Level Structure in Cr^{52} Populated in 5.7-Day Mn^{52} Decay*

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The energy-level structure in Cr^{52} populated in the decay of 5.7-day Mn^{52} has been studied with a toroidal-field electron spectrometer and Ge(Li) detector. The decay is found to populate only the states at (MeV, $J\pi$, v=dominant seniority) (3.6177, 5+, 4), (3.1146, 6+, 2), (2.7688, 4+, 2), (2.3703, 4+, 4), and (1.4345, 2+, 2). Low upper limits set on the intensity of gamma rays of 2.65, 1.73, 1.465, 1.214, 1.18, 1.07, and 0.61 MeV previously reported in Mn^{52} remove all evidence for the population by Mn^{52} of states at 3.832, 3.161, and 2.648 MeV (the latter two known from nuclear reactions). All 9 possible transitions of multipolarity $E2$ or lower between known levels have been seen, including new weak gammas of 0.504 and 0.398 MeV. Conversion coefficients indicate strong $M1$ mixing only in the transition of 1.2474 MeV from the 3.6177- to the 2.7686-MeV state, for which $\Delta v=0$, in agreement with seniority selection rule for half-filled shells; and $E2$ dominance in the 1.4345-, 1.3343-, 0.9358-, 0.8498-, 0.7443-, and 0.3460-MeV transitions. Seniority mixing coefficients in the two 4+ states deduced from gamma intensities agree with those derived from previously reported nuclear-reaction data. The ratio of electron capture to positron emission for decay to the 6+ state is 2.04, in good agreement with theory.

I. INTRODUCTION

THE level structure in ${}_{24}Cr_{28}{}^{52}$ below 4 MeV has been viewed[1–4] as the complex of seniority-labeled shell-model states, representing the recouplings of two and four $f_{7/2}$ protons. Interpretations attributing the excitations to collective vibrations[5,6] or rotations[7] have been relatively less successful in this region.

Of the 16 states below 4.7-MeV excitation [$Q_{\beta^+}(Mn^{52})$ =4.71 MeV] seen by nuclear reaction and inelastic scattering,[8–10] only the higher spin (J=5+, 6+) states are directly populated by allowed positron and electron capture decay from the 5.7-day Mn^{52} (J=6+, measured) ground state. The general fit of the well-established states seen in beta decay to the shell-model calculations of Edmonds and Flowers,[3] using a specific two-body interaction, or to the pure seniority states of Talmi,[1] calculated from levels in V^{51} and Ca^{42}, is not good enough to determine the extent of seniority mixing. Moreover, some features of the published decay scheme[9] are not consistent with any shell-model or collective-model predictions, or indeed with simple spin selection rules.

Figure 1 shows the decay scheme[9] of Mn^{52} taken mainly from Wilson *et al.*[6] and from Katoh *et al.*[11] together with the additional levels seen in inelastic scattering and (p,α) reactions. Particular questions are raised with respect to the following:

(1) The existence of the two levels at 3.832 and 3.614 MeV, both fed by allowed beta decay from Mn^{52}, and thus assigned J=5+, 6+, calls for one more 5+ or 6+ levels in this region than can be accounted for by the shell[1] or collective[6] models. The 3.832-MeV level is not seen in (p,p′),[8] and is thus based only on the very weak 1.07- and 1.463-MeV gammas, poorly resolved in NaI.[6]

(2) The 2.648-MeV level from which the 3% abundant 1.214-MeV transition originates, has no populating transition. This situation is indeed strange if the 0+ spin assignment to this level[12,13] is correct; for this spin no reasonable feeding transition can be proposed, nor can the 2.65-MeV gamma then be a feed-out to the ground state.

(3) The 3.161-MeV state is similarly lacking in feed-in intensity, if the 2+ spin assignment,[10,12,13] is correct, either by positron decay or by observed gamma. The intensity of the proposed exiting 1.73-MeV gamma ray seen by Katoh *et al.*[11] was reduced to an upper limit of 0.5% by Wilson *et al.*,[6] still too large to be supported from any higher levels in the beta deay scheme.

