TABLE VI. Beta-decay feeding of states in W^{183}.

Level energy (keV)	Level designation in Fig. 1	% Feeding: This experiment[a]	% Feeding: Nuclear Data Cards[b]
0	*A*	...	
46.5	*B*	0±6	
99.1	*C*	0±7	
207.0	*D*	0±6	
208.8	*E*	0±1	
291.7	*F*	3±2	~2
308.9	*G*	0±1	
309.5	*T*	7±2	~3
412.1	*H*	6±2	~3
453.1	*I*	84±4	91
595.3	*K*(*J*)	0.70±0.07	1

[a] Obtained using the gamma intensities of Edwards *et al.*, (Ref. 2) our experimental mixing results and the theoretical conversion coefficients of Rose (Ref. 18).
[b] See Ref. 21.

to slight changes in the matrix element values. Such effects could not account for the marked deviation of the mixing prediction from the value observed for transition *JH*. A possible explanation for this deviation is discussed below. The close agreement of the mixing predictions of Ref. 8 with our observed values lends strong support to the validity of the analysis of the W^{183} level scheme in terms of the Rotation Particle Coupling model employed by Brockmeier *et al.*

We have established upper intensity limits for the transitions *JF*, *JC*, and *JD* (Table V) from the $\frac{9}{2}^-$ [512] level *J* at 554.2 keV. Estimates of the strengths of these transitions indicate that they should be 200 to 1000 times stronger than the upper limits which we have set. The beta-decay feeding results of Table VI indicate that a $\frac{9}{2}^-$ [503] level should be fed far more strongly than a $\frac{9}{2}^-$ [512] level at approximately the same energy. These factors coupled with our observation of a new transition at 286.4 keV have led us to propose that the 142.3- and 286.4-keV transitions (*KI* and *KG*) both depopulate a level *K* at 595.33 keV. We believe this level to be the $\frac{9}{2}^-$ [503] level. Although a $\frac{9}{2}^-$ [512] level is expected to occur at ~554 keV we believe that this level is fed very weakly and thus transitions from it have not been observed.

ACKNOWLEDGMENTS

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Excited States of Fe^{57} Populated in Co^{57} Decay*

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The gamma-ray spectrum emitted in the decay of Co^{57} has been measured with a high-resolution Ge(Li) detector. In addition to the well-known gamma transitions of 136.4, 122.0, and 14.4 keV, the following weak transitions with energies given in keV (intensity per 10^5 Co^{57} decays) were observed: 229.8±1.0 (0.5), 339.7±0.4 (4.2), 352.5±0.4 (3.2), 366.8±0.5 (0.6), 570.0±0.4 (13.2), 692.1±0.3 (137), and 706.4±0.4 (5.7). A unique decay scheme is established on the basis of these energy measurements and gamma-gamma coincidence measurements employing NaI(Tl) scintillation detectors. The excited states of Fe^{57} at 366.8 and 706.4 keV have spin and parity $\frac{3}{2}$- and $\frac{5}{2}$-, respectively. The total internal-conversion coefficient for the 14-keV transition was measured by two independent methods: (1) A gamma-gamma coincidence measurement in a calibrated geometry yielded a value of 9.0±0.5. (2) A measurement of the Mössbauer absorption cross section of 14-keV gamma rays in iron yielded a value of 8.9±0.6. The good agreement between the results of these two independent methods resolves previously reported discrepancies. A more accurate determination of the half-life of the 14.4-keV first excited state by a gamma-gamma delayed-coincidence measurement gave a result of $(9.8\pm0.1)\times10^{-8}$ sec.

I. INTRODUCTION

A NUMBER of excited states in Fe^{57} have been previously located[1] by a variety of experimental techniques (e.g., radioactive decay, charged particle reactions, neutron capture γ-ray spectra). In some of these measurements, insufficient energy resolution or precision of energy measurement has obscured details of the decay of these states. Although the decay of the well-known 14.4-keV state has been extensively examined, different types of measurements have not always agreed on the value[2-5] of the total conversion

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC [61-2-13].
[2] H. R. Lemmer, O. J. A. Segaert, and M. A. Grace, Proc. Phys. Soc. (London) **68A**, 701 (1955).
[3] H. C. Thomas, C. F. Griffin, W. E. Phillips, and E. C. Davis, Jr., Nucl. Phys. **44**, 268 (1963).
[4] A. H. Muir, Jr., E. Kankeleit, and F. Boehm, Phys. Letters **5**, 161 (1963).
[5] S. S. Hanna, R. S. Preston, and W. S. Denno, Rev. Mod. Phys. **36**, 469 (1964).

