before enhancement. This observation is substantiated by the fact that the level density in the region of the analogs is approximately the same as that far away from the analog state. In Fig. 10, the integral plot of $\frac{5}{2}^+$ resonances shows no increase in level density with energy; if levels were missed due to their narrow widths, however, the increase in energy of the incident proton of about 2 MeV over the range of measurement would imply that more resonances would become visible. Further substantiation is offered by the fact that few resonances are not well resolved. For resonances with $\Gamma_p = \Gamma$, a reasonable estimate for a minimum observable reduced width for states with $J^\pi = \frac{1}{2}^+$ is $\sim$15 eV (corresponding to $\Gamma_p \sim 10$ eV at $E_p = 2$ MeV). The average observed reduced width for this J^π state is, however, about 4300 eV. Thus it would seem unlikely that many levels are missed in these measurements.

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$Ne^{22}(t,p\gamma)Ne^{24}$ Angular Correlation Study*

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The 1.99-, 3.87-, and 4.76-MeV levels of Ne^{24} have been studied employing particle-γ coincidence techniques. The $Ne^{22}(t,p)Ne^{24}$ reaction was used to populate the levels in Ne^{24}, employing incident triton bombarding energies near 2.5 MeV. Coincident p-γ pulse-height distributions were measured employing two-parameter analysis. Reaction protons were detected near 180° with respect to the incident beam direction in an annular solid-state detector, while γ-ray yields were measured at 0, 30, 45, 60, and 90° to the incident beam direction with a 10.2×10.2-cm NaI(Tl) crystal. The 3.87-MeV level was found to decay (90±2)% via cascade through the 1.99-MeV level ($3.87 \to 1.99 \to 0$), and (10±2)% via direct ground-state transitions. The 4.76-MeV level decays 100% via cascade through the 1.99-MeV level ($4.76 \to 1.99 \to 0$); an upper limit of 3% was placed on the $4.76 \to 0$ mode. Assuming spin 0 for the Ne^{24} ground state, analysis of measured γ-ray angular distributions demands $J=2$ for both the 1.99- and 3.87-MeV levels and restricts the spin of the 4.76-MeV level to $J=0$, 1, or 2. The $3.87 \to 1.99$ transition has an $(L+1)/L$ multipole admixture of $x = -(0.15 \pm 0.15)$. An upper limit, $\tau_m \leq 3 \times 10^{-8}$ sec, was set for the mean lifetimes of the 1.99-, 3.87-, and 4.76-MeV levels.

I. INTRODUCTION

THE published experimental information about the Ne^{24} nucleus gives its mass,[1,2] β-decay modes,[1–3] measured energy levels,[2] and first-excited-state lifetime.[4] The present experiment was undertaken to determine spins and electromagnetic decay modes of Ne^{24} levels below $\sim$5-MeV excitation energy. Levels in Ne^{24} were populated with the $Ne^{22}(t,p)Ne^{24}$ reaction ($Q = 5.587$ MeV)[2], and angular distributions of γ rays coincident with reaction protons detected in an axially symmetric counter centered at 180° were measured. With this geometry the residual Ne^{24} nuclei are aligned in magnetic substates with magnetic quantum numbers 0, ±1. The γ-ray angular distribution function has been formulated theoretically by Litherland and Ferguson,[5] who refer to this technique as Method II. Level spins and multipole-mixing ratios may be obtained from the measured γ-ray angular distributions, and γ-ray branching ratios may also be extracted from the experimental γ-ray spectra. Mean lifetime limits for these levels were obtained incidentally as a result of the technique of particle-γ coincidence measurement.

II. EXPERIMENTAL

The tritium beam from the Lockheed Palo Alto Research Laboratory Van de Graaff accelerator was momentum-analyzed and collimated to a spot size $\sim 1 \times 1$ mm at the target. The target was a gas cell 6.3 mm thick with 1.1 mg/cm² Ni foil entrance and

* Work supported by the Lockheed Independent Research Program.