(4) Weak gammas of 0.63 and 1.18 MeV were not assigned in the level scheme.[6]

(5) Talmi[1] has pointed out that the branching ratio from the 6+ level (seniority v=4) to the two 4+ levels provides a test of the seniority assignments to the latter (2.769 MeV, v=2; 2.370 MeV, v=4). The observed branching ratio of 346 keV/744 keV transitions indicated a large admixture of seniorities in the states,

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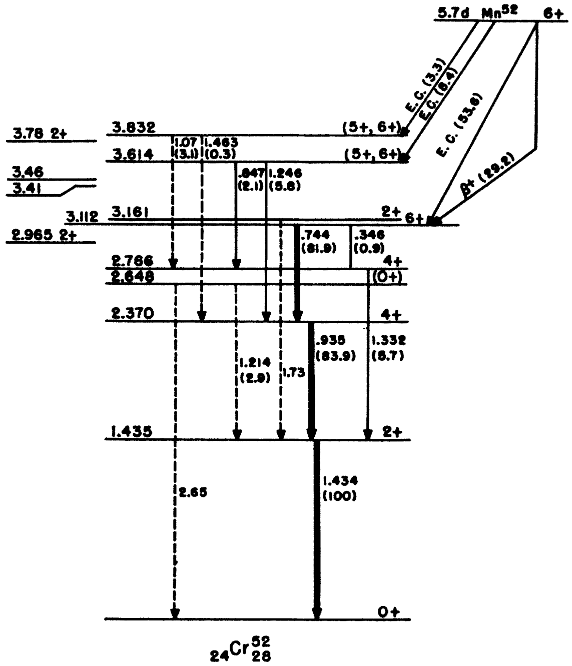

FIG. 1. Decay scheme of Mn^{52} ground state from previous work (Ref. 9) showing additional levels on left known from (p,α) reactions and (p,p'), (n,n'), and (α,α') inelastic scattering. Dashed lines are transitions not found in this study.

consistent with calculations of Komoda[14] on configuration mixing, and with the comparable cross sections for exciting these levels in (p,p') and (p,α) reactions.[2,8] Kaye and Willmott[13] see no evidence for the excitation of the 2.769-MeV ($v=2$) state in (p,p') with 6.5-MeV protons, but it is excited more strongly than the 2.370, $v=4$, state at 9-MeV proton energy,[8] as expected. The seniority assignments also predict a relative intensity for the unobserved $4+\rightarrow 4+$ transition. Thus, it is important to determine these gamma intensities accurately.

We considered the main features of the level scheme to be well established by the angular correlation results of Katoh *et al.*[11] on the main 6+ (744 keV) 4+ (936 keV) 2+ (1435 keV) 0+ cascade, and the additional coincidence and conversion line measurements of Wilson *et al.*[6] on the weaker 346-, 850-, 1247-, and 1334-keV transitions, which establish the second 4+ level at 2.769 MeV and the level at 3.618 MeV. This latter level has been assigned spin 5+ by the definitive gamma angular distribution measurements from aligned Mn^{52} nuclei by Kaplan and Shirley,[15] in agreement with the prediction of Edmonds and Flowers [3] for a seniority 4, $J=5$ state.

Thus we concerned these experiments with checking on the aforementioned questionable items, with gamma intensity measurements and conversion coefficients, and with accurate energy determinations in the beta spectrometer; we did no coincidence measurements or complete survey of the electron or positron spectrum.

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II. RESULTS AND REVISED DECAY SCHEME

For continuity of discussion we summarize our results and analysis here and present experimental details later. We surveyed the gamma spectrum of 5.7-day Mn^{52} for several weeks on a lithium-drifted germanium crystal detector whose absolute efficiency was carefully calibrated. The decay of each gamma was followed to verify the assignment to Mn^{52} (gammas from Mn^{54}, Cr^{51}, and Co^{57} were found in the source). Conversion electrons from the same sample were measured in the iron-free toroidal beta spectraometer at 0.62% resolution and 16% transmission.