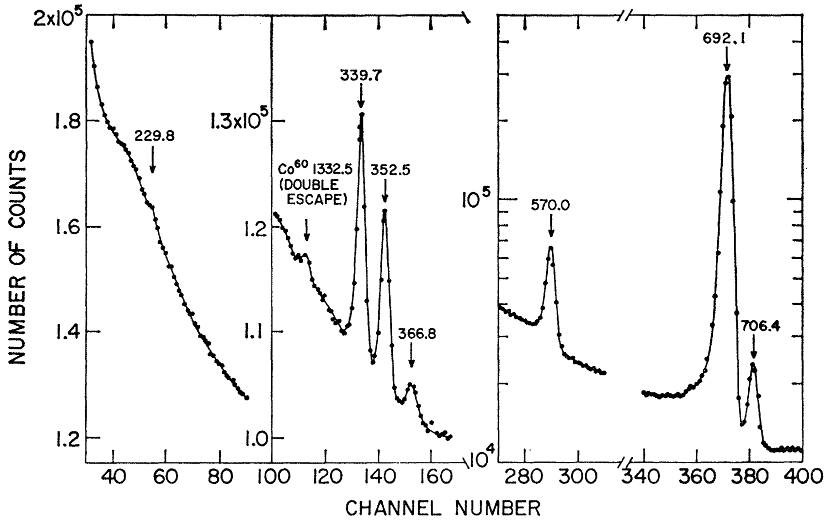

FIG. 1. Portions of the gamma-ray spectrum of Co^{57} as observed with a 3.6-cc Li-drifted Ge detector. Note transition from linear to logarithmic scale at channel No. 270.

coefficient. In addition, a more precise knowledge of the width of the 14.4-keV state would be useful in the interpretation of certain Mössbauer-effect experiments. We have performed the following series of experiments dealing with these problems: (1) The γ-ray spectrum following electron capture of Co^{57} has been examined with a high-resolution Li-drifted Ge detector. The weak population and subsequent decay of states previously seen in reaction and capture γ-ray experiments were studied. Gamma-gamma coincidence measurements were made using conventional scintillation detectors. From these measurements a unique decay scheme was obtained. (2) The half-life of the 14.4-keV state has been remeasured with about 1% precision. (3) The total internal-conversion coefficient of the 14.4-keV transition has been measured in two ways. The first method involves use of the Mössbauer effect. The second measurement is a conventional radioactivity experiment which determines the absolute number of 14.4-keV photons emitted per unit population of the 14.4-keV state.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Gamma-Ray Spectra

Portions of a gamma-ray energy spectrum taken with a Li-drifted Ge detector having a volume of 3.6 cc are shown in Fig. 1. Energies and intensities of the observed gamma rays are listed in Table I. The energy calibration of the γ-ray detection system is based upon the known energy[6] of the 661.595 ± 0.076-keV γ ray from the Cs^{137} decay. The energy calibration was achieved by comparing the photopeak pulse amplitudes to the pulse amplitudes from a precision pulser which fed directly into the preamplifier. The pulser output voltage was then measured with a precision potentiometer. Relative γ-ray intensities in Table I were established with the help of an empirically determined photopeak efficiency calibration curve. This calibration was obtained from a series of measurements on standard radioactive sources emitting gamma rays in known intensity ratios[1] (Hf^{180m}, Ag^{108m}, Na^{22}, Bi^{207}, Yb^{169}). Absolute γ-ray intensities for the γ rays above 136 keV were fixed by a coincidence measurement using NaI(Tl) detectors. In this measurement, the number of 570 keV-(122 keV+136 keV) γ-γ coincidences per recorded (122 keV+136 keV) photons in a calibrated geometry established the intensity of 570-keV photons relative to the previously known population of the 136.4-keV state. The geometry was calibrated by a similar measurement involving the 570- and 1064-keV gamma rays in the well-known Bi^{207} decay.

[6] R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instr. Methods 9, 245 (1960).

