Gamma-Ray Spectra of Co^{60} and Mn^{56} Following Resonance-Neutron Capture in Co^{59} and Mn^{55}†

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The gamma-ray spectra resulting from neutron capture in the 132-eV resonance of Co^{59} and the 336-, 1098-, and 2355-eV resonances of Mn^{55} have been observed with a Ge(Li) spectrometer at the Argonne fast-chopper time-of-flight system. The spectra are compared with the thermal-capture spectra and with the proton spectra observed in deuteron stripping. The reduced gamma-ray width for transitions in Co^{60} exhibit a dependence on the l_n value of the corresponding (d,p) transitions. The thermal and two higher-energy resonance spectra in Mn^{56} display significant correlation with the corresponding stripping strengths. No such correlation was observed for the 132-eV resonance in Co^{59} or the 336-eV resonance in Mn^{55}.

I. INTRODUCTION

THE thermal-capture gamma-ray spectra of Co^{60} and Mn^{56} have been studied with magnetic spectrometers,[1,2] and more recently with lithium-drifted germanium detectors.[3–5] The transitions observed in the latest work have been identified by comparison with deuteron stripping data[6,7] and in many cases the final states are now well defined.

On the basis of their analysis of the resonance parameters for the 132-eV resonance in Co^{59}, Jain, Chrien, Moore, and Palevsky[8] conclude that a negative-energy resonance exists and accounts for about 37% of the thermal-capture cross section. Their results also provide evidence that the spin of this resonance is $J=4$. From his scattering experiments with polarized neutrons, Schermer[9] also concludes that there is a significant contribution to thermal capture from negative-energy resonances that are predominantly $J=3$ in character.

An R-matrix analysis of the Mn^{55} total cross section[10] indicates the existence of negative-energy resonances in this nuclide also. The relative intensities of transitions populating the second to the fifth excited states associated with the resonances at 336, 1098, and 2355 eV have been observed by use of a NaI(Tl)γ-γ coincidence spectrometer.[11] These results indicate significant differences in the spectra at thermal and resonance energies.

In this work, we report on a measurement of the capture γ-ray spectra following resonance capture of neutrons. If the contribution from $J=3$ negative-energy resonances in Co^{59} is significant, one might also expect to observe differences between this spectrum and that following thermal capture.

II. EXPERIMENTAL DETAILS

Samples consisting of $\sim$800 g Co_2O_3 (99% purity) and $\sim$800 g Mn metal (99.999% purity) contained in a thin aluminum holder in the form of a slab 4 in. high $\times$2 in. wide $\times$1 in. thick, were placed in the flight path of the Argonne fast chopper.[12] The length of the flight path was 6.42 m and the rotor was operated at 15 000 rpm. The neutron time of flight was analyzed in 256 1-μsec channels, the pulse height from the gamma-ray detector in 1024 channels. Each event was recorded in the form of a two-parameter address on magnetic tape.[13]

The resultant gamma rays were observed with a 6-cc Ge(Li) detector coupled to the analyzer through a low-noise linear-amplifier system. The over-all gain of the system corresponded to approximately 6 keV/channel. The analyzer was gated by a photocell pulse signaling the opening of the chopper slits, and the linear gate of the analyzer ADC opened only for pulses whose heights correspond to energies greater than 3 MeV. The thermal-capture spectrum was also recorded in a separate experiment with the chopper fixed in an open position.

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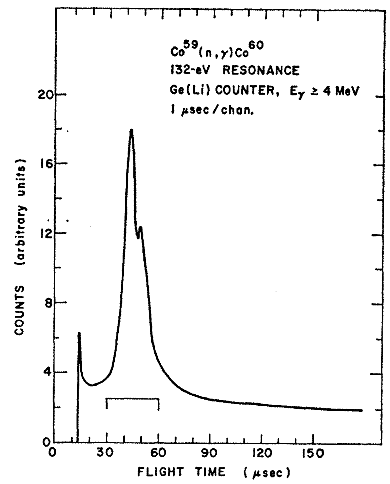

FIG. 1. The time-of-flight spectrum of all neutron captures on Co^{59}.