The results are shown in Tables I, II, and III and in the revised decay scheme in Fig. 2. Table I gives the gamma and conversion line intensities observed. Inspection of Fig. 2 shows that the maximum discrepancy between feed-in and feed-out of any level involving only gamma transitions does not exceed $\sim$6%. β-decay intensities calculated from the difference between measured gamma-ray feed-in and feed-out for levels to which allowed β transitions are permitted (5+ and 6+ levels) give a total β-decay intensity equal to 91% of the intensity of the 1.4345-MeV gamma transition. These intensity imbalances reflect the general accuracy of the relative gamma-intensity measurements (see Sec. IIIC and Fig. 3). The maximum discrepancy between energy sums of any parallel transition paths in the decay scheme is 0.6 keV, which supports the level scheme developed by the coincidence measurements of Wilson *et al.*[6] The absolute gamma energies are significantly different than those of Wilson *et al.* We believe all levels in Fig. 2 are accurate to $\pm$0.3 keV, of which

TABLE I. Gamma rays and conversion electrons in the decay of 5.72-day Mn^{52}.

Gamma energy (keV)	Intensity[a] per decay (%)	Conversion electrons observed	Intensity per decay[b] of K electrons (%)
1434.5[c]±0.2	100	K, L[d]	0.00567±0.00013
1334.3[c]±0.3	5.1 ±0.4	K	0.00037±0.00003
1247.4[c]±0.3	4.7 ±0.4	K	0.00027±0.00003
935.8[c]±0.2	93.0 ±5.	K, L[d]	0.0142 ±0.0003
849.8[c]±1.0	3.0 ±1.0	K	0.00056±0.0001
744.3[c]±0.2	82.1 ±7.	K, L[d]	0.0260 ±0.0004
504[e] ±1.0	1.0 ±0.5	...	
398[e] ±1.0	0.30±0.08	...	
346.0[c]±0.3	0.78±0.2	K, L[d]	0.0032 ±0.0002
Ann. rad.	54.1 ±2.		
835.0[c,f]±0.2			

[a] Normalized to 1435 γ=100%.
[b] Indicated errors reflect counting statistics for the electrons. An additional uncertainty of 10–15% is due to the uncertainty in the absolute counting efficiency of the Ge(Li) detector and thus the absolute decay rate of the sample.
[c] Beta-ray spectrometer results.
[d] Not well resolved from K line.
[e] Ge(Li) detector result.
[f] Mn^{54} in sample.

TABLE II. Transitions not found in decay of 5.7-day Mn^{52}.[a]

Gamma (MeV)[b]	Upper intensity limit, germanium detector (% per decay)	Upper limit of ratio of observed intensity to that previously reported: Gammas	K-conversion electrons
2.65	$\leq$0.005	1/15	
1.73	$\leq$0.02	1/25	
1.465	$\leq$0.03	1/10	1[c]
1.214	$\leq$0.5	1/6	1/4
1.18[d]	$\leq$0.7	1/3	
1.07	$\leq$0.3	1/10	
0.61±	$\leq$0.05	1/50	

[a] None of the weak gammas of Ref. 11 were seen in this work or in Ref. 6. Columns 3 and 4 pertain to Table I of Ref. 6 with the exception of the 1.73-MeV gamma for which Ref. 11 gives an intensity.
[b] Mean energy of region explored.
[c] The intensity of the 1.46-MeV transition, (0.3±0.2)% of the 1.43-MeV transition intensity, given in Table I of Ref. 6 is apparently derived from the conversion-electron data of Fig. 7, Ref. 6. This implies an intensity for the 1.46-MeV electron line of ~0.3% of the intensity of the 1.43-MeV line, a fraction which appears to be ~10 times smaller than the upper limit one might expect from the statistical fluctuations in that region of the spectrum.
[d] Assumed same as 1.214 in Ref. 6.

0.15 keV results from the imprecision of the calibration standard, Cs^{137} (see Sec. IIIB).

The major contribution of this investigation appears in Table II. The surprising conclusion is that a gross simplification in the decay scheme has resulted from the use of a detector with much higher resolution than a NaI scintillation spectrometer. From the ratios of maximum intensity limits set by statistical uncertainty in our data to the intensity values reported in previous work (columns 3 and 4, Table II), there appears to be no reason to accept any of these transitions as being involved in the Mn^{52} decay. We now treat the questions raised in the Introduction in order.