B. Total Conversion Coefficient for the 14.4-keV Transition

(1) One measurement of the 14.4-keV conversion coefficient was performed by recording the number of 14 keV–122 keV γ-γ coincidences per 122-keV photcn in a calibrated geometry. NaI(Tl) scintillators were used in these measurements. The efficiency for detection of the 14-keV gamma ray in this geometry was determined from a similar coincidence measurement with a Sr^{85} source. In this latter measurement, the number of RbK x-ray, 513-keV γ-ray coincidences per 513-keV photon was determined. Care was taken to ensure that no coincident events were missed in either experiment because of coincidence efficiency problems associated with the rather long half-lives of both the 14-keV state in Fe^{57} and the 513-keV state in Rb^{85}. In both cases a time-to-amplitude converter was used to record the time distribution of coincident events so that integration over the entire lifetime of the states could be easily performed. Care was also taken to ensure that no significant

Fe K x-ray contribution remained in the 14-keV detection channel. Derivation of the 14.4-keV total conversion coefficient from these measurements required consideration of the following factors:

(a) A K-shell fluorescence yield[7] of 0.629 was assumed for Rb.

(b) The fraction of Sr^{85} electron-capture events which take place by K electron capture was taken[8,9] to be 0.88.

(c) A small empirically determined correction was applied to account for small absorption differences in a thin Al absorber between the $\sim$13.2-keV K x rays of Rb and the 14.4-keV photons of Fe^{57}. This absorber was placed in front of the 1-mm-thick NaI(Tl) counter used to detect the 14-keV photons in order to minimize the presence of Fe K x rays in the 14.4-keV channel.

(d) The number of 122-keV photons relative to 136-keV photons as derived from our intensity measurements was taken as 8.0±0.5.

The final value derived from these measurements for the total conversion coefficient is $\alpha_T=9.0\pm0.5$.

(2) Another completely independent determination of α can be made from a measurement of the cross section for the resonant excitation of Fe^{57} to the 14.4-keV level as in the Mössbauer effect. The nuclear cross section for resonant absorption of incident radiation of energy E is given by

$$\sigma(E)=2\pi\lambda\!\!\!^{-2}\frac{(2I_e+1)}{(2I_g+1)}\frac{\Gamma_\gamma\Gamma}{4(E-E_a)^2+\Gamma^2},$$

where I_e and I_g are the spin of the excited state and ground state, respectively, Γ_γ is the partial width of the excited level due to gamma radiation, Γ is the total width, and E_a is the resonance energy of the level in the absorber. When the only other contribution to the decay of the level is from internal conversion, we can write

$$\Gamma_\gamma=\Gamma/(1+\alpha).$$

The cross section at resonance becomes

$$\sigma_0=2\pi\lambda\!\!\!^{-2}\frac{(2I_e+1)}{(2I_g+1)}\frac{1}{(1+\alpha)}.$$

The energy spectrum for the recoilless fraction of the 14-keV gamma rays emitted by the source is given by

$$I(E)dE=\frac{(2\Gamma/\pi)}{[(4E-E_s)^2+\Gamma^2]}dE,$$

where E_s is in general not equal to E_a. Resonance is established by the application of the appropriate relative velocity between source and absorber, thereby Doppler shifting the emitted gamma rays so that $E_s=E_a$. In the limit of a thin absorber and in the absence of any external line broadening, the resonant absorption of the incident 14-keV gamma rays as a function of the applied Doppler shift has a simple form. The resonance dip has a Lorentz shape of width $W=2\Gamma$ and a maximum depth $I_0=f_s[1-\exp(-\frac{1}{2}T_a)]$, where f_s is the probability for recoil-free emission in the source. $T_a=\sigma_0 N_a f_a$, where N_a is the area density of Fe^{57} atoms and f_a is the probability for a recoil-free transition in the absorber. For thicker absorbers up to $T_a=10$, Margulies and Ehrman[10] have shown that the resonance line is still very closely approximated by a Lorenztian form. The width W, however, is now greater than 2Γ and the intensity I_0 is given by

$$f_s[1-J_0(iT_a/2)\exp(-T_a/2)].$$

They have plotted the results of a calculation for W/Γ versus T_a.

The area under a Lorentzian curve of height $I_0(T_a)$ and full width at half-maximum $W(T_a)$, integrated between the limits of $E_0-\Delta E$ and $E_0+\Delta E$ is given by $I_0W\tan^{-1}(2\Delta E/W)$. T_a can thereby be evaluated for any given absorber by measuring the area of the Mössbauer resonance over any given limits provided f_s is known. The conversion coefficient α can then be extracted from T_a if f_a is known.

