Cross Sections and Isomer Ratios for the $Sc^{45}(He^3,\alpha)Sc^{44m,44g}$ Reactions from 6-19 MeV: Recoil-Range Studies for Sc^{44m} and Sc^{44g} in Sc^{45} †

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The absolute cross sections for the production of Sc^{44m} and Sc^{44g} by the $Sc^{45}(He^3, \alpha)$ reaction have been determined at 1-MeV intervals from 6–19 MeV. The experimentally determined isomer-ratio function has only a limited variance over the energy range studied. Calculations of the Huizenga-Vandenbosch type were performed. Spin cutoff parameters of 2 and 4 gave poor fits of the isomer data. Recoil ranges for Sc^{44m} and Sc^{44g} in Sc^{45} were determined. Recoil energies for Sc^{44} were calculated assuming (1) a compound-nucleus mechanism and (2) a pickup-type mechanism. Recoil ranges for Sc^{44} in Sc^{45} were then calculated using the formulation of Lindhard, Scharff, and Schiott. Comparison of the experimental recoil ranges with the calculated values resulted in poor agreement with both calculations. The inability to fit the isomer-ratio data with a spin cutoff parameter of 2, and the poor agreement of the experimental recoil ranges with the compound-nucleus-mechanism calculation, are interpreted as evidence for the occurrence of non-compound-nucleus-type processes.

I. INTRODUCTION

Isomer-ratio studies of isomer-producing nuclear reactions have been helpful in characterizing mechanisms for low-energy nuclear reactions. Predominantly direct processes result in isomer-ratio functions that have small variance, and compound-nucleus processes tend to demonstrate a somewhat larger variance.[1,2] He^3-induced reactions have generated much interest in recent years.[3-7] Studies have indicated that He^3 reactions of the same type, and with comparable energetics, have mechanisms that seem to vary with the target. (He^3, p) reactions have been characterized as being both predominantly direct and compound-nucleus. The isomer-ratio studies of Riley *et al.*, indicated that the $Sr^{88}(He^3, p)Y^{90g,90m}$ reaction was a stripping process within the 14–19 MeV interval of He^3 bombarding energies.[3] Hazan and Blann showed through application of range-recoil techniques that the $Fe^{56}(He^3, p)Co^{58}$ reaction was taking place with a complete momentum-transfer compound-nucleus mechanism.[4] Cox[5] has studied the isomer-producing reactions $Au^{197}(He^3, t)Hg^{197g,197m}$, $Sc^{45}(He^3, \alpha)Sc^{44g,44m}$, and $Sr^{87}(He^3, t)Y^{87g,87m}$ utilizing He^3 particles up to 28 MeV. His isomer-ratio data indicated that all three reactions were occurring by a compound-nucleus mechanism.

One would expect that the (He^3, α) reaction would occur mainly as a pickup-type process. Due to the relatively large binding energy of the last neutron of the α particle, low-momentum-transfer or large-impact-parameter collisions can result in removal of a neutron from the target to form the stable α particle. Most studies have interpreted the (He^3, α) reaction as a direct-type process.[6,7] Cox's[5] isomer-ratio data for the $Sc^{45}(He, \alpha)$ reaction, although not demonstrating a very large variance in σ_m/σ_g between 17–28-MeV (He^3 lab energy) is commensurate with what one would predict for a compound-nucleus mechanism, considering the spin of the Sc^{45} target ($\frac{7}{2}$) and the spins of the ground state (2) and metastable state (6) of the product Sc^{44}. Using a spin cutoff parameter of 4, Cox obtained a reasonable fit for his data using the Huizenga-Vandenbosch formulation which is predicated upon a compound-nucleus mechanism.[8] Cox concluded that a compound-nucleus mechanism was dominant, since he was able to fit the data.