III. RESULTS

A. Co^{60}

The data obtained were accumulated over a period of 10 days. They were then sorted into one-parameter form under various conditions corresponding to digital selection of a range of values for the integrated parameter.

One form of the data is illustrated in Fig. 1, a plot of the integrated counting rate versus neutron time of flight. Since the ratio of neutron width to total width for the 132-eV resonance[8] is $\Gamma_n/\Gamma \approx 0.9$ so that the dominant interaction is neutron scattering, the observed resonance shape displays a well-developed distortion[14] due to multiple events in the rather thick sample. Figure 1 also shows the limits of neutron energy used to record the γ-ray spectrum corresponding to the resonance. To correct for background, the off-resonance contribution, obtained from windows set on either side of the resonance, was subtracted from the resonance spectrum.

In Fig. 2, the spectrum for the 132-eV resonance is compared with the thermal spectrum. The thermal spectrum is in good agreement with that obtained previously.[3,4] The energies of the transitions have been adopted from the most recent set of published values,[4] although the present work indicates that the line reported at 5608 keV is probably a doublet, corresponding to transitions at 5603 and 5615 keV.

Table I presents a more detailed comparison of the resonance and thermal spectra. It lists the ratio of reso-

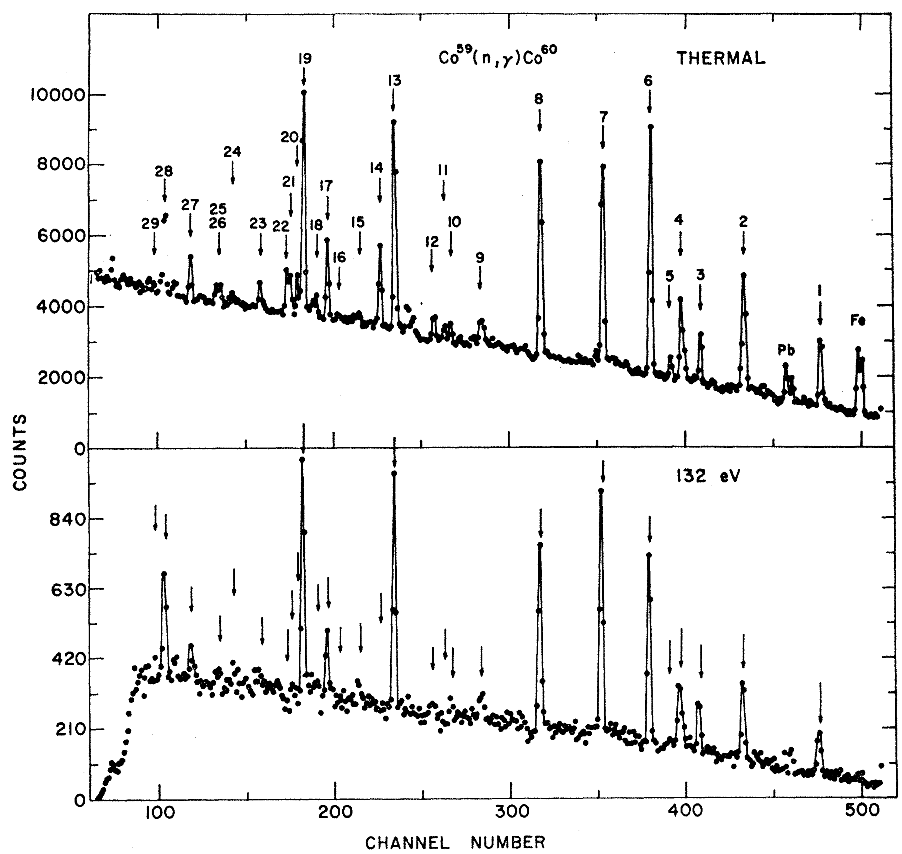

FIG. 2. The gamma-ray spectra associated with the $Co^{59}(n,\gamma)Co^{60}$ reaction. Upper curve: capture of thermal neutrons. Lower curve: capture of neutrons at the resonance energy (132 eV).

