Decay of the Zn^{71} Isomers*

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The decay of the Zn^{71} isomers has been reinvestigated using scintillation counter techniques. Samples of enriched Zn^{70} were exposed to reactor neutrons. Gamma rays of 120±5, 390±10, 510±5, 680±20, 920±10, 1120±10, and 1630±10 kev were found in the decay of the 2.45±0.10-min isomer. A beta ray group to the ground state of Ga^{71} with energy of 2.61±0.05 Mev was found from the 2-min isomer. Gamma rays of 390±5, 490±5, and 610±5 kev were found to be in cascade in the 4.0±0.1-hr isomer and to be fed by a single beta group of 1.46±0.05 Mev. A decay scheme for the Zn^{71} isomers is proposed.

INTRODUCTION

THE existence of an isomeric state in Zn^{71} was reported by LeBlanc *et al.*[1] Their measurements indicated that both isomers decayed only to excited states of undetermined spins and parities in Ga^{71}. They found gamma rays of 0.12, 0.91, 0.51, and 1.09 Mev in the decay of the 2-min isomer and of 0.38, 0.49, and 0.61 Mev in the decay of the 4-hr isomer. The 4-hr gamma rays were shown to be in cascade. They also found beta rays with a maximum energy of 2.4±0.2 Mev with the 2-min isomer and this energy did not appear to change when coincidence with the 0.51-Mev gamma ray was required. Beta rays with maximum energy of 1.5±0.1 Mev were found with the 4-hr decay.

It is expected on the basis of the nuclear shell model that the Zn^{71} isomers have J^{π} values of $1/2^-$ and $9/2^+$ as the Zn^{69} isomers appear to have. The decay scheme of the Zn^{69} isomers is shown for reference in Fig. 1.[2] No excited states in Ga^{69} are populated in the decay of either of the Zn^{69} isomers, although there are several states which it would be energetically possible to reach. Although the assignment of the shell-model values to the Zn^{71} isomers could not be made definite, it was generally assumed that the 2-min isomer was the $\frac{1}{2}^-$ state and the 4-hr isomer was the $9/2^+$ state.[2] This assignment did not explain the apparent absence of an allowed beta transition from the 2-min isomer to the $\frac{3}{2}^-$ ground state of Ga^{71}. The investigation of the decay of the Zn^{71} isomers reported here supports this assumption and clarifies some of the level structure in Ga^{71}. A preliminary version of this work was reported at the January, 1961 meeting of the American Physical Society.[3]

The scintillation spectrometer techniques employed in these experiments differ from those described previously[4] in that a 128-channel analyzer was used in some of the measurements instead of the 20-channel analyzer and that NaI crystals with better resolution ($\leq$8% Cs^{137}) were used generally except in some of the coincidence measurements. An anthracene crystal[5] of 2-in. diameter, 1-in. thickness, and 12% resolution (Cs^{137}) was used to take the 2-min beta ray spectra. All the results presented here were taken with samples of either Zn metal or oxide enriched to 59.3% Zn^{70}.[6] Gamma-ray calibration sources of Tm^{170}, Co^{57}, Hg^{203}, Au^{198}, Cu^{64}, Cs^{137}, Zn^{65}, Co^{60}, and Na^{24}, and beta-ray calibration sources of Cs^{137}, Au^{198}, Cu^{66}, and Al^{28} were used.

EXPERIMENTAL RESULTS

A. Gamma Rays from 2-Minute Isomer

Figure 2 shows the gamma-ray spectrum of 2-min Zn^{71} as taken with a 3-in.×3-in. NaI crystal. The sample in this case consisted of about 10 mg of Zn^{70} and was exposed for 3 min to the reactor neutron flux and then transferred to an unexposed polyethylene tube before counting. Figure 3 shows the lower energy gamma rays with greater dispersion and was taken with a 2 in.×2 in. NaI crystal. The sample in this case was again about 10 mg of Zn^{70} metal. It was exposed for 2 min and was retained in the tube in which it was exposed. The impuri-

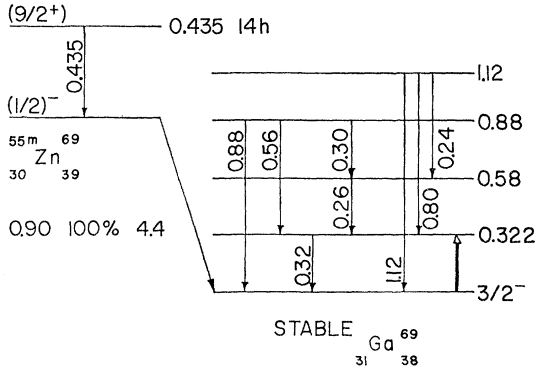

FIG. 1. Decay scheme of Zn^{69} isomers according to the nuclear data sheets.