(1) As the 3.832-MeV level was not seen in (p,α) or (p,p') to the extent of 1% intensity relative to the strongly excited levels, the absence of the 1.07- and 1.46-MeV gammas removes all evidence for the level's existence.

(2) While the existence of the 2.648-MeV level is

TABLE III. Conversion coefficients—5.7-day Mn^{52} decay.

γ energy (keV)	α_K(expt)	$\frac{\alpha_K(\text{expt})}{\alpha_2(\text{theoret.})^{a}}-1$ (%)	Multipolarity assignment
1434.5	5.67(−5)[b]	−11	*E*2
1334.3	7.26(−5)	0	*E*2
1247.4	5.65(−5)	−33	*M*1-*E*2
935.8	1.53(−4)[c]	−05	*E*2
849.8	1.86(−4)	−08	*E*2
744.3	3.24(−4)	+10	*E*2
346.0	3.87(−3)	+13	*E*2

[a] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958). Extrapolated to $Z=24$.
[b] See footnote b, Table I. Errors on all ICC are ~15%.
[c] Kaye and Willmott (Ref. 12) by γ-γ angular correlation measurements, found this transition to be pure *E*2 coming from a 4+ state, on the assumption that the 1434.5-keV transition is pure *E*2 between $J=2+$ and $J=0+$ states.

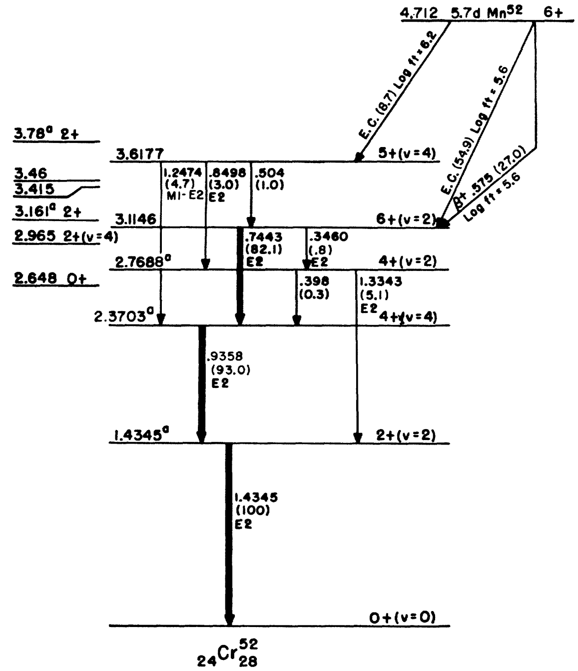

FIG. 2. Decay scheme of Mn^{52} ground state from this work. All levels shown, including those at left, are seen in (p,p') and (p,α) reactions; those labeled *a* are seen in (α,α') scattering. Numbers in parentheses are percent per decay.

well established by (p,α) and (p,p') [8,13,16] we note that the 1.214-MeV gamma, which appeared weakly in the scintillation spectrometer results of Wilson *et al.*[6] only after an extensive peeling subtraction, is not observed in our experiment at an intensity lower by a large factor, either in the gamma or in conversion electron spectra.[17] A similar peeling subtraction was necessary to discern the abundance of this otherwise not manifest gamma in the complex spectrum excepted by (n,n') scattering in the experiments of Van Patter *et al.*[12] It was the excitation function of this gamma near threshold on which the 0+ assignment was based. Although the errors in such a subtraction are clearly not small the conclusion of Van Patter *et al.*[12] as to the 0+ spin of the 2.648 level is supported by the results of Katsanos *et al.*[8] based on relative (p,p') *versus* (p,α) yields of this state, and by the γ-γ angular correlation measurements of Kaye and Willmott.[13]

The negation of any positive evidence that the 2.65-MeV gamma exists removes all support for the participation of the 2.648 level in Mn^{52} decay and the problem about its population. The absence of feed to the state from the 4+ level at 2.769 MeV is consistent with spin assignments of 0+ or of 2+ for the 2.648-MeV level.

[16] M. Mazari, W. W. Buechner, and A. Sperduto, Phys. Rev. **107**, 1383 (1957).

