2933.80 *12* | 2.96 *12* | unplaced | 3580.18 *7* | 9.8 *3* | C → 4239 | 4833.2 *9* | 0.34 *13* | 5116 → 282 |
| 2947.5 *7* | 0.25 *7* | unplaced | 3583.47 *14* | 3.10 *19* | 4239 → 656 | 4957.1 *4* | 2.2 *3* | C → 2862 |
| 2977.79 *25* | 0.69 *7* | unplaced | 3601.8 *4* | 0.64 *12* | 3668 → 67 | 5055.02 *12* | 4.22 *20* | C → 2765 |
| 3000.2 *5* | 0.36 *8* | unplaced | 3615.9 *4* | 0.56 *11* | C → 4204 | 5112.1 *5* | 0.84 *13* | C → 2707 |
| 3012.66 *11* | 2.89 *10* | 3668 → 656 | 3640.99 *18* | 1.95 *16* | C → 4178 | 5180.36 *9* | 3.93 *14* | C → 2639 |
| 3027.02 *18* | 1.06 *8* | C → 4793 | 3644.0 *4* | 0.90 *15* | 3711 → 67 | 5322.2 *7* | 0.73 *12* | 5390 → 67 |
| 3054.36 *18* | 0.92 *7* | 4239 → 1185 | 3687.24 *21* | 3.00 *25* | unplaced | 5515.4 *7* | 0.45 *12* | 6615 → 1099 |
| 3062.16 *10* | 1.75 *8* | 3062 → 0 | 3709.3 *5* | 1.2 *3* | 3776 → 67 | 5695.86 *4* | 157 *3* | C → 2123 |
| 3077.5 *3* | 0.60 *7* | 3144 → 67 | 3711.42 *11* | 6.8 *3* | 3711 → 0 | 5955.3 *8* | 0.41 *12* | 5955 → 0 |
| 3082.21 *21* | 0.78 *8* | 3738 → 656 | 3850.7[i] *6* | 0.53 *14* | 5036 → 1185 | 6090.5 *5* | 0.72 *12* | C → 1729 |
| 3104.6 *8* | 0.47 *15* | 4204 → 1099 | 3869.83 *12* | 3.81 *22* | 3869 → 0 | 6105.8 *4* | 0.33 *13* | unplaced |
| 3106.8 *4* | 1.30 *16* | 4239 → 1132 | 3949.97 *9* | 5.61 *23* | C → 3869 | 6292.3 *7* | 0.53 *13* | 6575 → 282 |
| 3129.1 *6* | 0.43 *10* | unplaced | 3974.37 *22* | 1.39 *13* | unplaced | 6634.40 *5* | 29.5 *4* | C → 1185 |
| 3132.05 *8* | 5.10 *13* | 3415 → 282 | 4043.33 *14* | 2.66 *18* | C → 3776 | 6719.97 *5* | 55.8 *7* | C → 1099 |
| 3144.7 *7* | 4.09 *13* | 3144 → 0 | 4081.6 *3* | 1.64 *15* | C → 3738 | 7163.9 *5* | 1.3 *3* | C → 656 |
| 3164.49 *24* | 0.84 *10* | 3231 → 67 | 4108.52 *8* | 10.5 *3* | C → 3711 | 7536.62 *6* | 705 *9* | C → 282 |
| 3180.8 *4* | 0.50 *11* | unplaced | 4111.5 *4* | 1.05 *19* | 4178 → 67 | 7819.56 *6* | 1236 *15* | C → 0 |

[a]In our notation, 67.42 *20* ≡ 67.42 ± 0.20, etc.
[b]In our notation, 32.9 *6* ≡ 32.9 ± 0.6, etc. Multiply by 0.0427 to obtain photons per 100 thermal neutron captures.
[c]C denotes the capturing state.
[d]Can also be placed as a 4240 → 2863 transition.
[e]Can also be placed as a 5956 → 3870 transition.
[f]Can also be placed as a 3526 → 1015 transition.
[g]Can also be placed as a 4793 → 1998 transition.
[h]Can also be placed as a 4515 → 1100 transition.
[i]Can also be placed as a 6616 → 2765 transition.