To reconcile this apparent discordance, the $Sc^{45}(He^3, \alpha)Sc^{44g,44m}$ reaction has been restudied (in a different energy range). Cross-section and isomer-ratio data has been obtained at 1-MeV intervals from 6–19 MeV and compared with Huizenga-Vandenbosch-type calculations.[8] Range-recoil studies of the Sc^{44g} and Sc^{44m} products in Sc^{45} have also been carried out at 2-MeV intervals from 8–18 MeV. The experimental average ranges of the recoil products were compared with the theoretical projected ranges of Lindhard, Scharff, and Schiott.[9]

II. EXPERIMENTAL

A. Isomer Ratios

The Sc^{45} targets were prepared by evaporating scandium metal (stated purity 99.9%) upon aluminum backings. The scandium thickness was determined by microbalance weighing and varied from 0.482 to 0.925 mg/cm^2. The targets were individually bombarded with 6–19 MeV He^3 particles from the Florida State University Tandem Van de Graaff accelerator. The incident He^3 energies were

known accurately (±50 keV or less). Energy loss in traversing the thin scandium targets was relatively small. Calculations utilizing the standard energy-loss equation yielded values from 0.33 MeV for the 6-MeV bombardment to 0.14 MeV for the 19-MeV irradiation.

Upon completion of the bombardment, each target underwent preparation for counting. The reaction was very clean, requiring minimum chemical removal of undesirable activities. The scandium targets and aluminum backings were dissolved in 6-*M* hydrochloric acid. Standard scandium carrier was then added to the dissolved target solution. The desired Sc^{44} was separated from the backing by neutralizing the above acid solution with ammonium hydroxide and then precipitating scandium hydroxide by the addition of saturated sodium hydroxide. The scandium hydroxide was redissolved with 6-*M* hydrochloric acid, and the preceding step repeated. The final precipitation of scandium hydroxide was done with 6-*M* ammonium hydroxide. The precipitate was washed, filtered, and mounted for counting as the hydroxide [$Sc(OH)_3$]. After counting, yields were determined by converting the hydroxide to the oxide (Sc_2O_3) at 900°C.

A 3×3-in. NaI(Tl) crystal scintillator, coupled with a 256-channel analyzer, was used for γ counting. The absolute disintegration rates were determined using the photopeak efficiencies of Heath.[10] A low-efficiency high-resolution spectrum was taken on one sample using a Ge(Li) detector coupled with a 1000-channel analyzer. The high-resolution spectrum indicated no unknown components, and all resolved peaks agreed with the assumed composition (some peaks unresolved) of the NaI(Tl)-generated spectrum.

Figure 1 shows the pertinent levels[11] of Sc^{44} and Ca^{44} that lead to the spectrum of interest. The 3.92-h ground state of scandium, Sc^{44g}, was determined by monitoring the 1.156-MeV decay of Ca^{44}. This ground-state activity was counted immediately after the sample had been chemically prepared. It was counted at a distance of 8.25 cm from the crystal to minimize summing of the 1.156-MeV photon and 0.511-MeV photons associated with the β^+ decay. Small corrections (usually negligible) for the unresolved 1.121-MeV photon of Ti^{46}, decay product of Sc^{46}, were made by monitoring the 0.889-MeV photon of Ti^{46}. After approximately 40 h the activity of the 2.44-day, 0.271-MeV isomeric level, Sc^{44m}, was determined by counting the sample against the crystal shield. The low-energy contribution of the 0.511-MeV photon from the β^+ equilibrium decay of the scandium ground state was subtracted out with the aid of a Na^{22} standard. The internal-conversion coefficient of the 0.271-MeV γ ray was taken to be 0.14, and

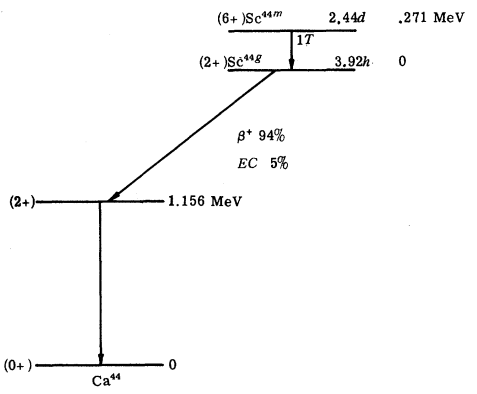

FIG. 1. Pertinent levels of decay scheme for Sc^{44}. Information taken from Lederer, Hollander, and Perlman (Ref. 11).

that of the 1.156-MeV photon was negligible.[11]

B. Recoil Experiments

The Sc^{45} targets were again prepared by evaporating scandium metal upon 6.9-mg/cm²-thick aluminum backings. Target thickness varied from 0.593 mg/cm² used for the 8-MeV irradiation to 1.169 mg/cm² used in the 18-MeV He^3 bombardment. The scandium targets were irradiated face-up at 2-MeV intervals from 8–18 MeV. Upon completion of each bombardment, the target was separated from the backing catcher foil by quickly dissolving off the scandium with 1-*M* hydrochloric acid. Aluminum is slow to react with 1-*M* hydrochloric acid and remains unchanged when this step is done quickly and carefully. The target and foil were then treated as separate samples by the procedure outlined in the above isomer experiments. Counting was identical except now two counts of each type were made, one for the target and one for the catcher foil.