* Supported in part by the U. S. Atomic Energy Commission and the National Science Foundation.

[1] J. M. LeBlanc, J. M. Cork, S. B. Burson, Phys. Rev. **97**, 750 (1955).

[2] Nuclear Data Sheets, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[3] T. T. Thwaites and W. W. Pratt, Bull. Am. Phys. Soc. **6**, 50 (1961).

[4] R. G. Cochran and W. W. Pratt, Phys. Rev. **109**, 878 (1958); **113**, 852 (1959).

[5] Both the anthracene crystal and the NaI crystals were obtained from Harshaw Chemical Company, Cleveland, Ohio.

[6] Obtained on loan and sale from the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

TABLE I. Energies and intensities of 2.5-min isomer gamma rays.

Energy in kev	120±5	390±10	510±5	680±20	920±10	1120±10	1630±10
Intensities in percent relative to 510 kev	7±3	10±2	100	≤2	24±2	10±2	1.1±0.3

ties in the polyethylene do not contribute any peaks in this energy region, only a continuum of counts. In both cases a $\frac{1}{4}$-in. Al beta ray shield was placed in front of the crystal and the long-lived activity was subtracted.

The half-lives of all the gamma rays except the 680-kev one were measured and found to be about 2.5 min. The 680-kev gamma ray was confirmed by gamma-gamma coincidence experiments. The 510- and 920-kev gamma rays can also be seen in natural Zn. Their intensities were found to vary according to the amount of Zn^{70} present when using weighed samples of natural and enriched Zn. Table I lists the energies and intensities of the 2-min isomer gamma rays. The intensities were inferred from spectra taken with a 2-in.×2-in. crystal, using the response curve method, and a 3-in.×3-in. crystal, using the photopeak method. The two measurements agreed.

The 390, 680, and 1630-kev gamma rays were not observed by LeBlanc *et al.*[1] The 120- and 390-kev gammas were found to be in coincidence with beta rays, thus showing that neither of them can be an isomeric transition. A gamma ray with the same energy as the 390-kev gamma, within experimental error, occurs in the decay of the 4-hr isomer. It thus appears to be the only transition in common between the two decays.

B. Gamma-Gamma Coincidences in the 2-Minute Isomer

Gamma-gamma coincidence measurements were made with a fast-slow coincidence circuit of $2\tau=0.5$ μsec gating the 20-channel analyzer. In order to increase the solid angles no collimation was used with the crystals. Beta ray shields of $\frac{1}{4}$-in. Al were employed. In all cases the exposures were adjusted so that the accidentals were only a few percent of the real coincidence rate. In the cases in which real coincidences were observed, runs were also made with the single-channel analyzer gate raised in order to show that the coincidences were due to the chosen photopeak and not the Compton tail of some higher energy gamma ray. The gamma-gamma coincidences found by this procedure were 0.51–1.12, 0.92–0.68, and 0.39–0.12 Mev.

On the basis of coincidence, energy, and intensity measurements the 2-min isomer gamma rays imply states in Ga^{71} at excitations of 0.39, 0.51, 0.92, and 1.63 Mev. At least three of these states, namely those of 0.51, 0.92, and 1.63 Mev must by populated by beta transitions in the decay of the 2-min isomer.

C. Beta Rays from 2-Minute Isomer

An anthracene crystal was used to take the beta-ray spectra presented as Fermi plots in Figs. 4, 5, and 6. The standard spectra in Fig. 4 were taken in order to establish confidence in the techniques employed. The accepted values of the end points for Au^{198}, Cu^{66}, and Al^{28} are 0.96, 2.63, and 2.87 Mev, respectively.[2] The largest deviation from these values is seen to be about 20 kev. The smaller curvature near the end point of the Cu^{66} spectrum as compared to those of Au^{198} and Al^{28} is attributed to the latter having coincident gamma rays. The Fermi plot in Fig. 5 was taken during the same run as those in Fig. 4 and was calculated using the same energy calibration.

