The general agreement between the two sets of (d,p) measurements is satisfactory, although in the $Ti^{48}(d,p)$-Ti^{49} case the agreement is just within the limits of error.

The agreement between the reaction data and the data computed from the mass table[23] is unsatisfactory for the Ti^{47}, Ti^{48}, and Ti^{50} cases, whereas it is acceptable in the case of Ti^{49}. The good agreement in the Ti^{51} case is not significant since the mass value for this nucleus was derived mainly from the MIT Q value. The reason for the above discrepancies is not understood but it is hoped that further reaction Q value measurements in progress applying more refined techniques will clarify the situation.

ACKNOWLEDGMENTS

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Coulomb Excitation of Low-Lying Excited States in Sc^{45}†

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Properties of the first excited state of Sc^{45} at 12.4 keV and the second excited state at 376 keV have been measured. A limit on the admixture of $E3$ radiation in the predominantly $M2$ decay of the first excited state has been set by looking for $E3$ Coulomb excitation of this state with Cl^{35} ions. Our result is that $B(E3,\frac{7}{2}^- \rightarrow \frac{3}{2}^+) \leqslant 105\ e^2\mathrm{fm}^6 = 2.7$ single-particle units. The mean lifetime has been remeasured as $\tau = 0.470 \pm 0.006$ sec. The K-conversion coefficient has been measured as 580 ± 120. The energy of the second excited state was determined to be 375.5 ± 1.0 keV. It was found to decay primarily to the first excited state with a branching ratio of 10.8 ± 0.5. The reduced matrix element for Coulomb excitation of the second excited state was measured to be $B(E2, \frac{7}{2}^- \rightarrow \frac{3}{2}^-) = 60.5 \pm 10\ e^2\mathrm{F}^4$.

I. INTRODUCTION

SINCE the discovery by Yntema and Satchler[1] that the scandium isotopes have $\frac{3}{2}^+$ states very near the ground state, a number of investigators have reported on the properties of these states.[2–5] Bansal and French[6] calculated the excitation energies of these states on the assumption that a $d_{3/2}$ hole is coupled to the ground state of the neighboring even-A nucleus. From their description, it follows that the transition from the hole states to the ground state should have predominantly an $M2$ character. The experimental lifetimes show a very retarded $M2$ transition rate. Lawson and Macfarlane[7] and Bansal and French[8] were able to explain this retardation as a result of a mutual cancellation of terms in the transition moments, an effect stemming from coupling the $d_{3/2}$ hole to the ground state and first excited state of Ti^{46}. From these wave functions Lawson[9] also calculated the $E3$ transition rate as 0.7 Moszkowski single-particle units.

On the other hand, there existed no direct experimental evidence for assigning these transitions a pure $M2$ character, and the presence of a sizeable $E3$ component could not be excluded. de-Shalit[10] pointed out that the low-lying positive-parity states in the Sc isotopes could be described in terms of a dominant configuration consisting of an $f_{7/2}$ particle coupled to a 3^- even-A core. Such a description would result in γ-ray transitions having predominantly an $E3$ character. These transition probabilities would have approximately the same values as the $3^- \rightarrow 0^+$ transitions in neighboring even-A nuclei. In these neighbors, the $E3$ transitions are enhanced to ~ 20 times the single-particle estimates.

In Sc^{45} the low excitation energy of the $\frac{3}{2}^+$ state means that the single-particle $E3$ transition probability is only 10^{-8} of the corresponding single-particle $M2$ transition rate. In order for the observed transition

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* On leave of absence from the Weizmann Institute of Science, Rehovoth, Israel.
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[2] J. L. Yntema and J. R. Erskine, Phys. Letters **12**, 26 (1964).
[3] R. E. Holland, F. J. Lynch, and K.-E. Nystén, Phys. Rev. Letters **13**, 241 (1964).
[4] M. S. Freedman, F. T. Porter, and F. Wagner, Jr., Phys. Rev. **140**, B563 (1965).
[5] K. W. Jones and A. Schwarzschild, Phys. Rev. **148**, 1148 (1966).
[6] R. K. Bansal and J. B. French, Phys. Letters **11**, 145 (1964).
[7] R. D. Lawson and M. H. Macfarlane, Phys. Rev. Letters **14**, 152 (1965).
[8] R. K. Bansal and J. B. French, Phys. Letters **14**, 230 (1965).
[9] R. D. Lawson (private communication).
[10] A. de-Shalit, in Proceedings of the Summer Study Group on the Physics of the Emperor Tandem Van de Graaff Region, Brookhaven, 1965, Brookhaven National Laboratory Report BNL 948 (C-46), Vol. 3, p. 1226 (unpublished).