III. EXPERIMENTAL RESULTS

A. Cross Sections and Isomer Ratios

The experimental results are tabulated in Table I. The error in the absolute cross sections for the separate states is estimated to be about ±20%. Excitation functions for the excited state with spin 6 and for the ground state with spin 2 are displayed in Fig. 2. The cross sections for both states are relatively small and of the same order of magnitude as those for (He^3, p) reactions.[3] The isomer ratios are also tabulated in Table I, and Fig. 3 shows the isomer-ratio results of this study. Also displayed for comparison is the isomer-ratio data of Cox.[5] The isomer ratios of the present study have an estimated error of ±10%.

TABLE I. Cross sections and isomer ratios for the $Sc^{45}(He^3, \alpha)Sc^{44m,44g}$ reaction.

He^3 energy (MeV)	σ_m (mb)	σ_g (mb)	σ_m/σ_g	$\sigma_m/\sigma_m+\sigma_g$
6	0.65	2.9	0.22	0.18
7	1.4	4.9	0.28	0.22
8	3.0	9.4	0.32	0.24
9	4.3	11.6	0.37	0.27
10	4.5	11.1	0.41	0.27
11	5.1	11.3	0.45	0.31
12	5.0	9.9	0.50	0.34
13	4.8	10.1	0.48	0.32
14	4.7	10.6	0.45	0.31
15*a*	5.6	11.8	0.48	0.32
15*b* [a]	...	...	0.50	0.34
16[a]	...	...	0.49	0.33
17	4.7	9.3	0.50	0.34
18	3.8	7.8	0.49	0.33
19	3.2	7.3	0.44	0.30

[a]Isomer ratios may be determined without cross-section measurements, because of cancellations in the ratio of such experimental quantities as beam flux, chemical yield, and target thickness.

B. Recoil Experiments

The mean projected ranges for Sc^{44m} and Sc^{44g} are tabulated in Table II for various He^3 bombardment energies. These mean ranges are shown in Fig. 4 as a function of energy. Several counts

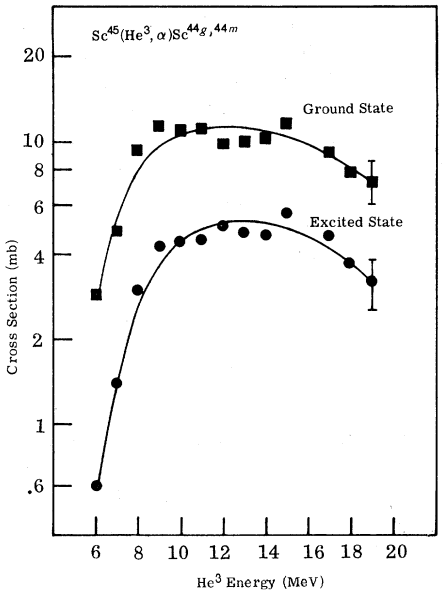

FIG. 2. Excitation functions for $Sc^{45}(He^3, \alpha)Sc^{44m,44g}$ reactions. Closed circles represent the $Sc^{45}(He^3, \alpha)Sc^{44m}$ excitation function. Closed squares represent the $Sc^{45}(He^3, \alpha)Sc^{44g}$ excitation function. He^3 energy is given in the lab system. Vertical bars represent the estimated ±20% maximum error in absolute cross sections.

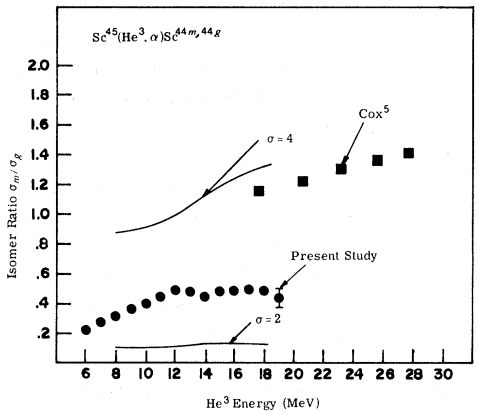

FIG. 3. Isomer ratios for the $Sc^{44g,44m}$ pair produced by $Sc^{45}(He^3, \alpha)Sc^{44m,44g}$. Closed circles represent present data, and closed squares the data of Cox.[5] The vertical bar represents the ±10% estimated error of the present data. Solid lines are calculated values for spin cutoff values of 2 and 4.