TABLE XVI. Level scheme of $^{61}$Ni from this work in tabular form.

| $E$(level)[a] (keV) | $J^\pi$ | Deexciting $\gamma$ rays[b] | $I_\gamma$ (in)[a] (mb) | $I_\gamma$ (out)[a] (mb) | $I_\gamma$ (in − out)[a] (mb) |
|---|---|---|---|---|---|
| 0.0 | $\frac{3}{2}^-$ | | 2390 *30* | | 2390 *30* |
| 67.41 *3* | $\frac{5}{2}^-$ | 67.42 | 27.6 *6* | 32.9 *6* | −5.3 *8* |
| 282.973 *21* | $\frac{1}{2}^-$ | 282.99, 215.51 | 784 *9* | 812 *28* | −28 *30* |
| 656.039 *22* | $\frac{1}{2}^-$ | 656.02, 588.59, 373.07 | 24.8 *5* | 27.0 *3* | −2.2 *6* |
| 908.59 *3* | $\frac{5}{2}^-$ | 908.59, 841.2, 625.60 | 7.40 *25* | 9.42 *13* | −2.0 *3* |
| 1015.32 *9* | $\frac{7}{2}^-$ | 1015.28, 947.90 | 0.14 *5* | 1.11 *9* | −0.97 *10* |
| 1099.684 *22* | $\frac{3}{2}^-$ | 1099.67, 1032.25, 816.70, 191.16 | 65.9 *8* | 73.0 *6* | −7.1 *10* |
| 1132.41 *3* | $\frac{5}{2}^-$ | 1132.40, 1065.01 | 8.6 *4* | 9.18 *11* | −0.6 *4* |
| 1185.301 *22* | $\frac{3}{2}^-$ | 1185.29, 1118.39, 902.27, 529.27, 277.0 | 52.7 *6* | 60.3 *7* | −7.6 *9* |
| 1454.84 *11* | $\frac{7}{2}^-$ | 1454.80, 1387.6, 546.3 | | 1.22 *9* | −1.22 *9* |
| 1609.80 *5* | $\frac{5}{2}^-$ | 1610.04, 1542.42, 701.22, 477.6, | 4.30 *18* | 5.49 *16* | −1.19 *23* |
| 1729.63 *3* | $\frac{3}{2}^-$ | 1729.74, 1662.17, 1446.71, 1073.52, 820.90, 629.86 | 6.9 *3* | 9.16 *17* | −2.2 *4* |
| 1998.12 *7* | $\frac{5}{2}^-$ | 1998.10, 1931.2, 1342.3, 1089.65, 982.6, | 2.20 *13* | 2.44 *16* | −0.24 *20* |
| 2123.949 *19* | $\frac{1}{2}^-$ | 2123.90, 1840.94, 1215.35, 1024.27, 938.62, 514.33, 394.33 | 160 *3* | 173 *3* | −13 *4* |
| 2639.51 *5* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 2639.44, 2356.6 | 3.93 *14* | 4.27 *11* | −0.34 *18* |
| 2707.63 *9* | | 2707.58 | 1.46 *16* | 2.60 *11* | −1.14 *20* |
| 2765.03 *7* | $\frac{3}{2}^-$ | 2764.69, 2482.07, 2108.99, 1665.18, 1633.08, 1580.03, 1154.9 | 4.72 *22* | 6.31 *25* | −1.6 *4* |
| 2862.94 *9* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 2795.3, 2579.84, 2207.0, 1253.23 | 3.0 *4* | 2.81 *19* | 0.2 *4* |
| 3062.16 *5* | $\frac{1}{2}^+$ | 3062.16, 2778.9, 2406.05, 1877.1 | 5.6 *3* | 5.82 *17* | −0.2 *3* |
| 3144.98 *3* | | 3144.7, 3077.5, 2861.95, 2488.84, 2045.32, 2012.47, 1959.71, 1535.60, 1415.43, 1146.69, 1021.06 | 20.3 *3* | 22.9 *4* | −2.6 *5* |
| 3231.67 *4* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3231.47, 3164.49, 2575.63, 2099.27, 1621.86, 1502.01, 1233.4, 1107.71 | 11.7 *3* | 11.34 *23* | 0.4 *4* |
| 3415.14 *4* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3415.04, 3347.7, 3132.05, 2759.38, 2315.35, 2282.66, 2229.84, 1685.54, 650.1 | 16.2 *4* | 16.0 *4* | 0.2 *6* |
| 3525.60 *8* | | 3525.1, 3242.59, 2340.56, 1795.61, | 1.99 *13* | 3.03 *15* | −1.04 *20* |
| 3668.99 *4* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3601.8, 3385.92, 3012.66, 2483.6, 806.0, | 12.1 *4* | 13.3 *3* | −1.2 *5* |
| 3711.49 *6* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 3711.42, 3644.0, 2802.7, 2611.73, 1587.77, 848.54 | 10.5 *3* | 10.2 *4* | 0.3 *5* |
| 3738.34 *18* | $\left(\frac{1}{2}^+\right)$ | 3082.21 | 1.64 *15* | 0.78 *8* | 0.86 *17* |
| 3776.80 *9* | $\left(\frac{1}{2}^-, \frac{3}{2}^-\right)$ | 3709.3, 2676.5, 2644.23, 1778.83, | 2.66 *8* | 3.2 *4* | −0.5 *4* |
| 3869.99 *7* | | 3869.83, 3213.9, 2684.58 | 5.61 *23* | 5.0 *3* | 0.6 *4* |
| 4178.90 *14* | | 4111.5, 1116.46 | 1.95 *16* | 1.47 *20* | 0.5 *3* |
| 4204.3 *4* | | 3104.6 | 0.77 *13* | 0.47 *15* | 0.30 *20* |
| 4239.76 *5* | | 4239.66, 4171.7, 3583.47, 3106.8, 3054.36, 2510.0, 2115.2 | 9.8 *3* | 12.2 *4* | −2.4 *5* |
| 4439.88 *13* | | 4439.2, 3531.51, 3254.8, 1377.3 | 2.38 *23* | 3.34 *24* | −1.0 *4* |