rate to be the result of an $E3$ transition, the $E3$ transition would have to be enhanced by a factor of 10^4 after making allowance for the conversion coefficient. This makes it unlikely that the $E3$ component is appreciable in this transition. Such quantities as conversion coefficients or angular distributions measure the average properties of a transition. Therefore in this case it is difficult to determine the $E3$ transition probability from such measurements even if the $E3$ transition is enhanced and the $M2$ transition retarded. A recent measurement of the K-conversion coefficient by Jones and Schwarzschild[5] gave a result not inconsistent with a pure $M2$ transition. However, this measurement sheds no light on the degree of enhancement of the $E3$ component. In the case of Sc^{45}, Coulomb excitation seems to be the best tool to measure the $E3$ transition probability because Coulomb excitation strongly favors electric over magnetic transition modes. Using Coulomb excitation with various bombarding particles, we have measured several properties of the low-lying levels in Sc^{45}. We have established an upper limit of 2.7 single-particle units for the strength of the $E3$ component in the ground-state transition of the $\frac{3}{2}^+$ state.

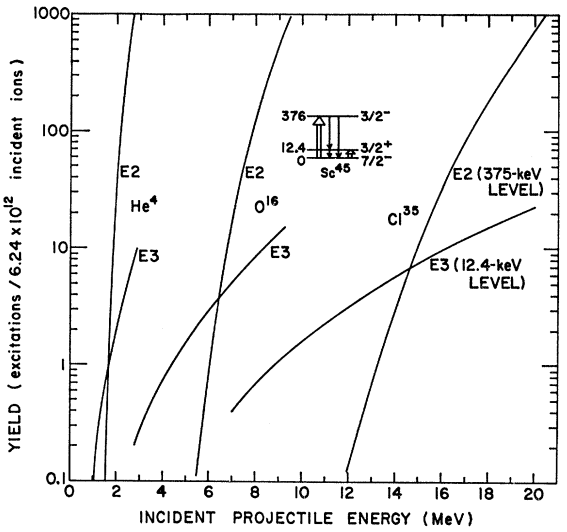

FIG. 1. Computed number of excitations in a thick scandium target as a function of the energy of He^4, O^{16}, and Cl^{35} projectiles. For each projectile two curves are plotted—one corresponding to $E3$ excitation of the 12.4-keV level, the other to $E2$ excitation of the 376-keV level. The reduced matrix elements $B(E2, \frac{7}{2} \rightarrow \frac{3}{2})$ and $B(E3, \frac{7}{2} \rightarrow \frac{3}{2})$ are assumed to be the Moszkowski single-particle estimate, as explained in the text.

II. EXPERIMENTAL

A. The $E3$ Transition Probability of the 12.4-keV Level

The $\frac{3}{2}^+$ state[4] in Sc^{45} lies 12.4 keV above the $\frac{7}{2}^-$ ground state and has a mean life[5] of 0.47 sec. The second excited state at 376 keV has spin and parity $\frac{3}{2}^-$ and can be Coulomb excited.[11] As will be discussed more fully in Sec. II D, this state decays predominantly to the 12.4-keV level. In trying to measure the $E3$ cross section for Coulomb excitation of the 12.4-keV level, therefore, one must be careful to excite this state directly and not through the 376-keV level.

Figure 1 shows thick-target yields for Coulomb excitation of the first two levels in Sc^{45} by bombarding with He^4, O^{16}, and Cl^{35}. The yield (number of excitations per 6.24×10^{12} incident particles) for $E2$ excitation was computed[12] from

$$\text{Yield}(E2)=\frac{A_1K^2 10^{59}B(E2)}{5.56\times A_2Z_2^2e^2}\int_0^E\frac{(E-\Delta E')f_{E2}(\xi)dE}{dE/d(\rho x)},$$

where A_2 is the atomic weight of the target, Z_2e is the nuclear charge of the target, A_1 is the mass number of the incident projectile, $K=A_2/(A_1+A_2)$, $\Delta E'=K^{-1}\Delta E$ with the excitation energy ΔE given in MeV, $dE/d(\rho x)$ is the stopping power of the target material in units of MeV cm^2/mg, E is the bombarding energy in MeV, $f_{E2}(\xi)$ is the semiclassical excitation function,[13] and the reduced matrix element $B(E2)$ was taken equal to the single-particle estimate of Moszkowski.[14] This estimate is