[17] The 1.18-MeV gamma, interpreted by Wilson *et al.* (Ref. 6) to be the 1.214-MeV gamma, is also reduced below detectability by a similar factor. The reduction factors for these gammas are not as large as for others because the region involved is the Compton edge rise of the strong 1.435-MeV gamma.

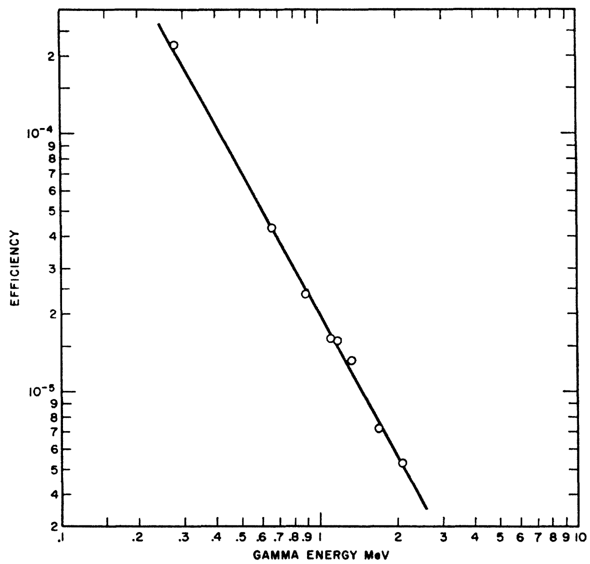

FIG. 3. Efficiency of Ge(Li) detector for full energy peaks as a function of energy for a source ~50 mm from the midplane of a 14-mm-diam detector.

(3) The problem of the feed intensity for the 3.161-MeV state is reduced by a factor of 25 to insignificance with our intensity limit of 0.02% for the 1.73-MeV gamma. $M3$ feed to this 2+ level[10,12,13] from the 5+ state would not be expected to supply even this intensity limit.

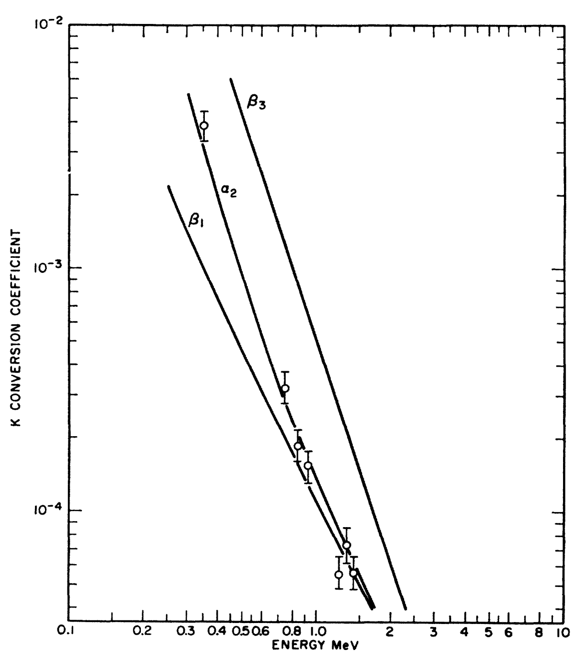

FIG. 4. K-conversion coefficients; (a) solid lines are theoretical values from the tables of M. E. Rose, extrapolated to $Z=24$; (b) open circles are experimental points. Error flags indicate ±15% uncertainty (due to uncertainty in gamma intensities).

(4) A large reduction factor (1/50) eliminates the 0.61-MeV gamma from consideration.

(5) The theoretically interesting branching ratio of the 346-keV/744-keV transitions, mentioned in the Introduction, which we obtain agrees within 10% with that of Wilson *et al.*,[6] the difference not being theoretically significant (see Talmi[1]). From the fact that the reduced $E2$ transition matrix element for the 744-keV transition (between the 6+, $v=2$ state and the 4+, $v=4$ state) is only 2.2 times that for the 346-keV, $\Delta v=0$ transition, Talmi[1] judges that seniority mixing in the states occurs. This expectation is based on the special selection rule[1] for half-filled shells of identical nucleons, which forbids $E2$ transitions between states for which $\Delta v\neq 2$ (e.g., the 346-keV transition).