The sources used for the spectra in Figs. 5 and 6 consisted of about 1 mg of Zn^{70} suspended in collodion. An exposure of 3 min was used in order to saturate the activity. In the case of the singles spectrum of Fig. 5 it was necessary to delay counting until 1 min after exposure to permit the decay of an unidentified contaminant in the sources with a half-life of about 12 sec. This contaminant emitted higher energy beta rays than those from the 2-min isomer of Zn^{71}. Backgrounds from long-lived activities and a collodion blank were subtracted.

The spectrum in Fig. 5 is found to have an end point of 2.61±0.05 Mev. It is to be noted that the points in Fig. 5 deviate from the straight line at a higher energy than do those for Cu^{66} in Fig. 4. This break at $E=4.5$

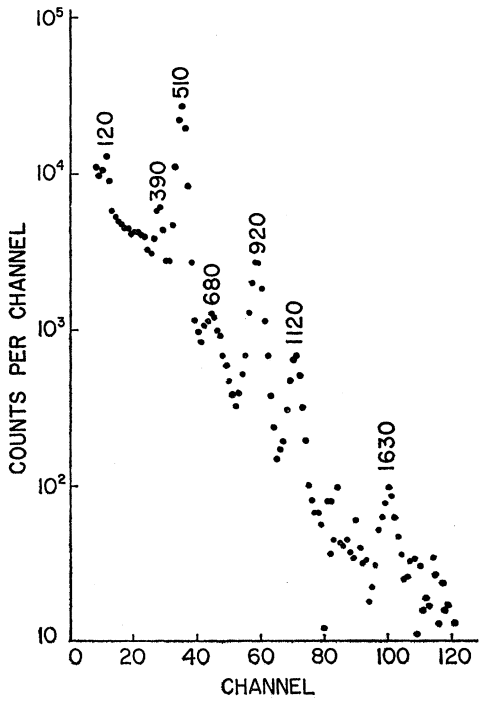

FIG. 2. Singles gamma ray spectrum of the 2-min isomer of Zn^{71}.

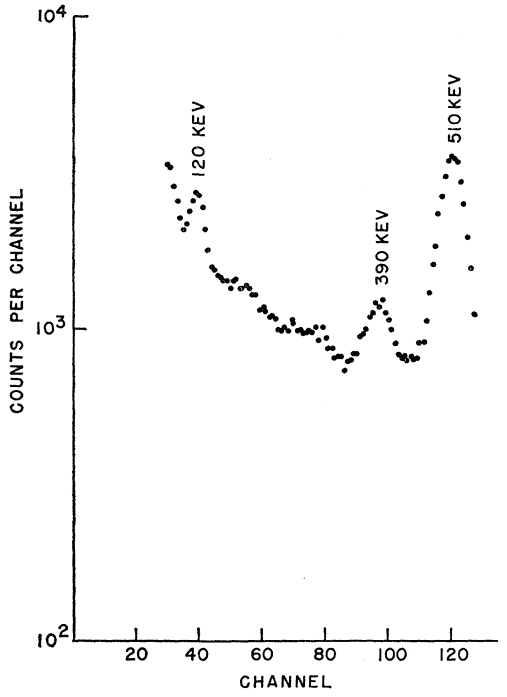

FIG. 3. Singles gamma ray spectrum of the lower energy gamma rays of the 2-min isomer of Zn^{71}.

is attributed to the presence, in the decay, of a weak (14%) interior beta group with end point of $E=5.1$. The break due to this group is apparently displaced to a lower energy because it is such a weak group.

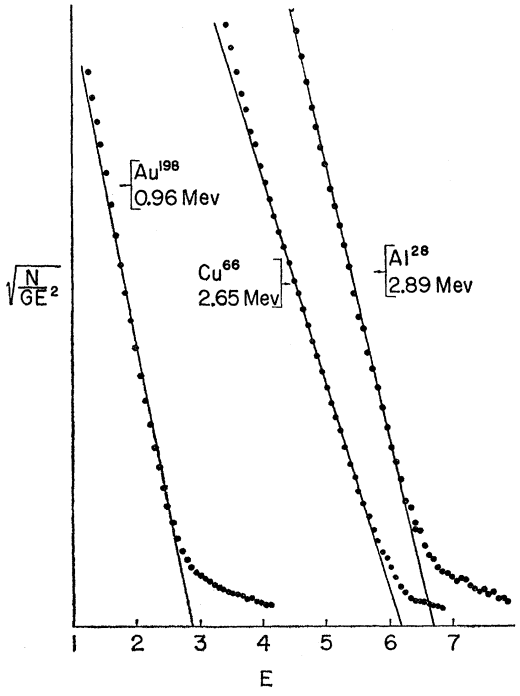

FIG. 4. Singles Fermi plots of calibration beta spectra from Au^{198}, Cu^{66}, and Al^{28}.