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[1] B. J. Dropesky and A. W. Schardt, Phys. Rev. **102**, 426 (1956).

[2] M. G. Silbert and N. Jarmie, Phys. Rev. **123**, 221 (1961).

[3] During the course of this work, delayed γ-ray spectra from Ne^{24} were examined with an 8-cm³ Ge(Li) detector. γ rays with energies of 473±2 and 873±4 keV were observed and assigned to the β decay of Ne^{24}. From the relative intensity of these two γ rays, β-branching ratios of 91.4±1.5 and 8.6±1.5% were deduced for decay to the Na^{24} 473-keV level and to the doublet at 1.34 MeV, respectively. These results are in excellent agreement with those of Ref. 1. Recent work [R. C. Greenwood (to be published)] has identified a close lying doublet at 1.34 MeV in Na^{24}. Our results were not precise enough to identify which of these levels was populated in the Ne^{24} β decay.

[4] C. Broude *et al.* (private communication), cited in Ref. 10.

[5] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961); A. J. Ferguson, *Angular Correlation Methods in Gamma-Ray Spectroscopy* (North-Holland Publishing Co., Amsterdam, 1965).

exit ports, and contained Ne^{22} enriched to 99.7% Ne^{22} at a pressure of approximately 0.25 atm. Reaction protons passed through the beam entrance port and were detected in an annular solid-state counter at angles between 164° and 176° in the laboratory system. The gas target, particle counter, and a Faraday cup were contained in a 15.3-cm-diam stainless-steel cylinder with walls 1.6 mm thick. The annular counter and target were aligned optically with the collimated beam axis. γ rays were detected in a 10.2×10.2-cm NaI(Tl) crystal whose front face was 8.8 cm from the target center. In addition to lead shielding 5 cm thick around the sides of the crystal a 1.8-mm-thick lead shield covered the crystal front face. The crystal assembly was mounted on a trolley that could be rotated about the target-chamber vertical axis. Systematic asymmetry was determined by measuring the angular variation of the γ-ray yield of a radioactive source prepared in the target position, and was found to be $\leq$2.5%. Those energy-analog pulses from the two detectors that were coincident in time were sorted and stored using two-parameter analysis. The coincidence resolving time was ~40 nsec. γ-ray angular distributions were measured by collecting p-γ coincidence data at angles between 0° and 90° to the beam axis. To monitor the reaction yield, the pulse-height distribution of charged particles from the annular counter was collected simultaneously with coincidence spectra. The experimental arrangement is similar to that previously described in more detail.[6]

A rough determination of the charged-particle yield at back angles had been made for several bombarding energies between 2.4 and 3.1 MeV; the triton bombarding energy used in the present investigations was subsequently chosen to facilitate the γ-ray angular distribution measurement. Proton groups corresponding to Ne^{24} levels at excitation energies of 0, 1.99, 3.87, and 4.76 MeV were observed in the charged-particle pulse-height distributions; the 3.96- and 4.89-MeV levels were populated weakly. Groups[7] from C and O were also observed which were found to be due to the bonding agent attaching the Ni foils to the beam entrance and exit ports of the gas cell. Because of these impurities and the weak population of the 3.96- and 4.89-MeV levels, γ-ray angular correlations were measured only for the 1.99-, 3.87-, and 4.76-MeV levels. Data for these levels reported herein were collected at incident triton bombarding energies of E_t=2.50, 2.50, and 2.59 MeV for the 1.99-, 3.87-, and 4.76-MeV levels, respectively.

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[7] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959); T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C. 1962), NRC 61 Sets 5 and 6.

