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Thermal neutron capture gamma rays from neutron capture in ^{59}Ni and ^{63}Ni†

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The thermal neutron capture γ-ray spectra for ^{60}Ni and ^{64}Ni have been observed from a sample previously irradiated to produce long-lived isotopes of ^{59}Ni and ^{63}Ni. New values of the neutron binding energy have been obtained for the compound systems ^{59}Ni, ^{60}Ni, ^{61}Ni, ^{62}Ni, and ^{64}Ni. The γ-ray spectra for neutron capture by ^{59}Ni and ^{63}Ni are not as strongly peaked at high energies as the γ-ray spectra observed for neutron capture by the even-mass target nuclei in the $A\approx 40-64$ mass region.

[NUCLEAR REACTIONS ^{58}Ni, ^{59}Ni, ^{60}Ni, ^{61}Ni, ^{63}Ni(n,γ); E_n=thermal; measured E_γ, I_γ; deduced binding energies, energy levels for ^{59}Ni, ^{60}Ni, ^{61}Ni, ^{62}Ni, ^{64}Ni. Irradiated natural target.]

The capture γ-ray spectra for thermal neutron capture by the even-mass target nuclei in the $A\approx 40-64$ mass region are usually strongly peaked at high energy. In view of the correlations observed between the reduced transition probabilities and the (d,p) single-particle strengths of the final states, this phenomenon has been attributed to channel capture.[1,2] Since the (d,p) single-particle strengths of the low lying states excited by stripping on odd-mass target nuclei are much smaller than those for stripping on even-mass targets, it is expected that the γ-ray spectra for thermal neutron capture in odd-mass target nuclei will not be as strongly peaked at high energies. This conjecture has been investigated in the present work for capture in ^{59}Ni and ^{63}Ni.

Thermal neutron capture γ-ray spectra have been previously measured for neutron capture in the stable isotopes ^{58}Ni,[3,4] ^{60}Ni,[5,6] ^{61}Ni,[4] ^{62}Ni,[3] and ^{64}Ni.[3] In the present work we have measured the spectra of capture γ rays (above 7.0 MeV) formed by neutron capture in the long-lived unstable isotopes ^{59}Ni ($t_{1/2}\approx 8\times 10^4$ yr)[7] and ^{63}Ni ($t_{1/2}\approx 10^2$ yr).[7] The ^{59}Ni-^{63}Ni sample was prepared by irradiating 25 g of natural nickel in a high neutron flux ($\sim 10^{15}\, n\,\mathrm{sec}^{-1}$) at the Oak Ridge high flux isotope reactor (HFIR). From the known capture cross sections, half-lives, and neutron flux it was estimated that after two months of irradiation the sample consisted of approximately 2.1% ^{59}Ni and 0.5% ^{63}Ni as well as ~64.6% ^{58}Ni, ~26.7% ^{60}Ni, ~3.1% ^{62}Ni, ~1.9% ^{61}Ni, and ~1.1% ^{64}Ni.

The capture γ-ray spectra were measured with the modified[8] high resolution annihilation pair spectrometer at the internal target facility[9] of the Argonne research reactor CP-5. A description of this system is given in Ref. 10 and references therein. The calibration standard for both relative intensities and energies is the ^{14}N(n,γ)-^{15}N reaction, which was measured just before the nickel run. The calibration technique is discussed by Thomas, Blatchley, and Bollinger.[9]

Since each peak is fitted with a reference line shape taken from the nickel spectrum, the fits are generally very good and the error in the peak area is mainly statistical.[11] The error in the γ-ray energy is a function of the errors in the energies of the nitrogen lines,[12] and the errors in determining the centroids of the nitrogen lines and the unknown line. The error in the excitation energy increases with excitation energy, i.e., as the separation between the binding energy line and final state line increases.

The data are shown in Fig. 1 where the numbers labeling the lines are the same as those in Table I. The results from this experiment are compiled in Table I and compared with the results of previous measurements. The relative intensities have been normalized to the 8999.3-keV ^{59}Ni ground state line, the intensity of which is arbitrarily set equal to 100. In general, the agreement between the γ-ray energies and/or excitation energies of the present work and those of previous measurements is very good. The improved precision of the new data results in more accurate estimates of neutron binding energies than was available earlier. The binding energies listed in Table I are the recoil-corrected γ-ray energies of the ground state transitions in each compound nucleus. The relative intensities can be compared with other measurements for only a few cases, but for these the agreement is good except for the weak ^{62}Ni lines, for which the intensity uncertainties are very large.