The half-life displayed by these beta rays was found to be 2.45±0.10 min and this value was taken to be the half-life of the 2-min isomer since the beta activity could be followed for several more half-lives than the gamma activity. Figure 6 shows a Fermi plot of beta rays in coincidence with 0.51-Mev gamma rays. Because of the very low counting rates encountered in this experiment, the data from 3 runs have been combined in 5-channel intervals. The result is an end point near 2.2 Mev, or about 0.4 Mev lower than for the singles spectrum. It thus appears that the end point of the singles spectrum applies to a transition to the ground state of Ga^{71} rather than to the 0.51-Mev state. This conclusion was confirmed and the intensity of the beta group populating the 0.51-Mev state relative to the total number of decays was determined by measuring the total beta-ray

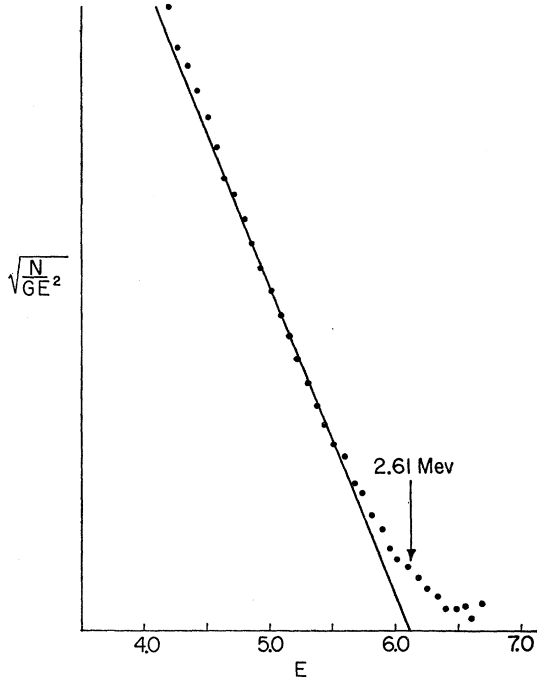

FIG. 5. Singles Fermi plot of beta rays from the 2-min isomer of Zn^{71}. The surplus of counts in the energy region below $E=\sim4.5$ is probably due to a weak (~14%) interior beta group.

intensity and the intensity of the 0.51-Mev gamma ray simultaneously. A sample of Au^{198} which has essentially one gamma per beta, was measured in the same geometry. A correction was made for the difference in sensitivity of the NaI crystal to the 412- and 510-kev gammas, but it was assumed that the sensitivity of the anthracene crystal was independent of energy. Subtractions were made for contributions from the collodion backing and from longer lived activities. The result of repeated measurements was that the 0.51-Mev state was populated in 14±2% of the decays. The energies and intensities of the other interior beta-ray groups were inferred from gamma-ray measurements and are

TABLE II. 2.5-min isomer beta groups.

Energy in Mev	2.61±0.05	2.10±0.06	1.69±0.06	0.99±0.07
Intensity in percent of decays	82±4	14±2	3±1	1.7±1
$\log_{10} ft$	5.1	5.4	5.7	5.1

listed along with their logft values in Table II. The logft values are reasonable for allowed transitions in all cases except possibly the 1.69-Mev group.

D. Gamma Rays from the 4-Hour Isomer

Figure 7 shows the gamma-ray spectrum of 4-hr Zn^{71} as taken with a 2-in.×2-in. NaI crystal. The sample consisted of about 10 mg of Zn^{70} metal and was exposed for 10 min and then allowed to decay for 20 min before counting was started. The energies of the 4-hr gamma rays are 390±5, 490±5, and 610±5 kev. In Fig. 7 the valley between the 390- and 490-kev peaks is largely filled by the 440-kev isomeric transition of Zn^{69}. A response curve analysis of the 4-hr gamma-ray spectrum showed that all three of the 4-hr gammas have approximately equal intensities. Coincidence measurements