The Mössbauer absorption spectrum was measured for an iron-foil absorber and a single line source of Co^{57} both at 296°K. The absorber consisted of three layers of iron foil each having an average area density of 3.82 mg/cm². The resonance lines for this system were found to be very close to natural linewidth and a straightforward analysis employing the above expressions could therefore be made.

The recoil-free fraction of the source was determined

TABLE I. Gamma-ray energies and intensities as observed in the decay of Co^{57}.

E_γ (keV)[a]	γ-ray intensity (per 10^5 Co^{57} decays)
229.8±1.0	0.5
339.7±0.4	4.2
352.5±0.4	3.2
366.8±0.5	0.6
570.0±0.4	13.2
692.1±0.3	137
706.4±0.4	5.7

$$\frac{122.0\ \gamma\text{-ray intensity}}{136.4\ \gamma\text{-ray intensity}}=8.0\pm0.5$$

[a] All γ rays listed in this table, with the exception of the 229.8- and 366.8-keV transitions, were also recently observed by G. D. Sprouse and S. S. Hanna, Bull. Am. Phys. Soc. 9, 717 (1964). *Note added in proof.* See also J. M. Mathieson and J. P. Hurley, Bull. Am. Phys. Soc. 10, 424 (1965).

[7] A. H. Wapstra, G. J. Nihj, and R. van Lieshout, in *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 81.

[8] H. Brysk and M. E. Rose, U. S. Atomic Energy Commission Report No. ORNL-1830, 1955 (unpublished).

[9] J. N. Bahcall, Phys. Rev. **132**, 362 (1963).

[10] S. Margulies and J. R. Ehrman, Nucl. Instr. Methods **12**, 131 (1961).

by the square-absorber method[11] to be 0.708±0.020. This method utilizes an absorber synthesized from a mixture of fluoroferrates, enriched in Fe^{57}, all of which have identical chemical shifts but different quadrupole splittings. When the proper mixture has been obtained, the absorption spectrum has a remarkably broad, flat-bottomed resonance with a full width at half-maximum of ~2 mm/sec (~20Γ). The advantage of such an absorber is that it is possible to make it essentially "black" to the resonant radiation with a relatively small attenuation due to the electronic cross section. The background under the 14-keV photopeak was approximately the same with the "square absorber" as with the iron absorber, thereby minimizing the systematic error resulting from an error in estimating its "shape." The 14-keV photopeak pulses constituted approximately 86% of the counts in the selection channel.

The areas of the six absorption lines were determined from several absorption spectra extending over different velocity ranges by integrating each line over a range of $\Delta E=7.7\Gamma$. At these limits of integration the wings of the lines are sufficiently flat so that effects due to instrumental resolution are negligible. A curve was plotted for the area of a Lorentzian line integrated over the above limits versus T_a. From this curve the partial T_a corresponding to each of the six resonance lines was determined. Corrections were made for the contributions to the integrated areas from the wings of neighboring lines. In the absence of any absorber polarization,[12] the sum of the six values of T_a determined in this way are equal to $\sigma_0 N_a f_a$. For the iron absorber $N_a=2.71\times10^{18}$ Fe^{57} atoms per cm² (with 2.19% as the natural isotopic abundance[1] of Fe^{57}). The resulting value for $f_a\sigma_0$ is $(1.84\pm0.09)\times10^{-18}$ cm². The Debye temperature for iron has been determined[13] from temperature-shift measurements of the Mössbauer spectrum as 400±30°K. With the help of the tabulations of Muir,[14] f_a at room temperature for iron is computed to be 0.77±0.03. Therefore $\sigma_0=(2.39\pm0.15)\times10^{-18}$ cm² and $\alpha=8.9\pm0.6$.

C. Half-Life of the 14.4-keV State

The half-life of the 14.4-keV state has been measured using a 2-mm-thick NaI(Tl) scintillation counter to detect 14-keV γ rays and a $1\frac{1}{2}$-×1-in. NaI(Tl) scintillation counter to detect 122-keV γ rays. A time-to-amplitude converter covering a time range of about 2×10^{-6} sec was used in this measurement. Precise time calibration of this converter was made by the counting of random coincidences with accurately known input counting rates. Our measurements were made at sufficiently low input rates to the converter so that distortion of the true time spectrum caused by the cumulative removal of "start" pulses due to recording of coincidences was negligible. Delayed events could be easily followed for more than six half-lives. The resulting half-life is $T_{1/2}=(0.98\pm0.01)\times10^{-7}$ sec.