Seventeen ^{60}Ni lines (from capture in ^{59}Ni) and two ^{64}Ni lines were identified. Another possible

TABLE I. The thermal neutron capture γ-ray energies, intensities, final state excitation energies, and binding energies measured in the present work and compared with previous measurements. The intensities in the present work are normalized to the ^{59}Ni 8999.3-keV line which is arbitrarily set equal to 100.0. The binding energies and final state excitation energies are computed from the recoil-corrected γ-ray energies.

Line number	Compound nucleus	E_γ (keV)	Relative intensity	(n,γ) (other work) E_γ (keV)	I_γ [a]	Final state excitation (keV) (present work)	Final state excitation (keV) (others)	Binding energy (keV) (present work)	Binding energy (keV) (others)
1	^{60}Ni	11 386.7 ± 0.7	22.76 ± 0.06			0.0		11 387.9 ± 0.7	11 387 ± 3 [b]
2	⋯	10 947.4 ± 0.9	0.11 ± 0.03			⋯			
3	^{62}Ni	10 594.6 ± 0.7	0.16 ± 0.03	10 597 ± 3 [c]	3.7 ± 0.8	0.0		10 595.6 ± 0.7	10 600 ± 3 [d] 10 596.2 ± 1.5 [c]
4	⋯	10 490.9 ± 2.0	0.08 ± 0.03			⋯			
5	⋯	10 364.5 ± 0.7	0.11 ± 0.03			⋯			
6	^{60}Ni	10 053.6 ± 0.5	8.93 ± 0.05			1333.4 ± 0.3	1332.52 ± 0.05 [b] 1332.8 ± 0.3 [e]		
7	^{64}Ni	9655.9 ± 0.4	2.51 ± 0.05			0.0		9656.7 ± 0.4	9659.3 ± 2.7 [f]
8	^{62}Ni	9422.3 ± 0.5	0.19 ± 0.04	9425 ± 3 [c]	5.0 ± 0.5	1172.5 ± 0.6	1171.7 ± 1.2 [d]		
9	^{60}Ni	9227.5 ± 0.4	1.30 ± 0.04			2159.6 ± 0.5	2158.9 ± 0.2 [g]		
10	^{60}Ni	9102.2 ± 0.4	9.77 ± 0.07			2284.9 ± 0.5	2284.8 ± 0.2 [g]		
11	^{59}Ni	8999.3 ± 0.4	100.00 ± 0.17	8996 ± 5 [h]	26	0.0		9000.0 ± 0.4	9001 ± 3 [b]
12	^{62}Ni	8551.3 ± 1.5	0.58 ± 0.08	8545 ± 3 [c]	4.6 ± 0.5	2043.7 ± 1.6	2047.1 ± 1.9 [d]		
13	^{59}Ni	8533.6 ± 0.4	48.40 ± 0.14	8525 ± 5 [h]	13	465.7 ± 0.1	466 ± 1 [b]		
14	^{64}Ni	8311.7 ± 0.5	0.37 ± 0.09			1344.4 ± 0.5	1345.9 [f]		
15	^{62}Ni	8302.5 ± 1.7	0.13 + 0.08	8296 ± 3 [c]	0.8 ± 0.3	2292.5 ± 1.8	2293 ± 3.0 [d]		
16	^{60}Ni	8263.2 ± 0.4	1.95 ± 0.09			3124.1 ± 0.7	3124.1 ± 0.2 [g]		
17	^{60}Ni	8200.5 ± 0.6	0.30 ± 0.09			3186.8 ± 0.9	3186.4 ± 0.2 [g]		
18	^{60}Ni	8192.7 ± 0.4	2.17 ± 0.09			3194.6 ± 0.7	3194.1 ± 0.2 [g]		
19	^{59}Ni	8119.9 ± 0.4	8.81 ± 0.10	8114 ± 5 [h]	2.5	879.5 ± 0.2	878 ± 1 [b]		
20	^{60}Ni	8069.3 ± 0.4	3.77 ± 0.09			3318.0 ± 0.8	3318.3 [i]		
21	^{60}Ni	7993.5 ± 0.5	0.44 ± 0.09			3393.8 ± 0.8	3393.6 ± 0.2 [g]		
22	⋯	7973.6 ± 0.8	0.19 ± 0.09						
23	^{61}Ni	7819.3 ± 0.4	23.63 ± 0.12	7819.7 ± 1.0 [j] 7819.6 ± 0.8 [k]	37.5 39.0	0.0		7819.8 ± 0.4	7817 ± 3 [b]
24	^{60}Ni	7799.4 ± 0.5	0.88 ± 0.09			3587.9 ± 0.9	3588 [b]		
25	^{60}Ni	7764.4 ± 0.7	0.12 ± 0.09			3622.9 ± 1.0	3619.7 ± 0.4 [g]		
26	^{62}Ni	7703.4 ± 1.5	0.16 ± 0.09	7693 [h]		2891.7 ± 1.7	2890 ± 2.0 [d]		
27	^{59}Ni	7697.0 ± 0.5	2.69 ± 0.09	7693 ± 5 [h]	0.79	1302.5 ± 0.3	1303 ± 1 [b]		
28	^{60}Ni	7652.2 ± 0.5	0.66 ± 0.09			3735.2 ± 0.9	3735.5 ± 0.3 [g]		
29	^{61}Ni	7537.2 ± 0.5	13.61 ± 0.11	7536.6 ± 1.0 [j] 7536.7 ± 0.8 [k]	22.9 23.3 ± 1.6	282.1 ± 0.3	282.9 ± 0.2 [b]		
30	^{60}Ni	7516.6 ± 0.5	2.54 ± 0.09			3870.8 ± 0.9	3871.4 ± 0.2 [g]		