[14] T. J. Kennett and L. M. Bollinger, Nucl. Phys. 12, 249 (1959).

nance to thermal intensity for each transition identified, as well as the relative intensity of the transitions for the resonance spectrum. These latter were calculated from the area of the corresponding double-escape peak, corrected for the energy dependence of the counter efficiency.

B. Mn^{56}

The time-of-flight spectrum is shown in Fig. 3. The small resonance on the tail of the 336-eV resonance corresponds to the 105-eV resonance in germanium.[15] Since only those transitions that have been previously identified in thermal spectrum and that correspond to known (d,p) excitations are included in the analysis, possible contributions from higher-energy Ge resonances in the kilovolt region do not seriously affect the results. As in the Co^{59}, the shape of the resonance line is greatly distorted by multiple scattering.

The γ-ray spectra obtained are shown in Fig. 4. Although the 1098- and 2355-eV resonances are not resolved for this flight path, the spectra corresponding to the flight time regions shown in Fig. 3 display significant differences. The positions indicated by arrows correspond to the observed (d,p) excitations. In Table II are shown the relative intensities, corrected for off-resonance contributions and for the efficiency of the Ge(Li) detector. The associated error quoted is that from counting statistics only. Those transitions for which the observed intensity was less than half the statistical error have been arbitrarily set to zero. The associated error represents the upper limit for this intensity.

TABLE I. The Co^{60} gamma rays following neutron capture in the 132-eV resonance of Co^{59}. The lines are numbered as shown in Fig. 2.

Line No.	E_γ (keV)	l_n	Γ_γ (10^{-3} eV)	r_γ = resonance intensity/thermal intensity
1	7495	1	12	1.05
2	7218	1(3)	13	0.77
3	7059	3	8	1.32
4	6990	1	14	1.06
5	6954	3	1.4	0.62
6	6881	1	30	1.06
7	6710		36	1.13
8	6490	1(3)	30	1.08
9	6278		7	1.42
10	6177		0.5	0.3
11	6152		0.3	<0.2
12	6112		2	0.41
13	5981	1	31	1.13
14	5927		2	<0.1
15	5851		4	3.6
16	5782		0.3	<0.4
17	5744		10	1.04
18	5705	3	3	0.7
19	5663	1?	31	1.22
20	5643	1	2	0.44
21	5615		0.7	0.2
22	5603		0.7	0.2
23	5512	3	2	0.8
24	5411		6	3.6
25	5375 }		6	1.3
26	5363 }			
27	5273		7	1.4
28	5184		14	1.1
29	5150		1	<0.4

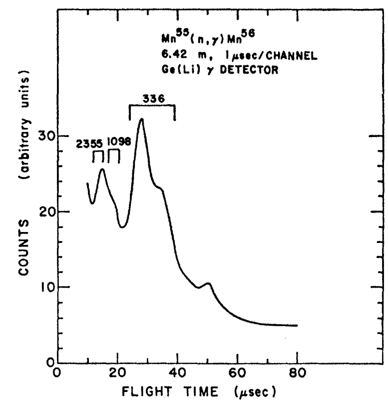

FIG. 3. The time-of-flight spectrum of all neutron captures in Mn^{55}.

The relative intensities observed in each case are in good agreement with the previous NaI coincidence results.[11] The latter experiment was performed with a flight path of 25 m and consequently higher time-of-flight resolution. In Table III the present results are compared with the NaI work for those transition observed in the latter. The good agreement indicates that the contributions to the higher-neutron-energy regions selected in this work correspond mainly to the resonances assigned, despite the poorer neutron resolution.

IV. DISCUSSION

The observation of the 7495-keV transitions with a measurable intensity, in the 133-eV Co^{59} resonance spectrum represents substantial confirmation of the spin assignment $J_c = 4$ for this resonance.[8,9] This gamma

TABLE II. Relative intensities of gamma rays from the $Mn^{55}(n,\gamma)Mn^{56}$ reaction. The lines are numbered as shown in Fig. 4.