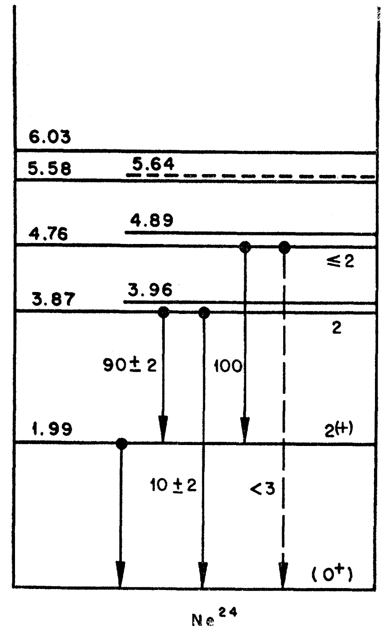

FIG. 1. Partial level scheme for Ne^{24}. The excitation energies (in MeV) are from Ref. 2. The γ-ray branching ratios are from the present work. The spin-parity assignment of 0^+ for the ground state has not been determined experimentally but is assumed.

III. RESULTS

Data reduction was effected by extracting the γ-ray pulse-height distribution coincident with the proton group of interest from each of the two-parameter distributions. Using a rough energy calibration based on annihilation radiation and the γ-ray decay of the 1.98-MeV level of O^{18}, the energy of the full absorption peaks observed in these pulse-height distributions was determined. Using the measured[2] location of the Ne^{24} levels, the observed γ rays were assigned to transitions in Ne^{24}. The γ-ray components and corresponding assignments are described below.

The particle group corresponding to population of the 1.99-MeV level was found to be in coincidence with a γ ray of energy 1.99±0.02 MeV, due to the γ-ray de-excitation of the 1.99-MeV level. An unresolved doublet with central energy of 1.93±0.03 MeV, as well as a transition of higher energy E_γ=3.83±0.05 MeV, was observed in coincidence with the particle group corresponding to population of the 3.87-MeV level. The measured energy of the unresolved doublet is consistent with that expected for the superposition of two equal intensity γ rays with energies of 1.99 and 1.88 MeV. Thus, the observed peaks are consistent with two modes of γ decay for the 3.87-MeV level, via cascade through the 1.99-MeV level and via a weak crossover transition. For the 3.87-MeV level, branching ratios (in %) were found to be 10±2 for the 3.98 → 0 mode, and 90±2 for the 3.87 → 1.99 → 0 mode. γ rays of energy 2.77±0.02 and 1.99±0.02 MeV were measured in coincidence with the particle group cor-

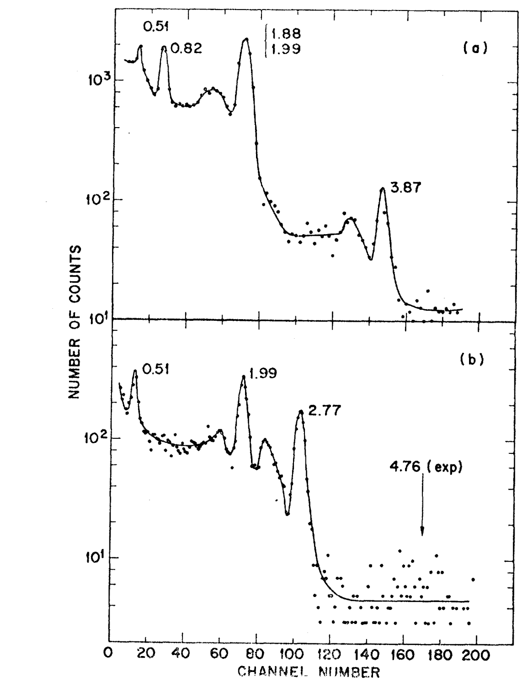

FIG. 2. γ-ray spectra from the decay of (a) the Ne^{24} 3.87-MeV level, and (b) the Ne^{24} 4.76-MeV level. γ-ray full-energy peaks are labeled by their energies in MeV.

responding to the population of the 4.76-MeV level; these γ rays are consistent with the cascade decay of the 4.76-MeV level through the 1.99-MeV level, $4.76 \rightarrow 1.99 \rightarrow 0$. We find the 4.76-MeV level decays less than 3% via direct ground-state transitions. These results are summarized in Fig. 1, while the γ-ray spectra from which they were obtained are illustrated in Fig. 2. These spectra are the sums of spectra recorded at the different angles to the beam axis. The γ-ray branching ratios were obtained using the photopeak efficiences of Coop and Grench[8] (and the angular distributions obtained herein). As indicated in Fig. 1, we shall assume in this work that the Ne^{24} ground state has $J^{\pi}=0^{+}$, since it is an even-even nucleus.