TABLE I *(Continued)*

Line number	Compound nucleus	E_γ (keV)	Relative intensity	(n,γ) (other work)		Final state excitation (keV) (present work)	Final state excitation (keV) (others)	Binding energy (keV) (present work)	Binding energy (keV) (others)
				E_γ (keV)	I_γ [a]				
31	^{60}Ni	7367.9 ± 0.5	2.43 ± 0.09			4019.5 ± 0.9	4020.4 ± 0.2 [g]		
32	^{59}Ni	7323.7 ± 0.6	0.15 ± 0.09			1675.8 ± 0.5	1680 ± 1 [b]		
33	^{60}Ni	7309.1 ± 0.5	0.25 ± 0.09			4078.3 ± 1.0	4078.7 ± 0.2 [g]		
34	^{59}Ni	7265.0 ± 0.6	0.46 ± 0.09	7258 ± 6 [h]	0.2	1734.5 ± 0.5	1735 ± 1 [b]		
35	^{60}Ni	7069.2 ± 0.7	0.51 ± 0.08			4318.3 ± 1.1	4318.9 ± 0.3 [g]		
36	^{60}Ni	7052.4 ± 0.7	0.26 ± 0.08			4335.1 ± 1.1	4335.0 ± 0.4 [g]		

[a] The intensities are absolute intensities per 100 captures in the enriched isotope except those quoted from Ref. 3 for which the intensities are absoluted intensities per 100 captures in a natural sample.

[b] Reference 14.

[c] Reference 4.

[d] Reference 15.

[e] Reference 19.

[f] Reference 16.

[g] Reference 17.

[h] Reference 3.

[i] Reference 18.

[j] Reference 5.

[k] Reference 6.