Line No.	Excitation (keV)	Relative intensities in resonances Thermal	336 eV	1098 eV	2355 eV
1	0	1.46 ±0.07	4.47±0.55	2.56±0.84	2.39±0.58
2	25	4.21 ±0.19	5.55±0.55	1.18±0.84	0 ±0.58
3	108	1.86 ±0.09	2.22±0.54	0.64±0.68	0 ±0.56
4	207	3.73 ±0.19	0 ±0.54	4.78±0.90	5.66±0.67
5	336	0.82 ±0.05	0.42±0.43	0.43±0.41	2.20±0.76
6	479	1.08 ±0.05	1.01±0.43	0.27±0.41	1.54±0.74
7	712	0.097±0.01	0 ±0.36	0.25±0.40	0 ±0.71
8	835	0.24 ±0.02	0 ±0.44	0.89±0.40	0 ±0.71
9	1161	0.49 ±0.05	1.34±0.31	0 ±0.40	0 ±0.66
10	1230	0.29 ±0.03	0.47±0.34	2.86±0.45	0 ±0.56
11	1345	0.30 ±0.03	0 ±0.32	1.86±0.40	0.76±0.50
12	1504	0.53 ±0.05	0 ±0.30	0 ±0.40	1.36±0.64
13	1739	1.74 ±0.17	1.23±0.30	0 ±0.40	1.88±0.57

[15] *Brookhaven National Laboratory Report No. BNL-325* (U. S. Government Printing and Publishing Office, Washington, D. C., 1958), 2nd ed.