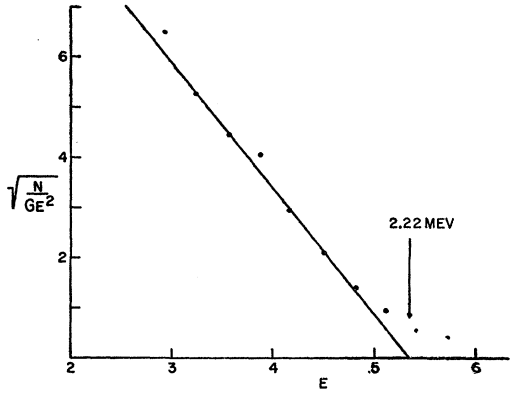

FIG. 6. Fermi plot of beta rays in coincidence with 0.51-Mev gamma rays.

confirmed that all three of these gammas are in cascade. A search was made for crossover gamma rays and an upper limit of a few percent of the intensity of the low-energy gammas was set on them. The decay of the 610-kev gamma was followed for several days and a half-life of 4.0±0.1 hr deduced.

Of the six possible orders for the 4-hr gamma cascade, four are eliminated if one assumes that the 390-kev gammas in the two isomers are identical. The 390-kev transition can then only be fitted in as the bottom member of the cascade. Angular correlation measurements have been unable to resolve the remaining ambiguity.[7]

E. Beta Rays from the 4-Hour Isomer

Attempts to observe singles beta-ray spectra of 4-hr Zn^{71} were not successful due to intense beta rays from

[7] H. J. van den Bold (private communication).

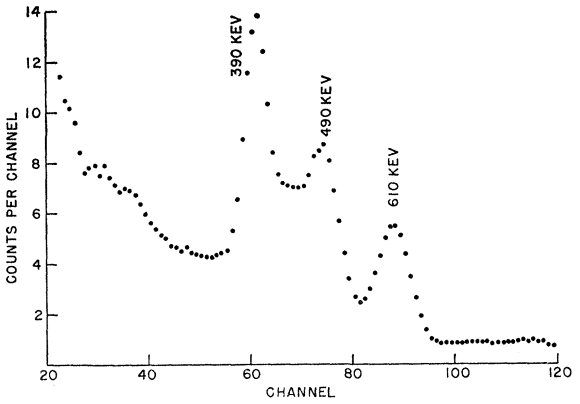

FIG. 7. Singles gamma-ray spectrum of the 4-hr isomer of Zn^{71}.

Zn^{69} which was a contaminant in our sources.[8] Calculations indicate that the 4-hr betas were about 2% as intense as the Zn^{69} betas immediately after a short exposure and rose to a maximum of about 7% about 3 hr after exposure. After this time the relative intensity dropped again due to the 14-hr Zn^{69} isomer feeding the ground state. Betas were observed beyond the end point of the Zn^{69} spectrum, but they did not yield a well-defined half life and a spectrum taken at the optimum time

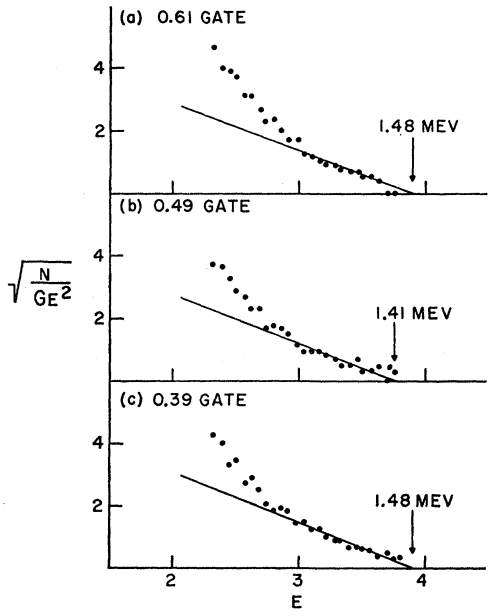

FIG. 8. Fermi plots of beta rays in coincidence with the 0.61, 0.49, and 0.39-Mev gamma rays, respectively, of the 4-hr isomer of Zn^{71}. The break in the curves at $E=\sim 2.8$ is attributed to the presence of a large amount of Zn^{69} in the source and is discussed in the text.

