Branching of Transitions in Some Mirror Nuclei*

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The possibility of branching in the decays of Na^{21}, Mg^{23}, Al^{25}, Si^{27}, S^{31}, and Ca^{39} has been investigated using NaI(Tl) scintillation detectors. The nuclear gamma rays emitted as a result of branching transitions were detected in coincidence with the accompanying positron annihilation radiation. Branching was found to the first excited states of the daughter nuclei in the decays of Na^{21}, Mg^{23}, and S^{31}, with intensities (compared to the total decay) of 2.2, 9.1, and 1.1%, respectively. The decays of Al^{25}, Si^{27}, and Ca^{39} were found to have no detectable branching to the lower excited states of the daughter nuclei, and upper limits of less than one percent were placed on the branching ratios for such branches. The lack of branching in the decay of Al^{25} to the 0.98-Mev level of Mg^{25} favors a unified model description for the nuclear states involved.

INTRODUCTION

In the past several years, the decays of many mirror nuclei have been studied by means of magnetic spectrometers in an effort to reduce the uncertainties of the comparative lifetimes for these decays. The mirror nuclei in the region $19 \leq A \leq 39$ have been studied using a 180° magnetic spectrometer,[1] and further studies have been made for $A=15$, 35, and 39 with a thin lens magnetic spectrometer.[2–4] These determinations have increased the precisions of the end-point energies to the extent that the comparative lifetimes of the decays are known to within about five percent, using the values of the most recent half-life determinations,[4–6] and neglecting branching in the decays. Comparisons of matrix elements calculated from different nuclear models for these positron decays can now be made with the experimentally determined values, in an effort to determine the accuracy of the descriptions of the models. However, if there exists more than one beta-decay branch, the half-life that should be used in the computation of the comparative lifetime is not the total half-life, but is the half-life for the ground state to ground-state transition.

Up to the time of this study, little information was available on the presence of branching in the decay of mirror nuclei. Weak branching has been reported in the decays of A^{35},[3] Al^{25},[7] P^{29},[8] and Cl^{33},[9] and an upper limit of about 0.1% has been reported for branching in the decay of Ca^{39}.[4] Thus, it was thought that a more extensive knowledge of branching in the decays of mirror nuclei was needed, and this study was undertaken to estimate the effects of branching in the decays of the mirror nuclei Na^{21}, Mg^{23}, Al^{25}, Si^{27}, S^{31}, and Ca^{39}.

EXPERIMENTAL METHOD

The mirror nuclei studied in this experiment were produced from their respective elements by irradiation in the 45-Mev bremsstrahlung beam of the Iowa State University Synchrotron. The Na^{21} and Al^{25} sources were produced by the $(\gamma,2n)$ photonuclear reaction on Na^{23} and Al^{27}, respectively, while the other activities were produced by the (γ,n) reaction on the most abundant stable isotopes of their respective elements. Contaminant activities did not prove to be of great concern in the experiment, except for the production of Al^{26m}, which was of higher yield than Al^{25} in the photonuclear reactions on Al^{27}. For this case, the result obtained is dependent upon the estimated relative intensities of the two activities which were produced.

Due to the short half-lives involved in the decays studied, and in order to reduce the background during the counting periods, the samples were transported by means of a pneumatic shuttle system a distance of 12 feet from the bombardment position to the shielded counters. The samples were mounted in blocks of balsa wood and were $\frac{1}{2}$ inch thick by $1\frac{1}{8}$ inches in extent. In a single cycle the samples were bombarded for a period of time equal to about three half-lives of the decay under investigation, and were counted for a similar duration. For the shorter lived samples as many as 1000 cycles were used.

The method which was used to observe branching in the positron decays of the mirror nuclei listed above involved the study of the gamma-ray spectra obtained in fast coincidence with annihilation radiation. The usual fast-slow coincidence arrangement with a resolving time of 10^{-8} second was used to gate a 256-channel analyzer. A gamma-ray pulse from one counter was recorded by the analyzer when it was in fast coincidence with an annihilation radiation pulse from the other counter. Unwanted coincidences between the two annihilation radiation photons were prevented by the

* Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
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[1] Roger Wallace and Jasper A. Welch, Jr., Phys. Rev. **117**, 1297 (1960).
[2] O. C. Kistner, A. Schwarzchild, B. M. Rustad, and D. E. Alburger, Phys. Rev. **105**, 1339 (1957).
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[4] O. C. Kistner and B. M. Rustad, Phys. Rev. **112**, 1972 (1958).
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[6] S. E. Arnell, J. Dubois, and O. Almén, Nuclear Phys. **6**, 196 (1958).
[7] D. Maeder and P. Ståhelin, Helv. Phys. Acta **28**, 193 (1955).
[8] H. Roderick, O. Lönsjö, and W. E. Meyerhof, Phys. Rev. **97**, 97 (1955).
[9] W. E. Meyerhof and G. Lindstrom, Phys. Rev. **93**, 949 (1954).

geometrical arrangement of the coincidence counters. These counters, which consisted of NaI(Tl) crystals coupled to RCA 6810A photomultiplier tubes, were placed with their symmetry axes forming the legs of a right angle. The sample was positioned in a brass container placed at the apex of the right angle and was beyond any line connecting any two points in the detection crystals. The container served to stop the positrons within a particular geometrical region, from which annihilation radiation coincidences could not be detected, since the annihilation radiation photons would be emitted in opposite directions. A lead absorber was placed between the crystals to prevent gamma radiation from scattering out of one detection crystal and into the other, which would also result in an unwanted coincidence.

With this arrangement, therefore, the measured coincidence spectrum consisted of gamma radiation resulting from a branch in the decay, if present, with

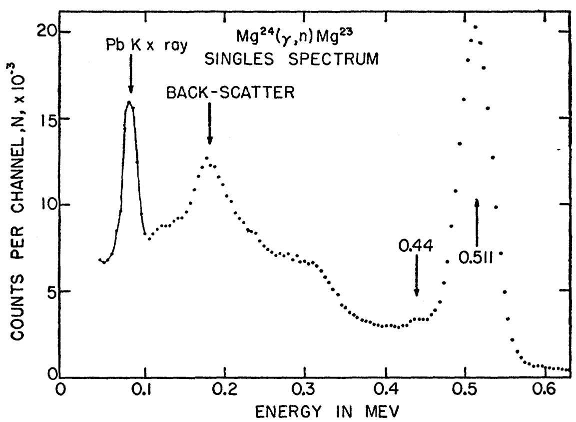

FIG. 1. Singles gamma-ray spectrum obtained from the decay of Mg^{23}.

the additional effects of positron bremsstrahlung, the back-scattering of one annihilation radiation photon, and annihilation-in-flight radiation. With careful analysis of the spectra obtained, the lowest branching ratio which could be detected with this method was estimated to be about 0.2%.

The branching ratio for each branch was calculated from the relative intensities of annihilation radiation and gamma radiation. The number of counts observed per unit time in the photopeak of the annihilation radiation in a singles spectrum is

$$N_{0.511}{}^{(1)}=2N_0\Omega^{(1)}(\epsilon P/T)_{0.511}{}^{(1)},$$

while the number of counts per unit time in the photopeak of a gamma ray in a coincidence spectrum is

$$N_\gamma{}^c=2N_0\beta\Omega^{(1)}\Omega^{(2)}(\epsilon P/T)_{0.511}{}^{(1)}(\epsilon P/T)_\gamma{}^{(2)}.$$

In these equations, Ω is the solid angle subtended by the detector at the source, ϵ is the efficiency of inter-

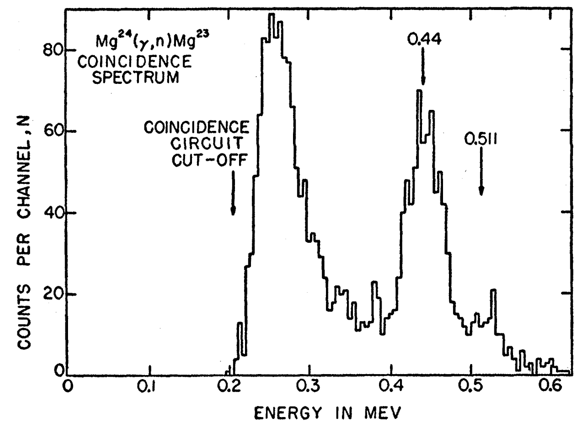

FIG. 2. Coincidence gamma-ray spectrum of the decay of Mg^{23}.

action of the gamma ray with the detection crystal, and (P/T) is the probability that an interacting gamma ray will lose all of its energy in the crystal resulting in a photopeak event. For a given geometry, ϵ and (P/T) can both be expressed as functions of the energy of the gamma ray. The superscripts (1) and (2) refer to the detection channels of the coincidence arrangement. β is the intensity of the branch decay expressed in percentage of total decays. Solving these equations for β gives

$$\beta=\frac{N_\gamma{}^c}{N_{0.511}{}^{(1)}\Omega^{(2)}(\epsilon P/T)_\gamma{}^{(2)}}.$$