$$B_{\text{s.p.}}(EL)=(a^{2L}/4\pi)(3/L+3)^3e^2S,$$

where $a=1.2\times10^{-13}\ A^{1/3}$ cm. The quantity S is a statistical factor given by

$$S=(2j_f+1)\{C(j_i, j_f, L; \tfrac{1}{2}, -\tfrac{1}{2}, 0)\}^2,$$

where $C(j_i, j_f, L; \frac{1}{2}, -\frac{1}{2}, 0)$ is a Clebsch-Gordan coefficient, j_i and j_f are the spins of the initial and final states, and L determines the multipolarity of the transition. In our case

$$B_{\text{s.p.}}(E2, \tfrac{7}{2} \rightarrow \tfrac{3}{2})=24.5e^2\ \text{F}^4.$$

The yield for $E3$ excitation is given by

$$\text{Yield}(E3)=\frac{10^{85}\times A_1K^4B(E3)}{2.86\times A_2Z_1^2Z_2^4e^2}\times\int_0^E\frac{E(E-\Delta E')^2}{(dE/d\rho x)}f_{E3}(\xi)dE,$$

where $f_{E3}(\xi)$ has been taken as the semiclassical excitation function and

$$B_{\text{s.p.}}(E3, \tfrac{7}{2} \rightarrow \tfrac{3}{2})=38.8e^2\ \text{F}^6.$$

One of the major sources of uncertainty lies in the rate of energy loss $dE/d(\rho x)$. We used the energy-loss tabulation of Northcliffe[15] for He ions. For oxygen and

[11] J. J. Schwartz and W. P. Alford, Phys. Rev. **149**, 820 (1966); Phys. Letters **21**, 441 (1966).
[12] F. K. McGowan, R. L. Robinson, P. J. Stelson, and J. L. C. Ford, Jr., Nucl. Phys. **66**, 97 (1965).
[13] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).
[14] S. A. Moszkowski, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965).
[15] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13**, 67 (1963).

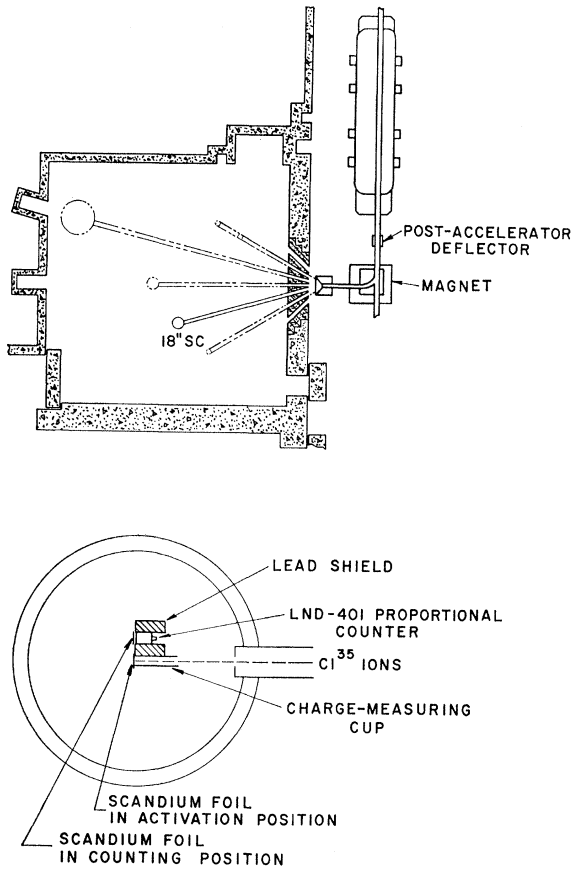

FIG. 2. Schematic diagram of equipment used to measure the number of excitations of the 12.4-keV level of Sc^{45} with a Cl^{35} beam.

chlorine ions we used the method due to Papineau[16] as described by McGowan *et al.*[12] The stopping power calculated in this way agreed with the measurements of Booth and Grant[17] for chlorine to within 10%.