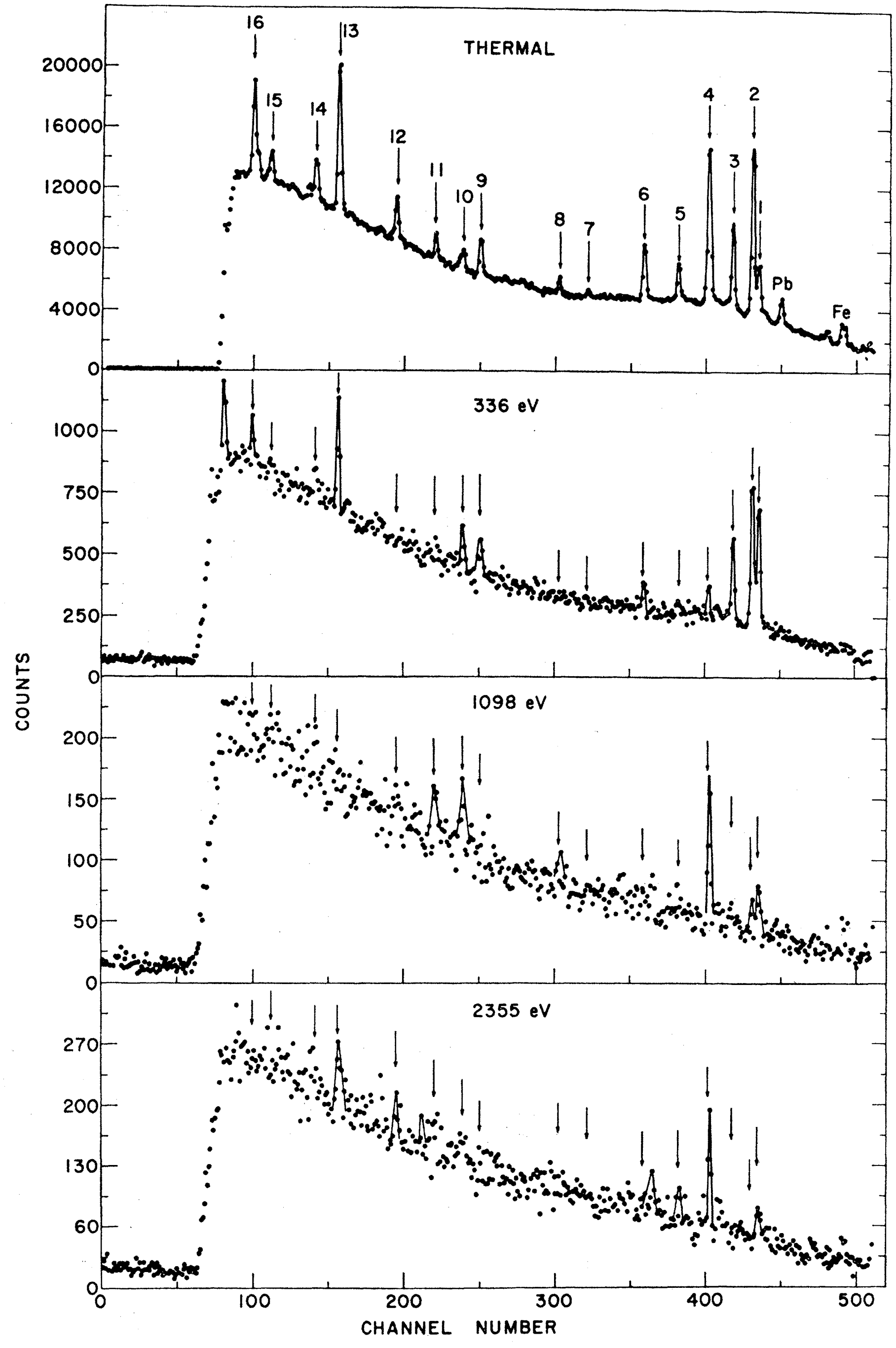

FIG. 4. Gamma-ray spectra from the $Mn^{55}(n,\gamma)Mn^{56}$ reaction for neutrons at thermal energy and at the resonance energies indicated.

TABLE III. Comparison of the present Ge(Li) measurements of Mn^{56} gamma rays with previous NaI measurements. The lines are numbered as in Table II and Fig. 4.

Line No.	Thermal Ge(Li)	Thermal NaI	336 eV Ge(Li)	336 eV NaI	1098 eV Ge(Li)	1098 eV NaI	2355 eV Ge(Li)	2355 eV NaI
3	1.6±0.2	2.2	4.3±0.9	4.3±0.4	0.73±0.9	1.4±0.3	0	0
4	3.4±0.4	3.6	0 ±0.9	0.5±0.3	5.5 ±0.9	3.4±0.6	4.0±0.6	5.3±0.5
5	0.8±0.1	0.6	0.8±0.8	1.4±0.3	0.5 ±0.6	1.6±0.2	1.7±0.8	0.8±0.3
6	1.1±0.1	0.6	1.9±0.8	0.9±0.3	0.3 ±0.6	0.6±0.2	1.2±0.8	1.0±0.3

ray has been identified as the ground-state transition. for which the final state has spin and parity $J_f^\pi=5^-$, On the basis of the relative intensity of this transition, an $E1$ multipole assignment (for which $J_c=4$) is much more probable than $M2$ (for which $J_c=3$).

The strong qualitative similarity between the resonance and thermal spectra indicates that the 132-eV resonance is dominant in the thermal spectrum. The most striking difference is the marked decrease in the intensity of the transitions at 6152 and 5927 keV. These transitions have been previously reported in the thermal spectrum,[3,5] with the same relative intensity as observed here. From this result it can be concluded therefore, that negative-energy resonances also influence the thermal spectrum.

The reduced widths for gamma-ray transitions leading to final states for which the l_n value for the corresponding (d,p) transition has been identified are shown in Fig. 5. Except for the transition at 5643 keV, the reduced gamma-ray widths are larger for those final states which are also populated by $l_n=1(d,p)$ transitions, than for those populated by $l_n=3(d,p)$ transitions. The ratio of the average reduced widths for these two classes of transitions is $\langle\Gamma_\gamma/E^3\rangle_{l=3}/\langle\Gamma_\gamma/E^3\rangle_{l=1}=0.12\pm0.08$. This effect has been discussed for the thermal spectrum[16] of K^{40} and recently for the thermal spectrum[5] of Co^{60}. A possible explanation for this effect and for its persistence at the resonance has been proposed by Lynn and Lane.[17] These authors point out that contributions to the radiative matrix element may be significant for the channel region of phase space. There are two terms involved, one of which displays a resonance behavior and the other does not. Physically, these correspond to the interaction between the system and the electric dipole field after the neutron has undergone resonant scattering in the first case, or is incident or has undergone potential scattering in the second case.

The contribution from the resonance channel will be large for those states that have large neutron widths, e.g., for the 132-eV resonance in Co^{59}. In addition, in the region near the maxima in the s-wave neutron strength function, this contribution will be large for those final states that have large components of the single-particle p state. These are the states that exhibit $l_n=1$ deuteron stripping patterns.