The determination of $\Omega^{(2)}$ was made experimentally, using a Na^{22} source, which has a known branching ratio of nearly 100%. The values of the photopeak detection efficiencies which were used throughout the experiment were taken from the calculations of Vegors, et al.[10] Normalization of the counting rates observed in this

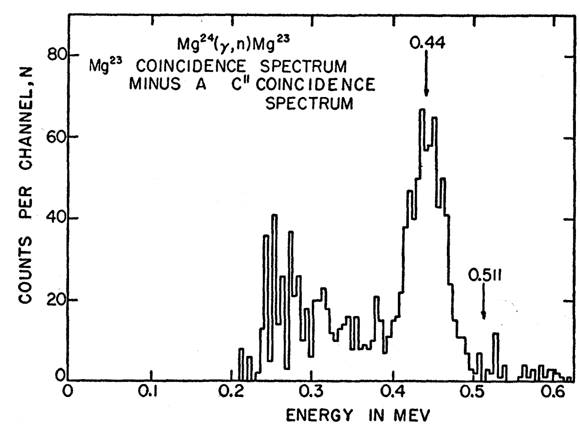

FIG. 3. Coincidence gamma-ray spectrum of the decay of Mg^{23} minus a C^{11} coincidence gamma-ray spectrum.

[10] S. H. Vegors, Jr., L. L. Marsden, and R. L. Heath, U. S. Atomic Energy Commission Report IDO-16370 (U. S. Government Printing Office, Washington, D. C., 1958).

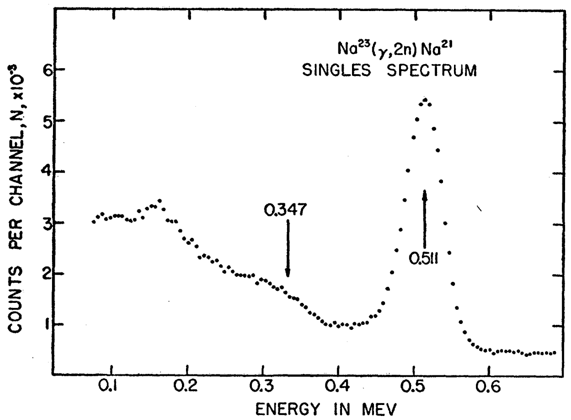

FIG. 4. Singles gamma-ray spectrum obtained from the decay of Na^{21}.

investigation was made to the amount of synchrotron beam dosage given the samples.

RESULTS

Some of the experimental gamma-ray spectra obtained in the investigation are shown in Figs. 1–7. Figure 1 shows a singles gamma-ray spectrum of the decay of Mg^{23}. There is a very slight indication of a gamma ray at an energy of 0.44 Mev corresponding to a transition to the first excited state of Na^{23}. However, an estimate of its intensity is extremely difficult to determine from Fig. 1 since the annihilation radiation peak is so intense. Figure 2 shows a coincidence spectrum of the decay of Mg^{23}, and it is seen that the 0.44-Mev gamma ray is a prominent feature of the spectrum. The apparent peak between 0.2 and 0.3 Mev was thought to be due to the detection of an annihilation radiation photon after it back-scattered from the surrounding shielding. This effect would increase further at lower energies, but the coincidence circuit cutoff causes it to appear like a peak. Figure 3 shows the result of the subtraction of a coincidence gamma-ray spectrum from the decay of C^{11}, for which no branching is known, from the spectrum of Fig. 2, indicating that scattered annihilation radiation was indeed the suspected source of the low-energy prominence in the coincidence spectrum.

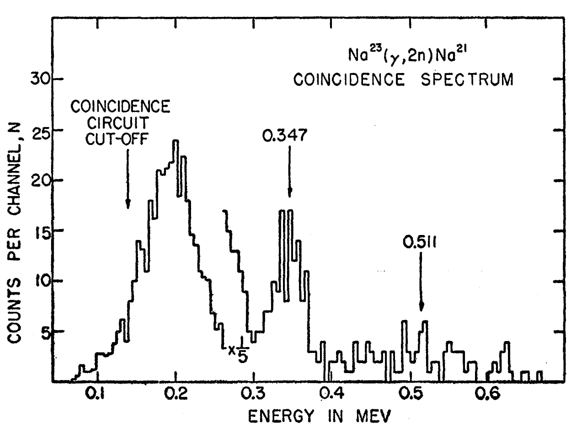

FIG. 5. Coincidence gamma-ray spectrum of the decay of Na^{21}.