After identifying the various spectral components

TABLE I. Results of least-squares Legendre-polynomial fits to p-γ angular correlations measured in the $Ne^{22}(t,p\gamma)Ne^{24}$ reaction.

E_x (MeV)	E_γ (MeV)	Assignment (MeV)	$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$ A_2[a]	A_4[a]	χ^2
4.76	2.77	$4.76 \rightarrow 1.99$	$+(0.01\pm0.04)$	$-(0.05\pm0.05)$	0.07
	1.99	$1.99 \rightarrow 0$	$-(0.03\pm0.05)$	$-(0.04\pm0.05)$	0.24
3.87	1.88[b]	$3.87 \rightarrow 1.99$	$+(0.17\pm0.03)$	$-(0.18\pm0.03)$	0.99
	1.99[b]	$1.99 \rightarrow 0$			
	3.87	$3.87 \rightarrow 0$	$+(0.54\pm0.16)$	$-(0.05\pm0.16)$	0.35
1.99	1.99	$1.99 \rightarrow 0$	$+(0.43\pm0.03)$	$-(0.87\pm0.04)$	0.2

[a] These coefficients do not include the corrections for the finite size of the NaI(Tl) detector. Attenuation coefficients for a 2-MeV γ ray are $Q_2=0.86$ and $Q_4=0.62$.
[b] These γ rays were unresolved in the spectrum.

[8] K. L. Coop and H. A. Grench, Nucl. Instr. Methods **36**, 339 (1965).

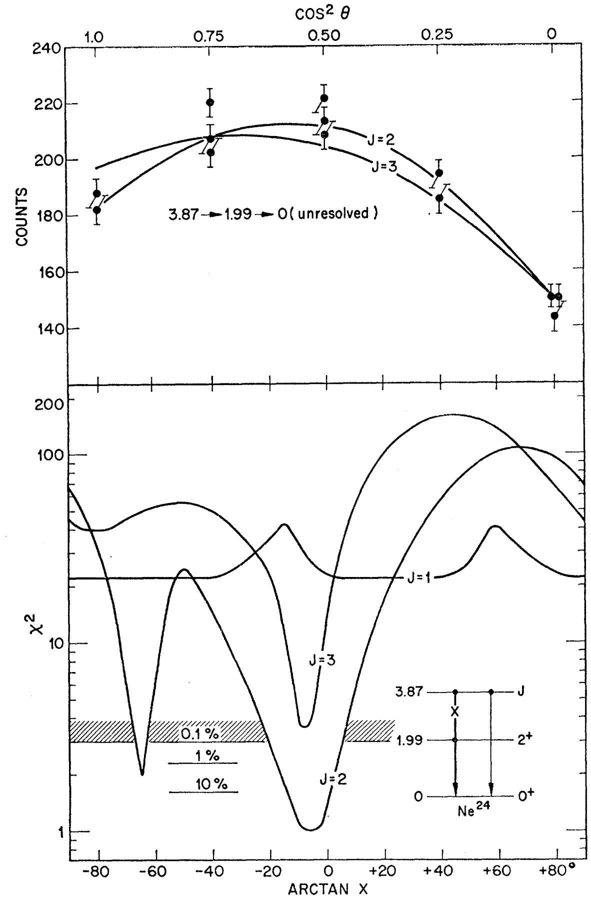

FIG. 3. χ^2 versus arctan$x$ for a fit to the two angular correlations observed following the decay of the Ne^{24} 3.87-MeV level. A simultaneous fit was made to the angular correlation of the $3.87 \rightarrow 0$ transition and the angular correlation of the two unresolved γ rays in the $3.87 \rightarrow 1.99 \rightarrow 0$ cascade as indicated in the insert in the lower part of the figure. Various probability limits are indicated. These give the probability that, for a correct solution, χ^2 exceeds the indicated value. The upper part of the figure illustrates the angular correlation measured for the two unresolved members of the $3.87 \rightarrow 1.99 \rightarrow 0$ cascade and the best fit to this correlation assuming $J=2$ or 3 for the 3.87-MeV level.