were made on each sample, and the activity was high enough to obtain very good statistics for all counts. The maximum error is estimated to be ±15%. Displayed in Fig. 4 are the average recoil ranges $\bar{R}$, as a function of energy for the metastable state, $\bar{R}_m$, and the ground state, $\bar{R}_g$. $\bar{R}$ is given by[12]

$$\bar{R} = ft\,, \tag{1}$$

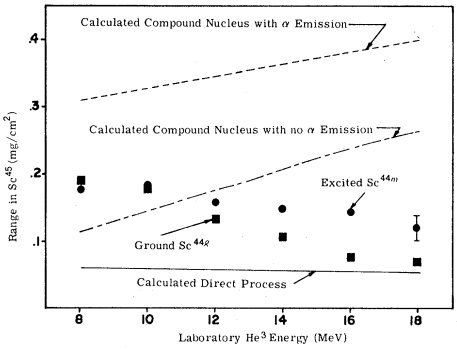

FIG. 4. Average recoil ranges for Sc^{44m} and Sc^{44g} in Sc^{45} along the beam axis. Squares represent experimental average projected ranges of Sc^{44g}, and circles the average projected ranges of Sc^{44m} in Sc^{45}. The lines are theoretical curves for projected ranges using the formulation of Lindard, Scharff, and Schiott (Ref. 9). The solid lower curve assumes a pickup-type mechanism with the α particle taking the beam direction. The dash-dot curve assumes the recoiling Sc^{44} has the same recoil energy as the compound nucleus. The dotted curve represents the projected ranges of Sc^{44} from a compound-nucleus reaction when α-particle emission is considered; the α particles were assumed to have 11 MeV of kinetic energy and a 50% forward and 50% backward angular distribution. The vertical bar represents an estimated ±15% maximum error of the data.

where f is the fraction of the total activity (target plus foil) found in the foil and t is the target thickness (Sc^{45}) in mg/cm^2. The ranges of the recoil products in both states are approximately equal at 8 and 10 MeV, but nuclei in the excited state have a perceptibly greater average recoil from 12–18 MeV. The ranges of the recoil products in both states decrease as the He^3 bombardment energy is increased.

TABLE II. Average recoil ranges, $\bar{R}$, for Sc^{44m} and Sc^{44g} in Sc^{45} produced by He^3 bombardment of Sc^{45}.

He^3 energy (MeV)	Target thickness (mg/cm^2)	Mean range ($\bar{R}_m$) Sc^{44m} (mg/cm^2)	Mean range ($\bar{R}_g$) Sc^{44g} (mg/cm^2)
8	0.59_3	0.18	0.19
10	0.59_7	0.18_5	0.18
12	0.81_7	0.16	0.13
14	0.87_4	0.15	0.11
16	1.10_6	0.14_5	0.08
18	1.16_9	0.12	0.07

IV. DISCUSSION

The isomer ratios displayed in Fig. 3 overlap the energy range of the data of Cox[5] at about 17.5 MeV. There is a large discrepancy between the two sets of data. Several factors could account for some discordance such as, thin targets versus Cox's thick targets, irradiation techniques, sample preparation and counting. In this study, any Sc^{44} product recoiling into the aluminum backings was picked up by the precipitation procedure utilized, but not by the preparatory procedure of Cox. Also thick-target results would be substantially different from thin-target results, as one would find by taking ratios of integrated segments of the excitation functions for both states. Cox determined his isomer ratios by following the decay of the 1.156-MeV photon only. In this work the ratios were determined by counting both the 0.271-MeV photon of the excited state and the 1.156-MeV photon related to the ground-state decay. This same counting method was used in a previous study of the $K^{41}(\alpha, n)Sc^{44m,44g}$ isomer ratios.[2] A subsequent study of the same isomeric pair by Keedy *et al.*[13] gave excellent agreement with those results. Keedy *et al.* employed the same counting techniques as Cox. It is doubtful that even these differences could account for this large discrepancy.