D. Other γ-γ Coincidence Measurements

The low intensity of the higher energy gamma rays listed in Table I suggests that an additional degree of certainty in the assignments would be afforded if coincidence relationships between appropriate γ rays could be established. One such coincidence relationship has already been mentioned in a different context in IIA where the 570-keV γ ray was shown to populate the well-known 136-keV state in Fe^{57}. A similar fast-slow coincidence experiment with a gate set on ≃(320–360) keV in one counter has established that the 353 keV+367 keV γ rays are in coincidence with the 340-keV photons. A time-to-amplitude converter measurement of the time distribution of these coincident events has established a limit of $T_{1/2}\leq4\times10^{-9}$ sec for the 367-keV state in Fe^{57}. Finally, in a coincidence experiment gating with 122 keV+136 keV photons, the observed intensity of 340-keV photons (due to the 340+230 cascade) relative to 570-keV photons (experimental ratio=1/25) is consistent with the 230-keV photon intensity observed in the Li-drifted Ge singles spectrum.

III. DISCUSSION

The gamma-ray spectrum observed with the Ge(Li) detector reveals a number of low-intensity gamma rays previously unobserved in the decay of Co^{57}. On the basis of energy sums alone, a unique decay scheme can be established which includes all of the observed transitions and which is consistent with the previously observed levels in this energy region. This decay scheme, shown in Fig. 2, is further supported by several gamma-gamma coincidence measurements performed with NaI(Tl) scintillation counters. The intensities of the transitions have been derived and are shown in Table I. It is interesting to note that a gamma transition has been observed between every pair of levels in this decay scheme.

With the help of information provided by a number of previous reaction experiments involving these levels, unique assignments may be made for the spin and parity of the 367- and 706-keV levels. Measurement of the proton angular distribution in the Fe^{56}-

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[11] R. M. Housley, N. E. Erickson, and J. G. Dash, Nucl. Instr. Methods **27**, 29 (1964).

[12] This treatment is correct only for a completely unpolarized absorber as first pointed out by R. M. Housley and R. H. Nussbaum (private communication). The observed intensities indicate a partial orientation of the magnetic axis within the plane of the foil amounting to approximately 9%. This alignment will affect the analysis only to the extent that it is directed along a particular direction in the foil. There is also the possibility of polarization effects due to local alignment when the thickness of the magnetic domains approaches the thickness of the foil. Both of these are greatly reduced by the "randomization" introduced when making up the absorber as in this case, from several randomly stacked foils.

[13] R. S. Preston, S. S. Hanna, and J. Heberle, Phys. Rev. **128**, 2207 (1962).

[14] A. H. Muir, Jr., Atomics International Report No. Al-6699, 1962 (unpublished).

$(d,p)Fe^{57}$ reaction[15] yields an $l=1$ assignment for the 367-keV state. The existence of an angular correlation[16] between the 7.28-MeV neutron-capture γ ray into this state and the following 353-keV γ ray rules out a spin-$\frac{1}{2}$ assignment for this state. The angular distribution of this 353-keV γ ray following Coulomb excitation[17] leads to the same conclusion. The spin and parity of the 367-keV state is therefore $\frac{3}{2}-$.

The stripping reaction[15] indicates no definite single-particle character for the 706-keV state and therefore gives no information about an l assignment for this level. The logft for electron capture to this level from the $\frac{7}{2}-$ ground state of Co^{57} is 7.6. This ft value, although large for an allowed transition, is too small for a unique first forbidden transition and therefore rules out a spin assignment of less than $\frac{5}{2}$. On the other hand, the observed intensity of the 706-keV transition to the $\frac{1}{2}-$ ground state relative to competing transitions to levels of high spin is inconsistent with a spin assignment of greater than $\frac{5}{2}$ for the 706-keV state. In addition, the parity of this state is most likely odd since an $M2$ transition is not likely to compete favorably with several parallel $E1$ transitions. The spin and parity assignments of $\frac{3}{2}-$ and $\frac{5}{2}-$ for the 367- and 706-keV levels, respectively, are further supported by the observation of primary neutron-capture gamma rays into the former level but not into the latter level.[18]