with the appropriate transitions in Ne^{24}, the γ-ray yields from transitions in Ne^{24} measured at the various detector angles were normalized and fit to a Legendre-polynomial expansion of the form

$$W(\theta)=I_\gamma[1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)]. \quad (1)$$

The Legendre-polynomial expansion coefficients are summarized in Table I.

In the course of measuring the p-γ coincidence distributions, the time relationship between the coincidence timing pulses derived from the charged-particle and γ-ray spectrometers was examined using time-to-pulse-height techniques. An upper limit, $\tau_m \leq 3\times10^{-8}$ sec, for the mean lifetimes of the 1.99-, 3.87-, and 4.76-MeV levels was deduced from the time-to-height spectrum. Lower limits on the radiative widths and transition strengths [in Weiskopf units (Wu)] re-

TABLE II. Lower limits on radiative widths and electromagnetic transition strengths in Ne^{24}.

Transition (MeV)	Minimum Γ_γ (eV)	Minimum transition strengths (Wu)[a] $E2$	$M2$	$E3$	$M3$	$E4$	$M4$	Restrictions on J and π[b]
$1.986 \rightarrow 0$	2.2×10^{-8}	2.1×10^{-4}	5.7×10^{-3}	1.4×10	3.8×10^{2}	1.4×10^{6}	3.8×10^{7}	$J=2$, or $J^\pi=3^-$
$3.873 \rightarrow 0$	1.3×10^{-9}	4.4×10^{-7}	1.2×10^{-5}	7.5×10^{-3}	2.1×10^{-1}	2.1×10^{2}	5.5×10^{3}	$J=2, 3$
$3.873 \rightarrow 1.986$	1.8×10^{-8}	2.4×10^{-4}	6.2×10^{-3}	1.6×10^{-3}	4.8×10^{2}	1.9×10^{6}	5.2×10^{7}	$J\leq4$, or $J^\pi=5^-$
$4.764 \rightarrow 1.986$	2.1×10^{-8}	3.8×10^{-5}	1.0×10^{-3}	1.3	3.5×10	6.5×10^{4}	1.8×10^{6}	$J\leq5$

[a] Assumes that the Ne^{24} ground state is 0^+.
[b] For the initial state of the transition. These restrictions follow from those on the maximum transition strengths inferred from sum rules and systematics (see, e.g., Refs. 9 and 10). They also include the restrictions due to the complexity of the angular correlation results listed in Table I.

sulting from these lifetime limits are listed in Table II for the four transitions involved. For the two branches observed in the decay of the 3.87-MeV level, the limits correspond to two standard deviations from the measured branching ratios. Restrictions on the spins and parities of the three initial states involved are also listed in Table II. These restrictions result from consideration of sum rules[9] and local systematics,[10] which indicate the largest possible transition strength for a given multipolarity. They also include the restrictions resulting from the complexity of the angular correlations summarized in Table I (i.e., for $A_2\neq0$, $J\geq1$ and for $A_4\neq0$, $J\geq2$).

The angular distributions were fitted with theoretical distribution formulas[5] following the method outlined by Poletti and Warburton.[11] In particular the results of the least-squares fits to these data with the correlation formulas are illustrated in the fashion outlined by these authors. We also follow their phase convention which, for natural mixtures (e.g., $E2/M1$), is the same as that recommended by Rose and Brink.[12] In these fits the spins of the 1.99-, 3.87-, and 4.76-MeV levels were restricted as given in Table II; (however, $J=0$ and 5 were tried for the 3.87-MeV level, and excluded with a confidence $>99.9\%$). The ground state was taken as $J^\pi=0^+$, as stated previously. The results of the χ^2 fits are described below.