Also shown in Fig. 3 are cross-section-ratio calculations made by the method of Huizenga and Vandenbosch, which assumes a compound-nucleus mechanism.[8] The transmission coefficients for He^3 and He^4 on Sc^{44} were calculated by the method of Konopiniski and Bethe,[14] and Bethe.[15] The specific values for the isomer ratios along with pertinent conditions are tabulated in Table III. $\bar{N}_\gamma$, the average number of γ rays emitted was determined by[16]

$$\bar{N}_\gamma = \tfrac{1}{2}(a E_r)^{1/2}, \tag{2}$$

where a is the level-density parameter for Sc^{44} (assumed to be 4.1 MeV^{-1}) and E_r is the energy of the residual nucleus. When fractional values for $\bar{N}_\gamma$ were calculated with (2), a linear interpolation was applied. The effect of the competition between neutron and α-particle emission was neglected.[17] The energy of the evaporating α particles was set equal to 11 MeV at all bombarding energies.

Spin cutoff parameters of 2 or 4 do not fit the data. A spin cutoff parameter of approximately 2 was found for Sc^{44} in a previous study.[2] It would appear that a value of about 3 would be required to fit the present isomer data.

The rather limited variation of the isomer ratios over the energy range studied is interesting. It is also noted that small values of the spin cutoff parameter result in an invariant calculated isomer-ratio function because of the spin considerations of this reaction. However, the value of 3 which is suggested here does not agree with the previously determined value of 2. A large variation of the isomer ratios as a function of energy would not be expected for a pickup-type mechanism. The spin, J_f, of the Sc^{44} products produced by the process is given by the vector sum

$$J_f = |I + s + l_n|, \tag{3}$$

where I is the spin of the target $Sc^{45}(\frac{7}{2})$, s is the spin of the picked-up neutron ($\frac{1}{2}$), and l_n is the orbital-angular momentum of the neutron. Direct production of Sc^{44m}, spin 6, may be brought about by

TABLE III. Calculated isomer ratios.

He energy (MeV)	Spin cutoff parameter σ	Number of γ's emitted $\bar{N}_\gamma$	$\frac{\sigma_m}{\sigma_g}$
8	2	2.4	0.11
	4		0.88
10	2	2.8	0.11
	4		0.91
12	2	3.0	0.11
	4		0.99
14	2	3.4	0.13
	4		1.13
16	2	3.7	0.13
	4		1.23
18	2	4.0	0.13
	4		1.33

$j=\frac{5}{2}$ to $\frac{19}{2}$, where $j=l_n\pm s$. For Sc^{44g}, spin 2, j may vary from $\frac{3}{2}$ to $\frac{11}{2}$. For direct production it would appear that removal of the last neutron of Sc^{45}, $1f_{7/2}$, would be responsible for most of the reactions since the $1d_{3/2}$ and $1d_{5/2}$ inner levels are more stable. If the $1f_{7/2}$ neutron is responsible, excitation of levels of Sc^{44} with J_f values from 0 to 7 is possible. γ decay of these states to the $J_f=2$ or $J_f=6$ level would then take place with preferential decay to the state with closer spin. The cross-section ratios would depend upon the density of states that preferentially decay to either Sc^{44m} or Sc^{44g}.

A logical speculation is that the reaction is occurring by a significant fraction of both the compound-nucleus and pickup-type mechanisms. The compound-nucleus process results in a small invariant σ_m/σ_g (spin cutoff parameter of 2), and the direct process produces ratios that are relatively constant, but larger. Characterization of the mechanism of this reaction by an isomer-ratio study alone is not possible. A more reliable characterization of the reaction mechanism would require a study which distinguishes between the complete momentum-transfer compound-nucleus process, and the partial momentum transfer that accompanies the pickup process. Recoil-range experiments give this information.

The utility of recoil-range experiments increased significantly with the availability of reliable theoretical range calculations for comparison. Lindhard, Scharff, and Schiott have developed a set of universal range-energy curves.[9] From these curves one may obtain the mean projected ranges of recoiling products. The dash-dot curve of Fig. 4 displays the mean projected range of Sc^{44}, calculated for the compound-nucleus case when α emission is not considered. It is assumed that the recoil of the compound nucleus is equal to the recoil of the product Sc^{44}. Complete momentum transfer is assumed in this calculation, with the energy of the recoiling product given by

$$E_R=E_3M_3M_{Sc^{44}}/(M_{Sc^{45}}+M_3)^2, \quad (4)$$

where E_R is the recoil energy of the compound nucleus, E_3 is the kinetic energy of the bombarding He^3 particle, M_3 is the mass of He^3 and the other M's are masses indicated by the subscripts.