From our measured branching ratio Lawson[5] has calculated the wave function of the upper 4+ state to be $[0.83(f_{7/2})_0{}^2(f_{7/2})_4{}^2(v=2)-0.56(f_{7/2})_4{}^4(v=4)]$ and $[0.56(f_{7/2})_0{}^2(f_{7/2})_4{}^2(v=2)+0.83(f_{7/2})_4{}^4(v=4)]$ for the lower 4+ state. This is in excellent agreement with the seniority mixing deduced from the (He^3,d) reaction data of Armstrong and Blair.[5,18]

$M1$ transition between pure seniority states of identical particles (in this case $4f_{7/2}$ protons) is forbidden.[1,19] Although the uncertainties in the conversion coefficients are large compared to the differences between the theoretical values for $M1$ and $E2$ (cf. Table III and Fig. 4) there is some indication that the 1247-keV transition is predominantly $M1$ whereas the 850-keV is mainly $E2$ ($\Delta J=1$ for both transitions). The result for the 1247-keV transition agrees with that of Kaplan and Shirley,[15] who found an $E2$ fraction of 3–23% by angular distribution from aligned nuclei. The 1247-keV transition connects states of the same seniority ($\Delta v=0$) between which $E2$ transitions are forbidden. That $M1$ predominates in violation of the above-mentioned $M1$ selection rule indicates the existence of configuration mixing[5,14] in the states involved, without which the transition would vanish. For the 850-keV transition $E2$ is allowed ($\Delta v=2$) and predominates.

Komoda[14] calculated the branching ratio between the 1247- and the 850-keV transitions with and without $M1$ admixture in each, for Serber and for Rosenfeld force mixtures, with the range parameter λ varying from 1.0–1.5 (Komoda's Table 5). The values ranged upwards from 9.0 (for $\lambda=1.5$ and Serber force), to be compared with our value of 1.7 and the Wilson *et al.*[6] value of 2.2. This experimental consistency removes the possibility of agreement with this calculation, which Komoda had assumed might exist within the experimental uncertainty, but suggests that larger λ values are more favorable.

Komoda also has calculated, for the same λ and force

[18] D. D. Armstrong and A. G. Blair, Phys. Rev. **140**, B1226 (1965).

[19] M. H. Macfarlane (private communication); R. D. Lawson and M. H. Macfarlane, Nucl. Phys. **66**, 80 (1965).

mixtures, the $M1$-$E2$ mixing of the 1247-keV transition (Table 6, Ref. 14). Values for the amplitude mixing ratio $\delta=E2/M1$ ranged from 0.41–0.95. Comparison to Kaplan and Shirley's[15] experimental value of $Q=0.03$–0.23 was erroneously judged as disagreement, as this range was assumed to be the δ value. From $|\delta|=[Q/(1-Q)]^{1/2}$, one obtains $|\delta|=0.17$–0.55, which overlaps the range of calculated admixtures, and again supports the choice of λ large.

Komoda has also calculated the $M1$ reduced transition probabilities for all three transitions from the 5+ state. A comparison of these relative values to those derived from our branching ratios, assuming each to be pure $M1$, gives indication of rough agreement only at $\lambda=1.5$, for a Rosenfeld mixture. However, both the 850- and 504-keV transitions are probably mainly $E2$ (conversion coefficients and $\Delta v=2$).

The 2.769-MeV level spin of 4+ is well founded (not 5+ or 6+, no $\beta+$ feed; not 3+ or lower, 0.346-keV γ intensity and conversion coefficient). Therefore the 1.334-MeV gamma can have no $M1$ component ($\Delta J=2$), and the $M3$ component is small or vanishing (cf. Fig. 4). As a pure $E2$ transition it also violates the special selection rule for the pure seniority states shown in Fig. 2. The seniority mixing in the upper 4+ state required to account for its intensity can only be deduced from the unknown value for $B(E2)$ for the transition.

In summary, the decay scheme of Fig. 2 is now complete in all possible transitions of multipolarity $E2$ or lower between all known levels below the 5+ at 3.618, with the possible exception of transitions to the levels at 3.46 and 3.415 MeV, to which no spin assignments have been made. The intensities of the new transitions, the 398 keV between the 4+ states and the 504 keV, can be tested for consistency with the seniority-mixed wave functions, although critical testing of the model will require determination of the $M1$-$E2$ mixing of these and of the 850-keV transition.