The 1.99-MeV level has $J=2$, because only with this spin assignment is an acceptable fit to the angular distribution of the $1.99\rightarrow0$ γ ray obtained (see Table II). The measured width[4] of this level is $(6\pm4)\times10^{-4}$ eV. This corresponds to transition strengths of 6 ± 4 and 150 ± 100 Wu for transition multipolarities $E2$ and $M2$, respectively. Because there is no known $M2$ transition for $A\leq40$ with strength >10 Wu, positive parity for this level is certainly favored; however, in view of the sparse systematic data and the uncertainties of the lifetime measurement, negative parity is not completely ruled out. For the 3.87-MeV level, $J=2$ is required, as may be seen from Fig. 3. $J=1$ is excluded with confidence $>99.9\%$ (i.e., above the 0.1% limit) as expected from the appearance of the term in $P_4(\cos\theta)$ listed in Table I. A $J=3$ assignment is also rejected with confidence $>99.9\%$.

Turning now to the 4.76-MeV level, we note (consulting Table I) that the angular distributions of the 2.77- and 1.99-MeV γ rays are isotropic within experimental error. The simultaneous fitting of these angular distributions to the theoretical formula allowing the multipole mixing (x) of the 2.77-MeV γ ray to vary, with $J=2$ for the 1.99-MeV level and $x=0$ for the 1.99-MeV γ ray, results in solutions below the 1% limit for $J=0$, 1, and 2 for the 4.76-MeV level. If there is no effect because of the finite size of the proton detector than $J=3$ is excluded at the 0.1% limit (see Fig. 4). Allowing for a possible finite-size effect[11] brings χ^2 down to the 1% limit. We conclude that $J=3$

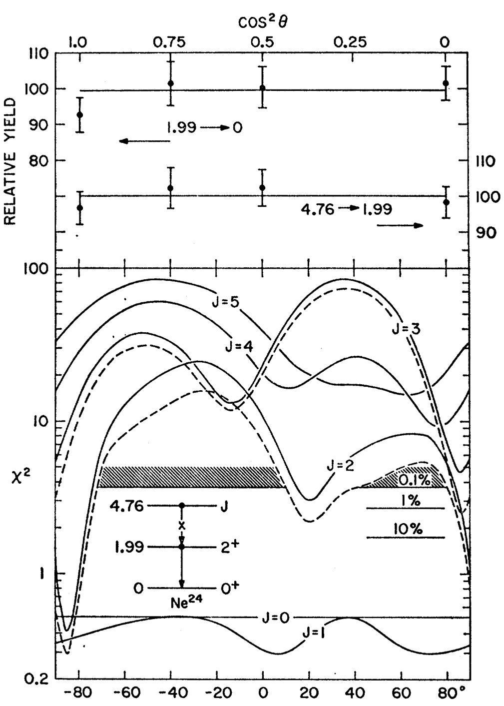

FIG. 4. χ^2 versus arctan$x$ for a simultaneous fit to the 2.77- and 1.99-MeV γ rays following the decay of the 4.76-MeV level of Ne^{24}. The fits to the angular correlations shown in the upper portion of the figure are for a $J=0$ assignment to the 4.76-MeV level. The dashed curve for $J=2$ is our estimate of the maximum possible effect of the finite size of the proton detector (see Ref. 11).

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[10] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data **A2**, 347 (1967).
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[12] H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967).

TABLE III. Restrictions on the $(L+1)/L$ amplitude ratio x for the Ne^{24} 1.99 → 0, 3.87 → 1.99, and 4.76 → 1.99 transitions.