A more detailed prediction[18] from the direct-capture model is that, within the subset of states with $l_n=1$, the reduced radiative widths should be related to the (d,p) widths. The size of this effect is measured by the correlation coefficient

$$\rho=\frac{\sum_i(x_i-\bar{x})(y_i-\bar{y})}{[\sum_i(x_i-\bar{x})^2\sum_i(y_i-\bar{y})^2]^{1/2}},$$

[16] A. M. Lane and J. E. Lynn, Nucl. Phys. **17**, 586 (1960).
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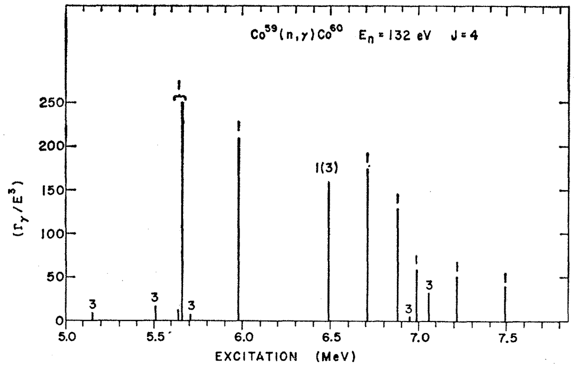
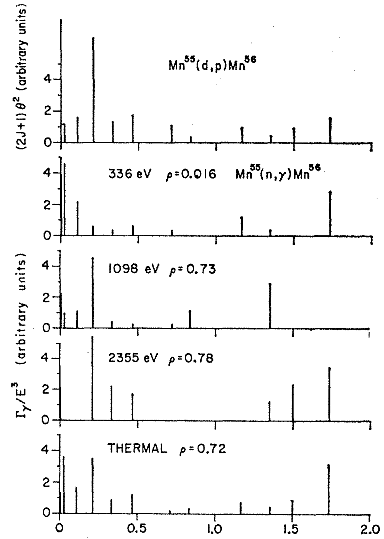


FIG. 5. The correlation between the reduced widths and the values of l_n for the final states in Co^{60}. The number in parenthesis is a possible alternative value of l_n.

where x_i and y_i are the reduced gamma and (d,p) widths for the ith level. The correlation coefficient for Co^{60} is -0.043; i.e., there is no significant effect.

For the $Mn^{55}(n,\gamma)Mn^{56}$ reaction, Fig. 6 compares the reduced widths for the $l_n=1$ transitions with the reduced neutron (d,p) widths. As in the case of the Co^{59} resonance the 336-eV resonance in Mn^{55} displays no significant correlation. On the other hand, there appears to be significant correlation (>70%) for the thermal, 1098-, and 2355-keV resonances. It must be stressed that the correlation coefficient is not sensitive to the detailed nature of the intensity distribution in these three cases, but merely reflects the gross structural feature corresponding to the predominance of the transition to the 207-keV state. As is revealed in the (d,p) strengths, this state carries the largest fraction of the single-particle p state. Moreover, averaging the three spectra, which individually exhibit significant correlation, increases the correlation to greater than 85%. This result is shown in Fig. 7.

FIG. 6. The reduced widths for the $l_n=1$ transitions in manganese compared with the reduced neutron (d,p) widths.



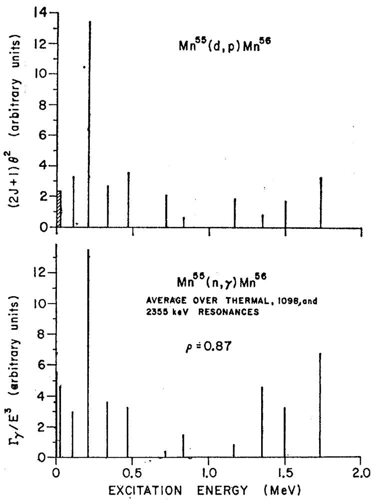


FIG. 7. Comparison between the reduced neutron (d,p) widths and the reduced widths for the $l_n=1$ transitions for manganese, averaged over the spectra for thermal energy and the 1098- and 2355-eV resonances.