its contribution to the thermal-neutron capture cross section is about 2.1 b. Resonances at higher neutron energy contribute less than 0.05 b, leaving a bound level contribution of perhaps 0.25 b. The small thermal-neutron scattering length $a_{J=1/2}$=2.8 fm is consistent with the dominance of the first resonance.

The cross sections for the individual primary $E1$ transitions are given in Table XVIII along with their $\gamma$ ray energies and $(d,p)$ spectroscopic factors of the final states. From these and the thermal-neutron scattering length, the direct-capture cross sections are calculated. These are also presented in Table XVIII. As with $^{58}$Ni capture, there are significant differences between the direct-capture cross section and the experimental value. Again, these differences are attributed to the admixture of compound-nuclear capture resulting from the nearest resonance levels. The two possible magnitudes of the compound-nuclear cross section, extracted using Eq. (1), for each transition are listed in the final column of Table XVIII.

The statistical method of Sec. III F is applied to these results. The results are summarized in Table XIX and compared with the model estimates, which are more precise than in the $^{58}$Ni case because the energy of the resonance level is known. Again, it is clear that the differences between the

TABLE XVI. (*Continued.*)

| $E$(level)[a] (keV) | $J^\pi$ | Deexciting $\gamma$ rays[b] | $I_\gamma$ (in)[a] (mb) | $I_\gamma$ (out)[a] (mb) | $I_\gamma$ (in − out)[a] (mb) |
|---|---|---|---|---|---|
| 4514.69 *13* | | 4514.6, 3382.3, 3328.6 | 1.62 *9* | 2.0 *3* | −0.4 *3* |
| 4793.12 *16* | | 4793.2, 2085.7 | 1.06 *8* | 1.13 *16* | −0.07 *18* |
| 5036.24 *9* | | 4753.0, 3850.7 | 2.41 *10* | 1.25 *21* | 1.16 *23* |
| 5116.61 *17* | $\frac{1}{2}^-, \frac{3}{2}^-$ | 4833.2, 2351.3 | 1.25 *9* | 0.64 *15* | 0.61 *17* |
| 5390.85 *14* | | 5322.2, 1721.5 | 1.11 *8* | 0.99 *14* | 0.12 *16* |
| 5955.52 *17* | | 5955.3, 4225.9, 1750.9 | 0.80 *8* | 1.21 *23* | −0.41 *24* |
| 6575.70 *18* | | 6292.3 | 0.67 *7* | 0.53 *13* | 0.14 *15* |
| 6615.8 *3* | | 5515.4 | 0.28 *5* | 0.45 *12* | −0.17 *13* |
| 7020.113[c] *21* | $\frac{1}{2}^+$ | 7819.56, 7536.62, 7163.9, 6719.97, 6634.40, 6090.5, 5695.86, 5180.36, 5112.1, 5055.02, 4957.1, 4757.86, 4675.05, 4588.26, 4404.82, 4294.44, 4150.92, 4108.52, 4081.6, 4043.33, 3949.97, 3640.99, 3615.9, 3580.18, 3380.29, 3305.30, 3027.02, 2783.80, 2703.38, 2429.15, 1864.55, 1244.39, 1204.2 | | 2308 *18* | −2308 *18* |

[a]In our notation, 67.41 *3* ≡ 67.41 ± 0.03, 2390 *30* ≡ 2390 ± 30, etc.
[b]See also Table XV.
[c]Capturing state.

theoretical direct-capture cross sections and the experimental values are consistent with one or more of the standard models of the compound-nuclear mechanism.