Transition (MeV)	Spin of initial level	Restrictions on x[a]
1.99 → 0	2	0
3.87 → 1.99	2	$-(0.15\pm0.15)$, $-(2.1\pm0.6)$[b]
4.76 → 1.99	1	no restrictions
4.76 → 1.99	2	$\|x\|>4.3$, $+(0.39\pm0.12)$[b]

[a] One standard deviation.
[b] Rejected at the 5% limit.

is most unlikely and reject it. The restrictions on the mixing ratio of the 4.76 → 1.99 transition for spin assignments of 1 or 2 for the 4.76-MeV level are listed in Table III. The solution for $J=2$ and $x_{2.77}=+0.39$ barely reaches the 5% limit while the solution for $|x|>4.3$ requires an essentially pure quadrupole transition. We suggest that the most likely spin of the 4.76-MeV level is either $J=0$ or 1.

IV. DISCUSSION AND SUMMARY

The main results of this experiment are illustrated in Fig. 1. The decay γ rays from the 1.99-, 3.87-, and 4.76-MeV levels of Ne^{24} are reported for the first time, and γ-ray branching ratios have been determined for these levels. The 1.99- and 3.87-MeV levels have $J=2$. Either $J=0$ or 1 is preferred for the 4.76-MeV level, with $J=2$ not entirely eliminated. These results require an assumption of $J=0$ for the ground state of Ne^{24}. Since $T=2$ for Ne^{24}, and according to the shell model in jj coupling, the neutron $d_{5/2}$ subshell is closed in Ne^{24}, one might expect the low-lying states in Ne^{24} to be fairly well described by jj coupling configurations involving two protons in the $1d_{5/2}$ and $2s_{1/2}$ orbits. (This picture has been applied to O^{18}, where two neutrons outside the O^{16} nucleus are in the $d_{5/2}$ and $2s_{1/2}$ orbits.[13]) The states which may be formed with these configurations are $d_{5/2}^2$ ($J^\pi=0^+$, 2^+, 4^+), $s_{1/2}^2$ ($J^\pi=0^+$), and $d_{5/2}s_{1/2}$ ($J=2^+$, 3^+). Of these six states, five may readily be identified with the ground and first four excited states of O^{18}. We note that there is a similarity in excitation energy between these O^{18} levels and the first few levels in Ne^{24}. If the 3.87- and 4.76-MeV levels in Ne^{24} are described by these configurations, the most reasonable assignment for the 4.76-MeV level is obtained with $J^\pi=0^+$. A more detailed attempt to identify the Ne^{24} levels with the appropriate shell-model configurations must await more experimental evidence.

[13] I. Talmi and I. Unna, Nucl. Phys. 39, 280 (1962).

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Direct Neutron Capture in $Co^{59}(n,\gamma)Co^{60}$†

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The variation in intensity of 40 individual γ rays produced by neutron capture in cobalt was observed for neutron energies less than 1500 eV. The observed variations were consistent with the existence of a direct component in the radiative capture reaction mechanism. A direct-capture cross section of 9.2 ± 2.4 mb at 1-eV neutron energy was deduced for the 7.492-MeV ground-state transition.

INTRODUCTION

EVIDENCE for the existence of a direct-reaction mechanism in the radiative capture of slow neutrons in the target nucleus Co^{59} was given in a previous article.[1] The present article gives more complete results, including a comparison of the γ-ray spectra obtained for thermal neutron capture with that from the 132-eV resonance as well as a measure of the variation in intensity of 40 γ rays in the neutron-energy region below 1500 eV. The present experiment used a thinner cobalt sample, a smaller Ge(Li) detector, improved detector shielding from neutrons scattered by the sample, and obtained better statistical accuracy. Within the statistical accuracy, the previous results were verified.

Studies of the γ-ray spectrum from the $Co^{59}(n,\gamma)Co^{60}$ reaction using thermal neutrons were reported by numerous authors.[2–7] The most recent measurements using Ge(Li) γ-ray detectors were done by Shera and Hafemeister[6] and by Prestwich, Kennett, and Hughes.[7] Shera and Hafemeister used γ-γ coincidence measurements to deduce some final-state spin assignments

† This work was supported by the U. S. Atomic Energy Commission.
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