It has been well-established that partial radiative widths exhibit independent fluctuations consistent with a random-matrix description of compound-nucleus formation.[19] Since the radiative widths observed for a given resonance represent a finite sampling of distributed quantities, it is necessary to examine the statics of the correlation coefficient. Figure 8 shows the distribution of the correlation coefficient for $N=11$ independently distributed variates. The probability of observing a correlation as large as 85% for independent samples is only 0.1%.

It is interesting to see to what degree these results are consistent with the detailed predictions of the direct-capture model. The radiative transition strength to a final state of spin J_f from capture in a target of spin J_i is given by[20]

$$(2J_f+1)\sum_{J_r=J_i\pm 1/2}\lambda_r(2J_r+1)\left[2\begin{Bmatrix}\frac{3}{2} & \frac{1}{2} & 1\\ J_r & J_f & J_i\end{Bmatrix}S_{3/2}-\sqrt{2}\begin{Bmatrix}\frac{1}{2} & \frac{1}{2} & 1\\ J_r & J_f & J_i\end{Bmatrix}S_{1/2}\right]^2,$$

where J_r is the spin of the capture state, $S_{1/2}$ and $S_{3/2}$ are the stripping amplitudes for the $p_{1/2}$ and $p_{3/2}$ components of the final state, and λ_r is the relative contribution from each intermediate spin state. For equal capture in both spin states $\lambda_{J_i+\frac{1}{2}}=\lambda_{J_i-\frac{1}{2}}$ and the expression reduces to $(2J_f+1)[S_{3/2}{}^2+S_{1/2}{}^2]$, which is just the (d,p) strength, if spin-orbit coupling is neglected.

In resonance capture, only one spin state contributes and the relationship between stripping strengths and partial radiative widths is no longer simple. Table IV compares the calculated stripping strengths and the partial radiative widths in the case of the Mn^{55} target for those spin states that can be populated by $E1$ radiation. As can be seen from this table, the correlation in individual resonances can be significantly reduced by either the fluctuations in spin factors or by interference between the $S_{1/2}$ and $S_{3/2}$ amplitudes.

TABLE IV. Comparison of (d,p) and (n,γ) intensities.

J_f	(d,p)	(n,γ) $J_r=3^-$	$J_r=2^-$
4^+	$9S_{3/2}{}^2$	$9S_{3/2}{}^2$	0
3^+	$7(S_{3/2}{}^2+S_{1/2}{}^2)$	$(7/9)[\sqrt{5}S_{3/2}-2S_{1/2}]^2$	$(7/9)[2S_{1/2}+\sqrt{5}S_{1/2}]^2$
2^+	$5(S_{3/2}{}^2+S_{1/2}{}^2)$	$(5/9)[\sqrt{2}S_{1/2}-\sqrt{7}S_{1/2}]^2$	$(5/9)[\sqrt{7}S_{1/2}+\sqrt{2}S_{1/2}]^2$
1^+	$3S_{3/2}{}^2$	0	$3S_{3/2}{}^2$

From the work of Schiffer *et al.*,[21] the $2p_{1/2}$ state is assigned to be approximately 2 MeV higher in excitation than the $2p_{3/2}$ state in this region, so the $S_{1/2}\ll S_{3/2}$ for the lower lying excitations. One simple explanation for the lack of correlation in the 330-eV resonance would be that the 207-keV state have $J_f{}^\pi=4^+$. In this case, since $J_r{}^\pi=2^-$, the transition is not allowed and the partial radiative width vanishes. This state carries the largest fraction of the single-particle p-wave strength, and its contribution to the correlation is dominant. For the $J^\pi=3^-$ resonance, the relationship for $J_f{}^\pi=4^+$ states is not affected. The effect of the spin factors on the more weakly populated levels will lessen, but not destroy, the correlation. In the case of Co^{60}, the effect of the fluctuations due to the spin dependence will have a greater effect on the observed correlation since there is no single dominant (d,p) transition. In addition, in the regions of higher excitation, above 1500 keV, significant $S_{1/2}$ contributions may occur; and these further destroy the correlation.