The $\frac{7}{2}-$ ground state of Co^{57} is largely described by an $f_{7/2}$ odd proton, as evidenced by the measured magnetic moment.[19] The somewhat large logft for the allowed electron-capture transition to the 706-keV level is therefore consistent with the observation that this state shows a lack of single-particle character in stripping. The $Fe^{56}(d,p)Fe^{57}$ proton angular distribution experiments[15] also reveal other levels without a definite single-particle character. In particular, there are such states at 1010 and at 1199 keV. Some or all of these states may arise from the coupling of a phonon to either the ground state or a low-lying excited state. Coulomb-excitation experiments would provide further information to help in understanding the character of these states. A rotational model for Fe^{57} used by Lawson and Macfarlane[20] has succeeded in accounting for the correct order of the low-lying states of Fe^{57}. The $\frac{5}{2}-$ state at 706 keV, however, does not appear to be adequately accounted for in their description.

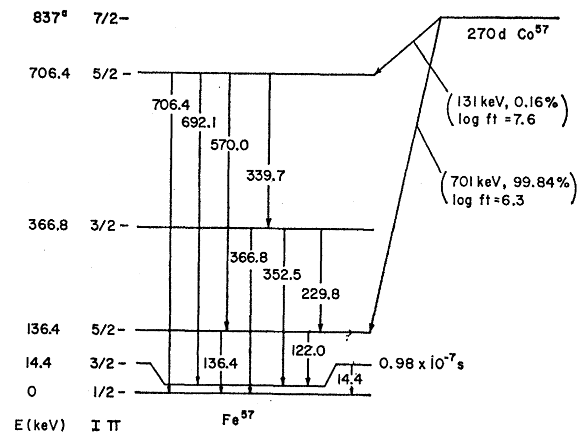

FIG. 2. Disintegration scheme of Co^{57}. ᵃC. H. Johnson and A. Golansky, Bull. Am. Phys. Soc. **5**, 443 (1960).

The half-life measurement reported here,

$$T_{1/2}=(0.98\pm0.01)\times10^{-7}\text{ sec},$$

is in agreement with the most precise previous determination[21] of Middelkoop *et al.*, who reported a value $T_{1/2}=(1.01\pm0.05)\times10^{-7}$ sec.

The two measurements of the total internal-conversion coefficient of the 14.4-keV transition, $\alpha_T=8.9\pm0.6$ from the Mössbauer-effect measurement and $\alpha_T=9.0\pm0.5$ from the "conventional" method, agree well with one another. Both of these measurements are to be compared with previous determinations[3,4] by "conventional" methods[22] which give values for $\alpha_T=9.94\pm0.60$ and 9.51 ± 0.5, respectively. Both of our measurements disagree with a previously reported measurement[5] by the Mössbauer-effect method.[23,24]

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[15] F. Alba, A. Sperduto, W. W. Buechner, and H. A. Enge, Bull. Am. Phys. Soc. **7**, 315 (1962).

[16] G. A. Bartholomew, Nucl. Phys. **50**, 209 (1964).

[17] R. C. Ritter, P. H. Stelson, F. K. McGowan, and R. L. Robinson, Phys. Rev. **128**, 2320 (1962).

[18] N. F. Fiebiger, W. R. Kane, and R. E. Segel, Phys. Rev. **125**, 2031 (1962).

[19] J. M. Baker, B. Bleaney, P. M. Llewellyn, and P. F. D. Shaw, Proc. Phys. Soc. (London) **69A**, 353 (1956).

[20] R. D. Lawson and M. H. Macfarlane, Nucl. Phys. **24**, 18 (1961).

[21] W. C. Middelkoop, A. Heyligers, L. H. T. Rietjens, H. J. van den Bold, and P. M. Endt, Physica **21**, 897 (1955).

[22] R. G. Albridge and D. C. Hall [Bull. Am. Phys. Soc. **10**, 244 (1965)] have recently reported a value of 8.95 for the 14-keV K conversion coefficient.

[23] R. H. Nussbaum and R. M. Housley (private communication) have recently determined α_T from a Mössbauer-effect measurement. Their result is $\alpha_T=9.0\pm0.4$.

[24] *Note added in proof.* S. S. Hanna and R. S. Preston, Phys. Rev. (to be published), report $\alpha_T=8.9\pm0.7$.