### D. Capture cross section of natural nickel

Combining the capture cross sections for $^{58}$Ni and $^{60}$Ni measured in this work with literature values [110], we obtain the following set (isotope, natural abundance in at. %, capture cross section): $^{58}$Ni, 68.077±0.009, 4.13±0.05 b, $^{60}$Ni, 26.223±0.008, 2.34±0.05 b, $^{61}$Ni, 1.140±0.001, 2.5±0.5 b, $^{62}$Ni, 3.634±0.002, 15±1 b, and $^{64}$Ni, 0.926±0.001, 1.6±0.1 b. The resulting capture cross section for natural nickel, 4.01±0.06 b, is lower and more precise than the value 4.6±0.4 b calculated by Holden [110] from previous literature values.

### E. Shell-model calculations of $^{61}$Ni levels

The calculated spectrum is compared with experiment in Fig. 8. There is a one-to-one correspondence between experiment and theory for the first 18 states. The doublet of $\frac{9}{2}^-$ states at 1807 and 1988 keV [73,76] is nicely reproduced (at 1847 and 1961 keV) by our calculations.

## VII. SUMMARY

We have studied the energy levels of $^{59}$Ni, $^{60}$Ni, and $^{61}$Ni via the $(n,\gamma)$ reaction with thermal neutrons. Approximately a third of the known number of levels in these nuclei below the respective neutron separation energies are populated measurably in this reaction. For these levels, we have determined accurate level energies and, whenever possible, good branching ratios. We have applied the direct-capture theory and current models of compound-nuclear capture to satisfactorily reproduce the partial cross sections of the strong primary $E1$ transitions. The low-lying portions of the level schemes have been compared with shell-model predictions. The overall agreement is good.

TABLE XVII. Increasing complexity in the study of the $^{60}$Ni$(n,\gamma)^{61}$Ni reaction.

| Number of | Ishaq *et al.* [28] McMaster (1977) | Harder *et al.* [30] Grenoble (1993) | This work LANL/ORNL |
|---|---|---|---|
| $\gamma$ rays | 49[d] | 143[e] | 240 |
| spurious $\gamma$ rays[a] | 4 | 33 | |
| placed $\gamma$ rays[b] | 42 | 136 | 179 |
| primary $\gamma$ rays | 22 | 25 | 33 |
| secondary $\gamma$ rays | 20 | 111 | 146 |
| unplaced $\gamma$ rays[c] | 7 | 7 | 61 |
| bound levels | 23 | 31 | 40 |

[a]Gamma rays sought but not observed in this more sensitive work and, therefore, considered spurious.
[b]Some of the placed $\gamma$ rays may be spurious.
[c]Some of the unplaced $\gamma$ rays may be genuine.
[d]Measurements limited to $E_\gamma > 2.1$ MeV using a Ge(Li)–NaI(Tl) pair spectrometer.
[e]This number represents placed $\gamma$ rays as well as the strongest unplaced $\gamma$ rays. A more complete list of 312 $\gamma$ rays was created in the course of the Grenoble study, but this list is not available from the authors.

TABLE XVIII. Direct-capture cross sections for primary $E1$ transitions in the $^{60}Ni(n,\gamma)^{61}Ni$ reaction. Columns 1, 2, and 3 give the energy, $J^{\pi}$ value, and the $l=1(d,p)$ spectroscopic factor multiplied by $(2J+1)$ for the final state, respectively. Column 4 is the primary transition energy. Column 5 is the average valency capture width and column 6 the potential-capture cross section, both calculated using a global optical properties (see Eqs. (4)–(7) of Ref. [3]). The entries in column 5 do not include the spin-coupling factor and the spectroscopic factor; those in column 6 do. Column 7 is the calculated cross section using the global plus valence $(G+V)$ procedure. The measured cross sections are given in column 8. Column 9 gives the hypothesized compound-nuclear contributions deduced from the differences between column 7 and column 8 via Eq. (8) of Ref. [3]. In the table subheading, $a(X)$ refers to the experimental scattering length, while $a(G)$ and $\overline{\Gamma_n^0}/D$ refer to the scattering length and the neutron strength function, respectively, both calculated using the global optical potential.