The remaining two curves predict the average recoil ranges of Sc^{44} when α emission is considered for a compound-nucleus process and for a direct-interaction pickup-type mechanism. These calculations are derived from conservation of momentum and energy. For the compound-nucleus results

$$P_r^2=P_3^2+P_4^2-2P_3P_4\cos\varphi, \quad (5)$$

where P_r is the momentum of the recoil Sc^{44}, P_3 is the incoming momentum of the He^3 particle, P_4 is the momentum of the emitted α particle, and φ is the angle between the incident He^3 beam and the outgoing α particles. The recoil energy of the product Sc^{44}, E_r, will be given by

$$E_r=\frac{1}{M_r}[M_3E_3+M_4E_4-2(M_3M_4E_3E_4)^{1/2}\cos\varphi], \quad (6)$$

where the M's and E's designate the masses and kinetic energies of the three particles involved. The angular distribution of the evaporating α particles was taken to be 50% forward and 50% backward ($\varphi=0$ and 180°) and they were ascribed an energy of 11 MeV, the Coulomb barrier energy. Blann and Ewart have shown that a 50% forward and 50% backward distribution is a good approximation for an isotropic angular distribution, and that a variation of several MeV in the energy associated with the emitted particles has little effect when range calculations are involved.[18] The upper dashed curve of Fig. 4 resulted from this calculation. This could be viewed as an α-particle-emission modification of the results obtained when Eq. (4) was used. The lower solid curve for the direct process results when (5) is combined with energy conservation. It was assumed that Sc^{44} was produced directly as Sc^{44g} (the calculated recoil of Sc^{44m} showed no difference) and that $\cos\varphi$ was unity for a forward distribution. Production of Sc^{44} in states other than the isomer states, which would then decay to Sc^{44g} and Sc^{44m}, would necessitate a variation of the energy of the outgoing α particles, which was not done in this simple calculation. Cascading probably accounts for the majority of the product Sc^{44}, regardless of whether the mechanism is pickup or compound nucleus.

The experimental projected ranges for the isomers do not agree well with either calculation. For comparison with a strictly compound-nucleus reaction, the reliability of the calculated compound-nucleus results is probably ±15%. The reliability of the direct calculation is unknown. The assumption of only direct production into the final states of Sc^{44m} and Sc^{44g} is certainly not correct, but it is interesting that this calculation appears to represent the trend of the experimental recoil data. Since the experimental data do not agree with the compound-nucleus calculation, the reaction must be partially or totally occurring by another mechanism. The recoil results, in addition to the inability to fit the isomer data with a spin cutoff parameter of 2, offer evidence that an incomplete momentum-transfer process is taking place, and that a compound-nucleus mechanism does not characterize this particular reaction completely. Characterization of the mechanism by comparison of isomer data with the Huizenga-

Vandenbosch formulation, which assumes a compound-nucleus mechanism,[8] is not necessarily valid even when it fits the data.

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$E0$ Transitions from $0_2^+ \rightarrow 0_1^+$ States in the $Z = 82$ Region*

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Energy spectra of internal-conversion electrons following $(p, 2n)$ reactions leading to even-even final nuclei in the $Z \simeq 82$ region were measured. $E0$ transitions leading from the 0^+ member of the two-phonon triplet to the 0^+ ground state were found, and the systematics of their transition rates was studied. They compete poorly with $E2$ transitions to the first excited (2^+) state, and the $E0$ transition rapidly becomes relatively less probable with decreasing A in this region.

INTRODUCTION

Throughout the Periodic Table, there is a scarcity of known $E0$ transitions, although there should be an $E0$ transition in nearly every even-even vibrational nucleus between the 0^+ member of the two-phonon triplet and the 0^+ ground state. Four different reasons can be given for this lack of $E0$ transitions. First, there is the strong competition from the decay of the 0^+ level via the $E2$ transition to the 2^+ level. Secondly, most experiments leave an excited nucleus with large amounts of angular momentum, and thus the decay chain will go through high-spin states and not a low-spin state, such as a 0^+. Thirdly, most experiments observe γ rays, and none are emitted in an $E0$ transition.