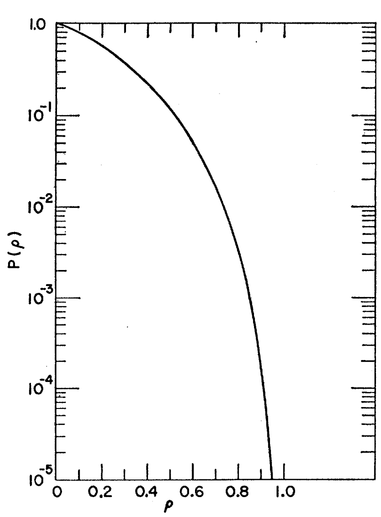


FIG. 8. The integral covariance distribution for a sample consisting of $N=11$ independently distributed variates.

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The remaining case to be discussed is that of the thermal spectrum of Mn^{56}. The ratio of capture in the two-spin state at thermal energies has been measured[22] to be $\sigma_{J=3}/\sigma_{J=2}=0.96$. Since the relative contributions from both spin states is roughly equal, a high degree of correlation might be expected in this case. However, Coté and Bollinger[23] have shown that interference exists between the partial radiative cross sections of two or more resonances. It is highly possible that the observed widths at thermal energies are affected by such interference effects, thus again weakening the correlation. It can be concluded therefore, that the results observed in this work may be encompassed within the framework of a direct-capture model. A more quantitative evaluation can only be made when further information regarding the spins and stripping amplitudes of the final states are obtained.

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Violation of Seniority in the Reaction $^{43}Ca(d,p)^{44}Ca$

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The reaction $^{43}Ca(d,p)^{44}Ca$ has been studied at 8.50- and 4-MeV bombarding energies. In the higher energy experiment, proton angular distributions were measured for 31 transitions, by means of the Aldermaston multiangle spectrograph. The l_n values and spectroscopic strengths were obtained from a distorted-wave analysis of the angular distributions. Energy levels were determined in the 4-MeV experiment by detecting the protons in the Copenhagen heavy-particle spectrograph. A ground-state Q value of 8920 ± 10 keV was obtained. The spectroscopic strengths were analyzed in terms of the non-energy-weighted sum rules for multipole orders $\lambda=0$, 1, and 2. Eight $f_{7/2}$ transitions were observed, compared with four predicted by the seniority-coupling scheme.

I. INTRODUCTION

THE configuration $(f_{7/2})^4$ with $T=T_z=2$ is one of the simplest cases in which the angular-momentum quantum numbers are not sufficient for characterizing the states allowed by the Pauli principle. A study of the neutron-transfer reaction $^{43}Ca(d,p)^{44}Ca$ therefore may give valuable information on the coupling-scheme situation in ^{44}Ca.[1] The only previous work on the $^{43}Ca(d,p)^{44}Ca$ reaction[2] gave information on the ^{44}Ca energy levels; in the present experiment the l_n values and spectroscopic strengths were measured in addition to level energies.

II. EXPERIMENTAL METHOD, RESULTS, AND ANALYSIS

The ^{43}Ca target was prepared in the Copenhagen isotope separator[3] to an isotopic purity of $\gtrsim 99\%$.

The angular-distribution measurements were made at the Aldermaston tandem accelerator at a bombarding energy of 8532 keV. The multiangle spectrograph of Middleton and Hinds[4] was used for momentum analysis of the reaction protons. The over-all energy resolution was 15 keV. A proton spectrum is shown in Fig. 1, and the measured angular distributions are presented in Figs. 3–6.

The cross-section scale in mb/sr was established by measuring the ratio of (d,p) yield to (d,d) yield at a bombarding energy of 8522 keV and by using the elastic-scattering cross sections of Ref. 3. It was assumed that the (d,p) cross sections at 8532 and 8522 keV were identical. The estimated uncertainty on the cross-section scale is $\pm25\%$.

A more detailed description of the experimental procedures may be found in a previous paper.[5] Energy levels in ^{44}Ca were also determined from the $^{43}Ca(d,p)$ process at about 4-MeV bombarding energy. The deuterons were accelerated in the Copenhagen 4.5-MeV

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