| $E_f$ (keV) | $J^{\pi}$ | $(d,p)$ $(2J+1)\,S^a$ | $E_\gamma$ (keV) | $\Gamma_{\gamma,\mathrm{val}}/DE_\gamma^3$ $(10^{-7}\ \mathrm{MeV}^{-3})$ | $\sigma_{\mathrm{pot},\gamma}$ (mb) | $\sigma(G+V)$ (mb) | $\sigma_\gamma(X)$ $^b$ (mb) | $\sigma_{\mathrm{CN},\gamma}$ (mb) |
|---|---|---|---|---|---|---|---|---|
| Reaction $^{60}Ni(n,\gamma)^{61}Ni$; $a(X)=2.8$ fm; $a(G)=7.03$ fm; $\overline{\Gamma_n^0}/D=3.8\times10^{-4}$ | | | | | | | | |
| 0 | $\frac{3}{2}^-$ | 1.49 | 7820 | 0.30 | 1.1 | 579 | 1236 *15* | 123 or 3510 |
| 283 | $\frac{1}{2}^-$ | 1.23 | 7537 | 0.21 | 0.46 | 355 | 706 *9* | 60 or 2060 |
| 656 | $\frac{3}{2}^-$ | 0.053 | 7164 | 0.0097 | 0.040 | 15 | 1.3 *3* | 7.2 or 25 |
| 1100 | $\frac{3}{2}^-$ | 0.108 | 6720 | 0.027 | 0.30 | 36 | 55.8 *7* | 2.1 or 180 |
| 1185 | $\frac{3}{2}^-$ | 0.255 | 6634 | 0.24 | 0.73 | 84 | 29.5 *4* | 14 or 210 |
| 1730 | $\frac{3}{2}^-$ | 0.044 | 6091 | 0.012 | 0.18 | 13 | 0.72 *12* | 7.8 or 20 |
| 2124 | $\frac{1}{2}^-$ | 0.392 | 5696 | 0.30 | 1.37 | 88 | 157 *3* | 10 or 480 |
| 2640 | if $\frac{1}{2}^-$ | 0.087 | 5180 | 0.025 | 0.41 | 18 | 3.9 *2* | 5.0 or 38 |
| 2640 | if $\frac{3}{2}^-$ | 0.087 | 5180 | 0.030 | 0.60 | 22 | 3.9 *2* | 7.4 or 35 |
| 2765 | $\frac{3}{2}^-$ | 0.054 | 5055 | 0.018 | 0.39 | 13 | 4.2 *3* | 2.6 or 32 |
| 2863 | if $\frac{1}{2}^-$ | 0.032 | 4957 | 0.010 | 0.17 | 6.3 | 2.2 *3* | 1.0 or 16 |
| 2863 | if $\frac{3}{2}^-$ | 0.032 | 4957 | 0.012 | 0.24 | 7.7 | 2.2 *3* | 1.7 or 18 |
| 3232 | if $\frac{1}{2}^-$ | 0.011 | 4588 | 0.0037 | 0.069 | 2.0 | 11.7 *3* | 4.0 or 2.3 |
| 3232 | if $\frac{3}{2}^-$ | 0.011 | 4588 | 0.0044 | 0.093 | 2.4 | 11.7 *3* | 3.5 or 2.5 |
| 3358 | if $\frac{1}{2}^-$ | 0.022 | 4462 | 0.0076 | 0.144 | 3.9 | $<3$ | 0.05 or 14[c] |
| 3358 | if $\frac{3}{2}^-$ | 0.022 | 4462 | 0.0090 | 0.194 | 4.7 | $<3$ | 0.2 or 15[c] |
| 3415 | if $\frac{1}{2}^-$ | 0.045 | 4405 | 0.016 | 0.30 | 7.8 | 16.2 *4* | 1.5 or 47 |
| 3415 | if $\frac{3}{2}^-$ | 0.045 | 4405 | 0.019 | 0.40 | 9.5 | 16.2 *4* | 0.90 or 50 |
| 3669 | if $\frac{1}{2}^-$ | 0.054 | 4151 | 0.020 | 0.40 | 8.8 | 11.8 *4* | 0.22 or 41 |
| 3669 | if $\frac{3}{2}^-$ | 0.054 | 4151 | 0.024 | 0.52 | 11 | 11.8 *4* | 0.03 or 45 |
| 3711 | if $\frac{1}{2}^-$ | 0.033 | 4109 | 0.013 | 0.24 | 5.3 | 1.64 *5* | 1.1 or 13 |
| 3711 | if $\frac{3}{2}^-$ | 0.033 | 4109 | 0.015 | 0.32 | 6.4 | 1.64 *5* | 1.6 or 15 |
| 5116 | if $\frac{1}{2}^-$ | 0.108 | 2703 | 0.069 | 1.1 | 11 | 1.25 *9* | 4.7 or 19 |
| 5116 | if $\frac{3}{2}^-$ | 0.108 | 2703 | 0.078 | 1.3 | 12 | 1.25 *9* | 5.9 or 22 |