Figure 4 shows a singles spectrum from the decay of Na^{21}, in which there is no indication of a branch to the 0.347 Mev first excited state of Ne^{21}. However, the coincidence spectrum of Na^{21} shown in Fig. 5 shows that such a branch is clearly present. The broad peak at 0.2 Mev is also due largely to the detection of scattered annihilation radiation photons.

The singles spectrum obtained from the decay of S^{31} is shown in Fig. 6. There is a slight indication that a branch is present in the decay to the first excited state of P^{31}. Examination of the coincidence spectrum for S^{31} shown in Fig. 7 also indicates that such a branch does occur, although the intensity of the branch is quite weak, accounting for the poor statistics observed.

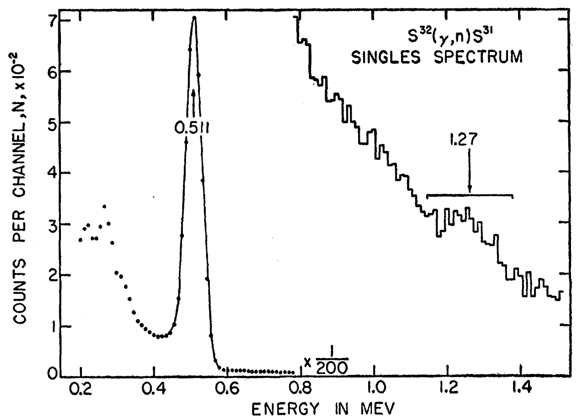

FIG. 6. Singles gamma-ray spectrum obtained from the decay of S^{31}.

The peak at 0.511 Mev and the continuous portion of the spectrum are due to bremsstrahlung-annihilation radiation coincidences.

The spectra obtained in the studies of Al^{25}, Si^{27}, and Ca^{39} are not shown, but they exhibited no indications of branching to the first or second excited states of the daughter nuclei.

Table I shows the results of this experiment, along with the comparative lifetimes, or *ft* values, calculated from the tables of Moszkowski and Jantzen.[11] References are given for the values of the end-point energies and half-lives used.

DISCUSSION

The results of this experiment can be interpreted in terms of either the shell or unified models of the nucleus for all cases except for the decay of Al^{25}, where

[11] S. A. Moszkowski and K. M. Jantzen, University of California at Los Angeles, Technical Report No. 10-26-55 (unpublished).

TABLE I. The branching ratios and comparative lifetimes for the decays of the mirror nuclei studied in this investigation.

Parent isotope	Daughter level (Mev)	End-point energy (Mev)	Branching ratio (percent)	Total $t_{\frac{1}{2}}$ (sec)	Transition $t_{\frac{1}{2}}$ (sec)	$ft\times10^{-3}$ (sec)
Na^{21}	0	2.51 ± 0.02[a]	97.8 ± 0.3	23.0 ± 0.2[b]	23.5 ± 0.2	3.91 ± 0.15
	0.347	2.16 ± 0.02	2.2 ± 0.3		1045 ± 140	90 ± 12
Mg^{23}	0	3.09 ± 0.01[a]	90.9 ± 0.5	12.1 ± 0.1[c]	13.3 ± 0.1	5.49 ± 0.10
	0.440	2.65 ± 0.01	9.1 ± 0.5[d]		133 ± 7	28 ± 2
Al^{25}	0	3.38 ± 0.03[a]	>99.1	7.15 ± 0.12[b]		4.30 ± 0.19
Si^{27}	0	3.85 ± 0.02[a]	>99.8	4.14 ± 0.03[c]		4.41 ± 0.13
S^{31}	0	4.39 ± 0.03[a]	98.9 ± 0.1	2.72 ± 0.02[c]	2.75 ± 0.02	5.16 ± 0.17
	1.267	3.12 ± 0.03	1.1 ± 0.1		247 ± 22	99 ± 10
Ca^{39}	0	5.490 ± 0.025[e]	>99.9[e]	0.88 ± 0.01[e]		4.33 ± 0.10