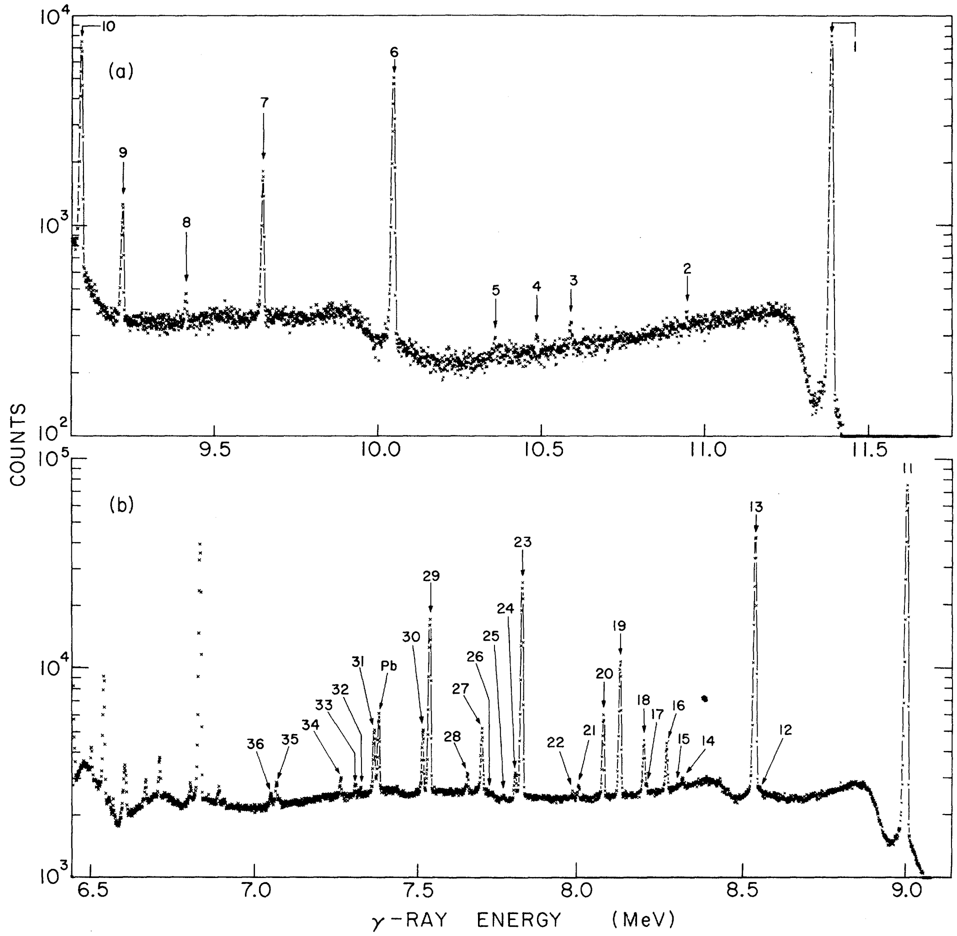

FIG. 1. Thermal neutron capture γ-ray spectrum above 7.0 MeV for irradiated nickel. The percentage abundance for each isotope including ^{59}Ni and ^{63}Ni are given in the text. The line numbers are the same as those in Table I. The lead impurity line is the strong ^{208}Pb 7381.1-keV line.

^{64}Ni line (decay to the second excited state[16]) is obscured by the strong 7381.1-keV ^{208}Pb line. Every other line has been identified from previous (n,γ) measurements except for line numbers 2, 4, 5, and 22. The first three lines are very weak, within a few standard deviations of zero intensity. A survey of (n,γ) measurements[13] eliminated the possibility that the lines were due to capture by contaminants in the sample. We conclude that lines 2, 4, and 5, if real, are secondary transitions from highly excited states (a few hundred keV below the neutron separation energy) in the compound nuclei ^{60}Ni and/or ^{62}Ni. Similarly, we infer that the 7973.6-keV line (number 22) is a secondary transition line.

The absolute intensities of the ^{60}Ni and ^{64}Ni lines can be calculated from the relative isotopic abundances in our sample, the relative intensities measured in the present work, the known total capture cross section for each isotope,[7] and the absolute intensity of the ^{61}Ni 7819.3-keV line, which has been recently measured by Kopecky, Abrahams, and Stecher-Rasmussen.[6] The absolute intensity of the ^{60}Ni 11386.7-keV line is ~15% (i.e., 15 photons per 100 captures in ^{59}Ni); the absolute intensity of the ^{64}Ni 9655.9-keV line is ~27%. The absolute intensities of the other ^{60}Ni and ^{64}Ni lines can be inferred from these numbers. As a check on the internal consistency of our data and of this method for determining absolute intensities, we have calculated the absolute intensity of the ^{59}Ni 8999.3-keV line. Our value of 28% (28 photons per 100 captures in natural nickel) compares well with the values ranging from 26 to 32% given in Ref. 3.

We note here that, as expected, the transitions to the ground and first excited states account for

~20% of the total capture cross section in ^{59}Ni and ~31% in ^{63}Ni. This is in contrast to the much stronger high-energy peaking of the γ-ray spectra for capture in even nuclei. For example, Kopecky *et al.*[6] have observed that the transitions to the ground and first excited states account for ~62.3% of the total capture cross section in ^{60}Ni, ~77.3% in ^{62}Ni, 65.4% in ^{52}Cr, and 78.3% in ^{54}Fe.

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