[a]From Ref. [78].
[b]From Table XV.
[c]Assuming the upper limit for $\sigma_\gamma(X)$.

TABLE XIX. Average compound-nuclear cross sections for $E1$ transitions in the $^{60}Ni(n,\gamma)^{61}Ni$ reaction and comparison with model predictions. See discussion in Sec. III F. The quantity $a$ is in units of $b\cdot\mathrm{MeV}^{-b}$. Model 1 is Cameron's semi-empirical result [112]. Model 2 is the Weisskopf single-particle model [100]. Model 3 is the generalized valence model [113]. Model 4 is Brink's version of the photonuclear giant-dipole resonance model [101]. Model 5 is Brink-Axel-Lone model [111].

| | Experiment | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|---|
| $b$ | $a$ | $a$ | $a$ | $a$ | $a$ | $a$ |
| 3 | $(4\pm2)\times10^{-4}$ | $6\times10^{-5}$ | $3.5\times10^{-4}$ | $2\times10^{-4}$ | | |
| 4 | $(1.0\pm0.3)\times10^{-4}$ | | | | $2.3\times10^{-5}$ | |
| 5 | $(2.0\pm0.7)\times10^{-5}$ | | | | | $3.5\times10^{-5}$ |

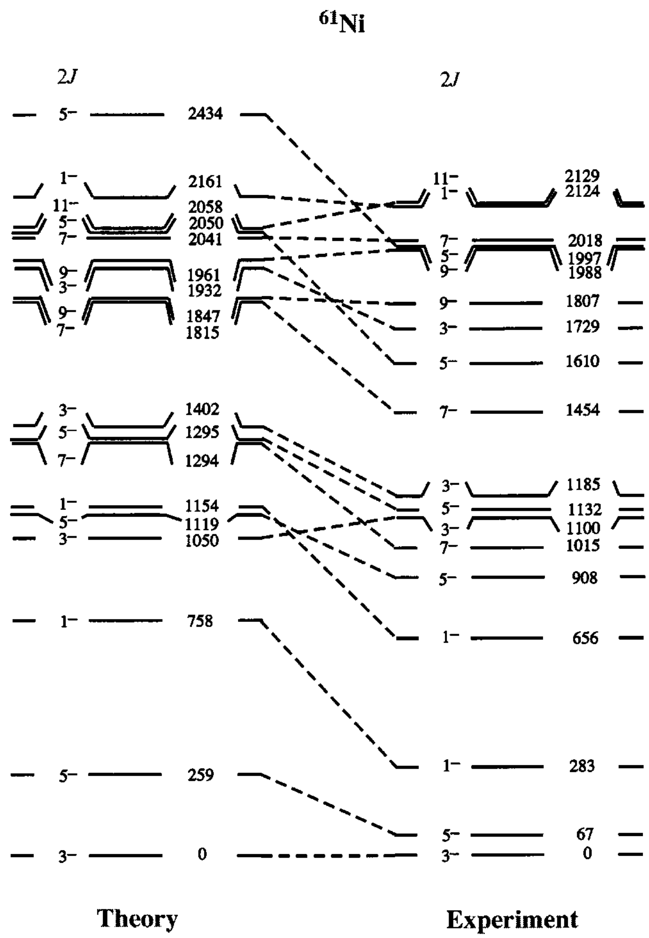


FIG. 8. Comparison between the shell-model predictions and the experimental level scheme of $^{61}$Ni. The levels are labeled by $2J^{\pi}$ on the left and by level energies (in keV) on the right.


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