[a] See reference 1.
[b] See reference 6.
[c] See reference 5.
[d] R. S. Storey and K. G. McNeill, Can. J. Phys. **37**, 1072 (1959), have also recently reported this mode of decay to occur with a relative intensity of $6.5\pm2.5\%$.
[e] See reference 4.

the unified model appears to give a better interpretation. Using the configurations assigned to the ground states of parent and daughter nuclei and the daughter excited states, the appropriate selection rules for beta decay can be applied to determine the predictions of branches in the nuclei studied. The shell model configurations for the first two excited states of the daughter nuclei can be assigned in all the nuclei studied except Ca^{39}, where the spins and parities for the excited levels of K^{39} are not yet reported. Unified model configurations have been assigned to the levels of Na^{23},[12] Mg^{25},[13] and P^{31},[14] and plausible assignments can be made by comparison to these cases for Ne^{21}, Al^{27}, and K^{39}.

The branches observed in the decays of Na^{21} and Mg^{23} are predicted in a qualitative sense by both the shell and unified model descriptions. Both models predict beta transitions to the first excited states of the daughter nuclei, resulting from a recoupling of three $1d_{\frac{5}{2}}$ nucleons from $j=\frac{3}{2}$ for the ground states to $j=\frac{5}{2}$

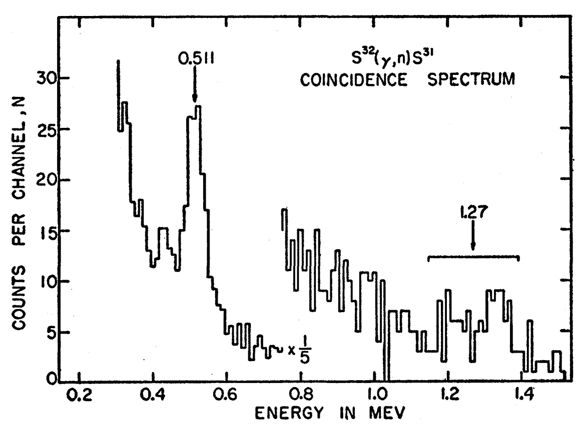

FIG. 7. Coincidence gamma-ray spectrum of the decay of S^{31}.

[12] E. B. Paul and J. H. Montague, Nuclear Phys. **8**, 61 (1958).
[13] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).
[14] C. Broude, L. L. Green, and J. C. Willmott, Proc. Phys. Soc. (London) **72**, 1122 (1958).

for the excited states using the shell model description, and resulting from a rotational state transition in the representation of the unified model.

The decay of Al^{25} is explained more accurately by the unified model, in that the shell model predicts a transition from the $1d_{\frac{5}{2}}$ ground state of Al^{25} to the 0.98 Mev $1d_{\frac{3}{2}}$ state of Mg^{25}, with an expected branching ratio of the order of ten percent, using equal Gamow-Teller matrix elements for the ground-state and excited-state transitions. Using the unified model configurations, however, the first (0.58 Mev) and second (0.98 Mev) excited states belong to the rotational band of the $2s_{\frac{1}{2}}$, $K=\frac{1}{2}$ single-particle level.[13] Thus, the transition from the ground state of Al^{25} to the 0.98-Mev state of Mg^{25} is K forbidden, so the lack of branching, which was the observed result of this experiment, seems to be explained more accurately by the unified model than by the shell model, at least in a qualitative sense. The weak branch to the 1.61 Mev ($I=\frac{7}{2}$) state of Mg^{25} [7] is expected to be a rotational transition, using the unified model configurations.

The decays of Si^{27} and Ca^{39} are expected to have no branching to the first or second excited states by consideration of both the shell and unified models, and none was observed in this investigation. In the case of Si^{27}, a transition to the first excited state of Al^{27} (0.84 Mev, $I=\frac{1}{2}+$) is second forbidden. The shell model forbids a transition to the second excited state of Al^{27} (1.01 Mev, $I=\frac{3}{2}+$) since this would involve a two-particle transition. In the unified model description, if the first and second excited states of Al^{27} belong to the rotational band of the $2s_{\frac{1}{2}}$, $K=\frac{1}{2}$ single-particle level, a transition to the second excited state is K forbidden, as well as involving a two-particle transition.

Both models also forbid a transition to the first excited state of P^{31} in the decay of S^{31}, but this branch was observed in this investigation. In both the shell model and unified model descriptions, the ground state and first excited state are due to the $2s_{\frac{1}{2}}$ and $1d_{\frac{3}{2}}$ single-particle levels. Thus, a transition to the first excited state of P^{31} is a two-particle transition and is forbidden.