Figure 1 shows that heavy bombarding particles of low energy have to be used in order to populate the 12.4-keV level directly and, at the same time, achieve reasonable yield. Beams of nuclei heavier than Cl^{35} offer some advantage, but the particles require very large magnets for their analysis and high-beam currents are difficult to obtain. This part of the experiment was carried out with $Cl^{35,4+}$ and $Cl^{35,5+}$ beams from the Argonne tandem Van de Graaff accelerator. The beam was produced by feeding CCl_4 vapor into the exchange canal of the negative-ion source. Krypton gas was used in the ion source proper. Under optimum conditions, 5 μA of analyzed $Cl^{35,4+}$ could be obtained. A pulsed beam with an indicated peak current of 0.5–1.0 μA was used to bombard a metallic scandium target.

The beam was pulsed by deflecting it over a narrow slit, the period being 1.572 sec. During one-third of this period, the beam struck the target. During the remaining time the beam was interrupted by the slit jaws and the target was moved over in front of a proportional counter (LND type 401) filled with a 90% Xe+10% CH_4 mixture at 1-atm pressure. The window of the counter was made of 2-mg/cm^2 beryllium in order to avoid excessive absorption of the 4.1-keV scandium K x rays; its sensitive volume was small (1.5 cm^3) in order to reduce background. Figure 2 is a schematic diagram of the experimental arrangement. During the 1-sec counting interval, pulses from the proportional counter were stored in a 64×64-channel two-dimensional analyzer with energy as one dimension and time as the other. In this way both the time and the energy dependence of the observed radiation could be established by subsequent analysis of the data.

Figure 3 shows the observed yield of scandium K x rays as a function of the energy of the incident chlorine ions. Because of considerable uncertainties in the counter efficiency and in the number of bombarding particles, the yield at high energies has been normalized to the calculated yield for $E2$ excitation of the 376-keV level. The $B(E2)$ used in this calculation was obtained from a separate experiment which will be discussed below. The curve marked $E3$ represents the calculated thick-target yield following $E3$ Coulomb excitation of the 12.4-keV level, assuming a $B(E3)$ equal to 2.7 single-particle units.

It is evident from Fig. 3 that the $E3$ transition to the first excited state in Sc^{45} is not enhanced. At 14-MeV bombarding energy, no x-ray peak was discernible above background. These data were used to establish an upper limit for the reduced transition probability for $E3$ excitation of the 12.4-keV level. The value, with 90% confidence, is

$$B(E3)_{\text{exc}} \leqslant 105e^2 \text{ fm}^6 = 2.7 \text{ single-particle units.}$$

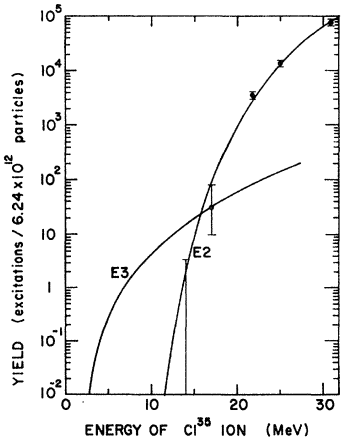

FIG. 3. Number of excitations of the 12.4-keV level of Sc^{45} per 6.24×10^{12} incident Cl^{35} particles. The observed excitations above 17-MeV incident energy correspond to $E2$ excitation of the 376-keV level from which the 12.4-keV level is populated. The curve marked $BE3$ corresponds to the limit $B(E3, \frac{7}{2} \rightarrow \frac{3}{2}) \leqslant 2.7$ single-particle units given in the text.

[16] M. A. Papineau, Compt. Rend. **242**, 2933 (1956).
[17] W. Booth and I. S. Grant, Nucl. Phys. **63**, 481 (1965).

The single-particle unit is based on Moszkowski's estimate[14] discussed above.

B. *K* Conversion Coefficient of the 12.4-keV Transition

A slightly different experimental arrangement was used for the measurement of the K conversion coefficient. A 15-MeV O^{16} beam hit a stationary scandium target (2.5 mg/cm^2) which was mounted on the window of a large proportional counter (Reuter-Stokes model RSG-30A) filled with 90% Xe and 10% CH_4 at 1-atm pressure. The beam was pulsed and the data were analyzed and stored in the same way as described in the preceding section. During the counting time, a mechanical shutter prevented any scattered beam from reaching the target. A typical energy spectrum summed over the time channels is shown in Fig. 4. The ratio of the intensity in the x-ray peak to that in the γ-ray peak is 27.3 ± 2.8. To obtain the conversion coefficient, this ratio has to be corrected for absorption in the target and in the counter window and for the fluorescent yield. The intensity of the γ-rays also has to be corrected for the presence of a very small $[(4\pm2)\%]$ escape peak.