[8] It is to be noted that the Zn^{69} isomers obey the empirical isomeric ratio rule which states that the isomer with spin closer to the spin of the capture state will be more abundantly produced in thermal neutron capture. See, for example, E. der Mateosian and M. Goldhaber, Phys. Rev. **108**, 766 (1957). Thus the 55-min isomer of Zn^{69} is produced in about 10 times the amount as the 14-hr isomer and the relative gamma-ray intensities of Fig. 7 are not indicative of the relative beta-ray intensities.

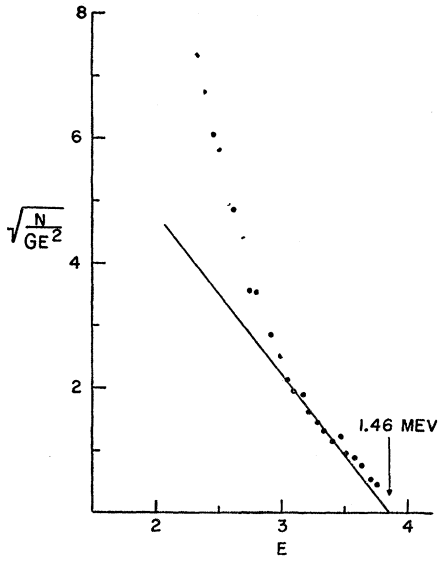

FIG. 9. Fermi plot of beta rays from 4-hr isomer of Zn^{71}.

of 3 hr after exposure did not yield an acceptable Fermi plot. Therefore, only coincident beta spectra of 4-hr Zn^{71} are presented. Figures 8(a), (b), and (c) show Fermi plots of the beta rays in coincidence with the 0.61, 0.49, and 0.39-Mev gamma rays, respectively. Figure 9 shows a Fermi plot made by adding all the data for the three spectra in Fig. 8. The breaks in these curves at $E=2.8$ are attributed to accidental coincidences from Zn^{69} betas. Although accidentals were measured and subtracted, they were taken up to an hour later and no decay correction was applied to them. The end points of the spectra in Fig. 8 are sufficiently similar to show that the cascade is fed by a single beta transition to a state at 1.49 Mev in Ga^{71}. The end point of 1.46±0.05 Mev from Fig. 9 agrees with the average of the three end points in Fig. 8 weighted by the number of gates. The logft value for this transition is 5.9 assuming that the unobserved isomeric transition is indeed negligible. This logft value could indicate either an allowed or first-forbidden decay.

F. Cross-Section Ratio

An estimate of the cross-section ratio for the production of the two isomers by thermal neutrons was made by comparing the intensities of the 510-kev gamma in the 2-min decay and the 390-kev gamma in the 4-hr decay. A sample of about 10 mg was exposed for 1 min. The 510-kev decay was followed and extrapolated back to the time of removal from the reactor. The 390-kev intensity was measured after the 2-min activity had died away. The isomeric cross section ratio was then computed using the intensities and half-lives quoted earlier. The result was that the 2-min isomer is formed in 83±10% of the captures.

CONCLUSION

Figure 10 shows the decay scheme of the Zn^{71} isomers proposed on the basis of the experiments described in this article. A strong ground-state transition from the 2-min isomer is seen to be present, thus supporting the interpretation of this isomer as the $\frac{1}{2}^-$ state. This interpretation is also supported by the allowed decay to the 0.51-Mev state which, on the basis of Coulomb excitation experiments,[9] almost certainly has negative parity. Although the 390- and 120-kev cascade gammas from the 0.51-Mev state were not observed in the Coulomb excitation experiments, this is not a serious objection to the decay scheme in Fig. 10. The 120-kev radiation would have been completely masked by extraneous gammas. An upper limit of approximately 5% (relative to the 510-kev gamma) of 390-kev radiation could have been present.[10] This is not in serious disagreement with the intensities of 7% and 10% for the cascade radiations listed in Table I, but may imply a weak beta group to the 0.39-Mev state. Such a group might also resolve the apparent difference in intensities between the cascade gammas.