Parkinson,[15] however, has reported configuration mixing to be present in the shell model description of the ground state of P^{31}, and such mixing can be used to explain the presence of the branch in the decay of S^{31}. In the unified model description, the configurations are also expected to be mixed,[14] and again this would allow a transition to the first excited state of P^{31} in the decay of S^{31}.

[15] W. C. Parkinson, Phys. Rev. **110**, 485 (1958).

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Decay of Ga^{66} and Cu^{66}†

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The 9.5-hour decay of Ga^{66} and the 5.1-minute decay of Cu^{66} have been studied by a variety of techniques including gamma-ray spectroscopy, internal conversion measurements, and angular correlation studies. All but one of the 18 gamma rays observed have been ordered into a structure of 11 levels and the spins and parities of all but one of these levels have been determined. It is shown that Ga^{66} has spin zero and even parity and that its 4.166-Mev β spectrum is a pure Fermi transition. The energy of the internal conversion line of the 4.300 ± 0.005 Mev transition was measured with great care and this line may be useful for spectrometer calibration. The second excited state of Zn^{66}, at 1.875 Mev, has 2+ spin and parity. The stopover transition from this state contains at least 10% $M1$ radiation: the stopover to crossover ratio is greater than 100 to 1.

I. INTRODUCTION

THE decay of Ga^{66} to Zn^{66} was investigated in great detail by Mann, Meyerhof, and West.[1] Earlier work, mainly magnetic spectrometer measurements of the positron spectra, was performed by Langer and Moffat[2] and by Mukerji and Preiswerk.[3] The decay of Cu^{66} was studied by Friedlander and Alburger.[4] Recently, Horen and Meyerhof,[5] in a new study of the decay of Cu^{66} to Zn^{66}, found a level at 1.865 Mev (the second excited state) which strongly suggested that some of the gamma rays in the decay scheme of Ga^{66} had been misplaced. This conclusion was strengthened by the (p,p') reaction data of Beurtey et al.,[6] who were able to resolve inelastic proton groups corresponding to excitation of the lowest levels in Zn^{66}.

Magnetic moment measurements of Ga^{66} indicate that its spin is zero,[7] while shell-model considerations imply that the parity of this state is positive. The 4.17-Mev ground-state positron spectrum in the Ga^{66} decay is thus expected to be a pure Fermi transition. Measurements of the polarization of these positrons[8] have figured significantly in the determination of the beta-decay invariants of the Fermi interaction. It therefore seemed valuable to check that the 0+ assignment to Ga^{66} was in agreement with the Ga^{66} decay scheme, and to determine the purity of the higher energy portion of the positron spectrum.

The second excited state of Zn^{66} at 1.865 Mev, while similar in many respects to the second excited states of Zn^{64} and Zn^{68}, has a very much smaller crossover to stopover transition ratio.[9] Its behavior was, therefore, studied in some detail.

We have been able to place all but one of the 18 gamma rays we observed into an ordered scheme containing 11 levels and to determine unambiguously the spins and parities of all but one of these levels. The measurements which led to our decay schemes of Ga^{66} and Cu^{66} are described in the following sections and are summarized as follows:

(1) The energies and intensities of the gamma rays fed in the decay of Ga^{66} were determined by single-crystal scintillation spectrometry, by three-crystal pair

† Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] L. G. Mann, W. E. Meyerhof, and H. I. West, Jr., Phys. Rev. **92**, 1481 (1953).
[2] L. M. Langer and R. J. D. Moffat, Phys. Rev. **80**, 651 (1950).
[3] A. Mukerji and P. Preiswerk, Helv. Phys. Acta **25**, 387 (1952).
[4] G. Friedlander and D. E. Alburger, Phys. Rev. **84**, 231 (1951).
[5] D. J. Horen and W. E. Meyerhof, Phys. Rev. **111**, 559 (1958).
[6] R. Beurtey, P. Catillon, R. Chaminade, H. Faraggi, A. Papineau, and J. Thirion, Nuclear Phys. **13**, 397 (1959).
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[8] M. Deutsch, B. Gittelman, R. Bauer, L. Grodzins, and A. Sunyar, Phys. Rev. **107**, 1733 (1957); S. Frankel, P. Hansen, O. Nathan, and G. Temmer, Phys. Rev. **108**, 1099 (1957).
[9] D. J. Horen, Phys. Rev. **113**, 572 (1959).