In order to evaluate the absorption of the x rays in the target and the window, we measured the absorption coefficient for scandium K x rays in scandium and in beryllium. The x rays were produced by bombarding a scandium target with 1.5-MeV α particles from a 4-MeV Van de Graaff accelerator. The radiation was detected by a proportional counter, and foils of scandium and beryllium of various thicknesses were interposed between the target and the counter. The mass-absorption coefficients were obtained from the observed transmissions and the surface densities of the foils. The latter were measured by weighing the foils and determining their area. The absorption coefficients for scandium K x rays are 214 ± 10 cm^2/g in scandium and 8.0 ± 0.3 cm^2/g in beryllium. For the 12.4-keV γ rays, absorption coefficients given in the literature[18] were used.

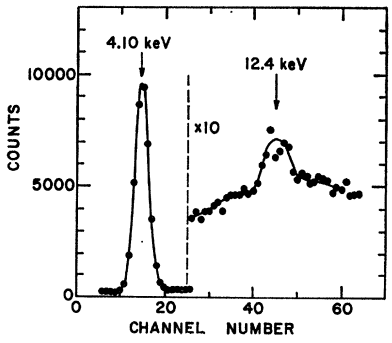

FIG. 4. Typical pulse-height spectrum obtained in the large proportional counter after bombardment of the scandium target with 15-MeV O^{16} ions.

[18] C. M. Davisson, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965).

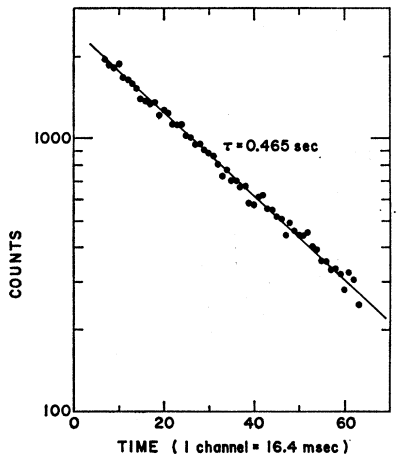

FIG. 5. Typical time spectrum showing the decay of the 12.4-keV level of Sc^{45} as observed from the number of K x rays.

The distribution of the Sc^{45*} ions in the target was calculated with the aid of Coulomb excitation probabilities and angular distributions given by Alder *et al.*[13] In these calculations, values for the specific energy loss of oxygen and scandium in scandium were interpolated from values given by Northcliffe.[15] Once the distribution of the radiating nuclei in the target is known, the transmission of x rays and γ rays can be calculated for given geometrical parameters and absorption coefficients. These calculations resulted in a correction factor 1.62 ± 0.25 for the difference in absorption of x rays and γ rays in the target. A correction factor of 1.98 ± 0.20 was calculated for the absorption in the beryllium window (46 mg/cm^2). Using a fluorescent yield[19] of 0.144 ± 0.005, we arrive at $\alpha_K = 580\pm120$ for the K conversion coefficient for the 12.4-keV ground-state transition in Sc^{45}.

This figure is somewhat higher than the value $\alpha_K = 413\pm37$ measured by Jones and Schwarzschild[5] and the value $\alpha_K = 380$ which was calculated by Bhalla.[20]

C. The Lifetime of the 12.4-keV Level

The decay time of the first excited state in Sc^{45} was obtained from the same data as the K conversion coefficient. The time spectrum of the radiation was obtained from the two-dimensional spectrum by summing the counts above background in the K x-ray peak. A typical time spectrum is shown in Fig. 5. Mean lives derived from three independent sets of measurements were 0.470 ± 0.005 sec, 0.465 ± 0.0005 sec, and 0.480 ± 0.007 sec. The standard errors quoted reflect statistical uncertainties only. The average of these three measurements, allowing for possible systematic errors of $\approx1\%$ in the time measurements, is

[19] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

[20] C. H. Bhalla (private communication).

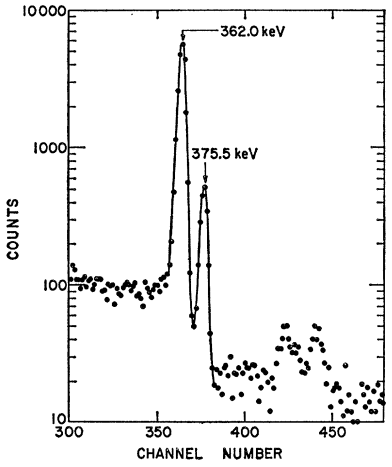

FIG. 6. Typical gamma-ray spectrum from a thick scandium target under bombardment by Cl^{35} ions.