The isomeric cross section ratio is also consistent with the 2-min isomer being the $\frac{1}{2}^-$ state since in the case of thermal neutron capture in Zn^{70} the capture state can only have spin $\frac{1}{2}$.[8]

An isomeric transition of 340±100 kev is implied by the decay scheme of Fig. 10. If this transition has $M4$ character, as does the analogous transition between the Zn^{69} isomers, it should be present with an intensity

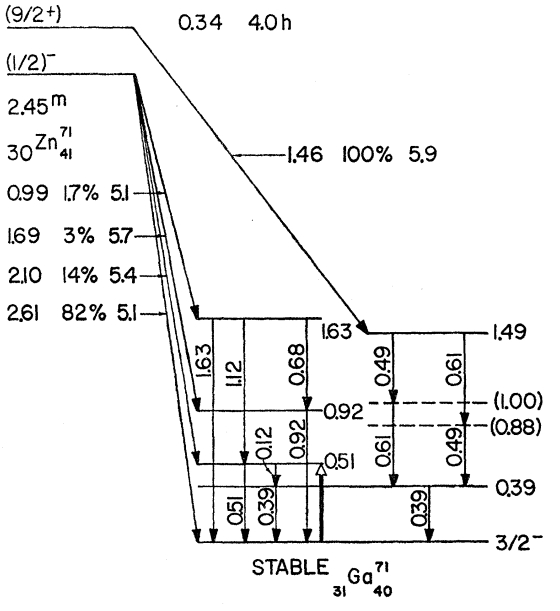

FIG. 10. Proposed decay scheme of Zn^{71} isomers.

[9] L. W. Fagg, E. H. Geer, and E. A. Wolicki, Phys. Rev. **104**, 1073 (1956).
[10] E. A. Wolicki (private communication).

of the order of 10% of the 4-hr gamma rays. No such transition has been observed.

ACKNOWLEDGMENTS

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Differential Cross Sections for $(n,n'\gamma)$ Reactions in Several Nuclei*

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Differential cross sections for the production of gamma rays by inelastic neutron scattering have been measured and compared with the predictions of the statistical model, employing a diffuse surface complex potential to represent the neutron-nucleus interaction. Transitions have been observed in Mg^{24}, Mn^{55}, Fe^{56}, and Pb^{206}. Predictions of the statistical model were in good agreement with total $(n,n'\gamma)$ cross sections measured for first-excited state transitions in Fe^{56} and Mg^{24}, and in agreement with measured transition rates from the second and third excited states of Fe^{56}. Angular distributions for Mn^{55} transitions are consistent with recent spin assignments for the second and third excited states, but the comparisons of the measured and calculated total cross sections are not as satisfactory as the comparisons in Fe^{56} and Mg^{24}.

INTRODUCTION

DIFFERENTIAL cross sections for the production of gamma rays from inelastic neutron scattering have recently been measured for several nuclei,[1–5] and these measurements have been compared to the expectations of the statistical model for nuclear reactions.[6] Within the framework of this model the differential cross sections depend only upon the form of the potential chosen to represent the neutron-nucleus interaction. The comparisons mentioned showed good agreement with the assumption of the diffuse surface potential of Beyster *et al.*[7] Comparisons of measured and calculated cross sections were also made[3,5] for the assumption of a complex square-well potential, the diffuse surface potential of Emmerich and also that of Campbell *et al.* The success of the diffuse well model in representing the measurements led Day and Walt[2] to suggest that these reactions might serve as a useful spectroscopic tool for bound states of nuclei.

The purpose of the measurements reported here was to further test the $(n,n'\gamma)$ reactions with respect to their use in nuclear spectroscopy. This was done by exciting states which produced gamma-ray transitions between states of known spin and parity. The length of time required to study a particular transition limited the number of nuclei studied to four, and the number of gamma-ray lines studied as a function of angle to six. The four nuclei chosen for study were selected to cover a large range of mass number. In selecting the nuclei to test the statistical model, interest centered on even-even nuclei. Consideration of the production cross sections, gamma-ray energy, atomic density, isotopic purity, and gamma-ray self-absorption influenced the choice of nuclei. Among transitions selected were those from the first-excited states to the ground states of Fe^{56}, Mg^{24}, and Pb^{206}, and the second to first excited state transition in Pb^{206}. For these transitions differential cross-section measurements were made at five angles between 0° and 90°. Two other transitions in Fe^{56}, one between the second and first excited states and the other between the third and first excited states were also observed at 90°.

Transitions from the second and third excited states of Mn^{55} were studied in order to provide additional information relevant to the determination of the spins of those states.

EXPERIMENTAL APPARATUS AND PROCEDURE

Neutrons of approximately 2.9 Mev were produced at a 180-kev deuteron accelerator via the $D(d,n)He^3$ re-

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[3] M. Hosoe and S. Suzuki, J. Phys. Soc. Japan **14**, 699 (1959).

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