$\tau=0.470\pm0.006$ sec. This value supersedes the value of 0.440 ± 0.025 sec given by Holland, Lynch, and Nystén.[3]

D. Branching Ratio and $B(E2)$ of the 376-keV Level

A thick scandium target was bombarded by 33-MeV Cl^{35} ions. The γ radiation was observed with a lithium-drifted germanium detector with a volume of 5 cm^3 placed at an angle of 54° with respect to the beam direction. This spectrum is shown in Fig. 6. The energy of the second excited state in Sc^{45} is 375.5 ± 1.0 keV. It can be seen from Fig. 6 that this level decays predominantly to the first excited state. The ratio of the intensity of the cascade to that of the cross-over transition is $\lambda=10.8\pm0.5$. The ratio includes a small correction of $(6\pm2)\%$ for the difference in photopeak efficiency of the Ge(Li) counter which was estimated from data of Ewan and Tavendale.[21] No correction for possible anisotropies of the radiation was necessary because the second Legendre polynomial is zero at the angle of 54°.

The $B(E2)_{\text{exc}}$ for the 376-keV level was measured by bombarding a thick scandium target with α particles from a 4-MeV Van de Graaff accelerator. The combined yield of the 363-keV and the 376-keV γ rays measured by a 3×3-in. NaI(Tl) crystal placed at an angle of 54° with the beam and at a distance of 10 cm from the target for alpha energies of 2.6 MeV and 3.0 MeV. The photopeak efficiency of the NaI(Tl) crystal was taken from Heath.[22] Small corrections of $4\pm2\%$ for absorption in the target and the crystal can were also taken into account. The value of $B(E2)$ was calculated from the thick-target yields by use of formulas given by Alder *et al.*[13] The value of the specific energy loss of α particles in scandium was calculated by interpolation from data in the compilation of Northcliffe.[15] Measurements at 2.6 MeV and at 3.0 MeV gave the same value for the reduced probability for Coulomb excitation. This probability is

$$B(E2, \tfrac{7}{2}\rightarrow\tfrac{3}{2})=60.5\pm10e^2\ \mathrm{F}^4,$$

or, on the basis of Moszkowski's estimate,[14]

$$B(E2)=2.5 \text{ single-particle units}.$$

This result is somewhat lower than the value $93e^2\ \mathrm{F}^4$ $\pm30\%$ measured by Alkhazov *et al.*[23]

III. DISCUSSION

The upper limit of 2.7 single-particle units found for the $E3$ transition probability for the first excited state in Sc^{45} does not confirm a pure core-excitation configuration. For such a configuration one would expect a $B(E3)$ approximately equal to that of the $3^-\rightarrow0^+$ ground-state transition in neighboring Ca^{44}, where $B(E3)\approx20$ single-particle units. However, this limit does not exclude the possibility that this configuration constitutes a sizeable fraction of the structure of this state. From this upper limit and the measured lifetime, it follows that the 12.4-keV transition has a practically pure $M2$ character. From the experimental K conversion coefficient and the K/L ratio calculated by Bhalla,[20] a partial $M2$ lifetime $\tau_{M2}=320$ sec is obtained. A comparison with Moszkowski's estimate[14] ($\tau_{M2}=1.25$ sec for this level) indicates that the 12.4-keV $M2$ transition is retarded by a factor of 260.

From the measured $B(E2)$ of the 376-keV transition and from the cascade-to-cross-over ratio, the lifetime of the second excited state in Sc^{45} was calculated to be

$$\tau(376 \text{ keV})=88\pm13 \text{ psec}.$$

On the assumption of an $E1$ character for the $\frac{3}{2}^-\rightarrow\frac{3}{2}^+$ cascade transition, this transition is retarded by a factor of 1.2×10^4 in comparison with the single-particle estimate. This large inhibition of $E1$ transitions between $\frac{3}{2}^-$ and $\frac{3}{2}^+$ states has been observed in similar cases in this region.

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[21] G. T. Ewan and A. J. Tavendale, Can. J. Phys. **42**, 2286 (1964).

[22] R. L. Heath, Idaho Operations Office Report IDO-16880-1 (unpublished).

[23] D. G. Alkhazov, A. P. Grinberg, G. M. Gusinskii, K. I. Erokhina, and I. Kh. Lemberg, Zh. Eksperim. i Teor. Fiz. **37**, 1530 (1959) [English transl.: Soviet Phys.—JETP **10**, 1086 (1960)].