From the relative intensities of 1.435-MeV gamma and annihilation radiation one obtains a positron intensity of 0.27 ± 0.01 per disintegration. This is assigned wholly to the 0.575-MeV $\beta+$, since the theoretical ratio of positron emission to electron capture (E.C.) for the beta transition to the 3.618-MeV state is ~1/5000. From the measured intensities of the γ transitions into and out of the 6+ state, one has then for this the ratio of E.C./$\beta+=2.04\pm0.24$, the large error coming from the uncertainties in the gamma counting efficiencies (see Table I). This value is in excellent agreement with that of Konijn *et al.*[20] (1.99 ± 0.06) which comes from β^+-γ coincidence measurements. It is not clear however from that paper which of the members of the main 744-, 936-, 1434-keV γ cascade was used for this coincidence measurement, for each of which a different result is expected because of significant parallel feeds from the weaker transitions. If their measurement was done with the 744-keV gamma, their result is directly comparable to ours, without correction. The decay scheme published does not show the 5+ state, and thus exhibits no awareness of the parallel decay branches. The previous measurements by Good *et al.*[21] and by Sehr[22] using Geiger tubes determined total capture to $\beta+$ ratios (1.86 ± 0.17 and 2.01 ± 0.22, respectively). These values, corrected for the 8% capture branch to the 5+ state, are 1.63 and 1.77. The theoretical value of this ratio for the transition to the 6+ state, from the tables of Zweifel[23] for K capture, with correction for capture in other shells according to the tables given by Wapstra,[24] is 2.01.

[20] J. Konijn, B. Van Nooijen, and H. L. Hagedoorn, Physica **24**, 377 (1958).

III. EXPERIMENTAL

A. Source Preparation

The source for this experiment was obtained as a by-product of a preparation of 18-h Co^{55} by the (d,n) reaction on 97.4% enriched Fe^{54} metal as foil. Deuterons at 21.4 MeV from the Argonne cyclotron were attenuated to ~9 MeV with a 42-mil aluminum covering foil. A 90-μA-h irradiation gave $\sim2\times10^8$ disintegrations per minute of Mn^{52} by the Fe^{54} (d,α) reaction. Gammas were observed in the sample from Cr^{51}, produced from 45-min Mn^{51} formed by $(d,\alpha n)$ on Fe^{54}; from Co^{57}, produced by (d,n) on the 2.5% Fe^{56} in the target; and from Mn^{54}, produced by (d,α) on Fe^{56}.

The target was dissolved in concentrated HCl, the iron was oxidized to Fe^{3+} with concentrated HNO_3, taken up in 8N HCl, and passed through a 2-ml Dowex resin column. At this acid concentration the cobalt and most of the iron are adsorbed on the resin[25] and the manganese elutes. Acid wash was continued with 3 column volumes of 7N HCl until the characteristic scintillation spectrum of Co^{55} (monitored on a portable NaI scintillation head with multichannel analyzer) was observed to begin to bleed through, superimposed on the Mn^{52} spectrum. The last fraction was discarded, and the rest, after drying, was taken up in water and deposited on an ~$\frac{1}{4}$-in. area on 7-mg/cm² aluminum foil by evaporation under a heat lamp. This, on a standard $\frac{3}{4}$-in.-diam aluminum ring mount, served as the source for the electron and gamma spectroscopy. Source thickness is estimated as ~0.5 mg/cm².

The iron adsorbed on the resin column was eluted to separate it from the cobalt activity. After removing the cobalt from the resin, a thin source of Co^{55} was made by volatilization from a wolfram filament onto a 6-mg/cm²

[21] W. M. Good, D. Peaslee, and M. Deutsch, Phys. Rev. **69**, 313 (1946).
[22] R. Sehr, Z. Physik **137**, 523 (1954).
[23] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).
[24] A. H. Wapstra, G. J. Nijgh, and R. Van Leishout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1957), p. 61.
[25] K. Orlandini (private communication).

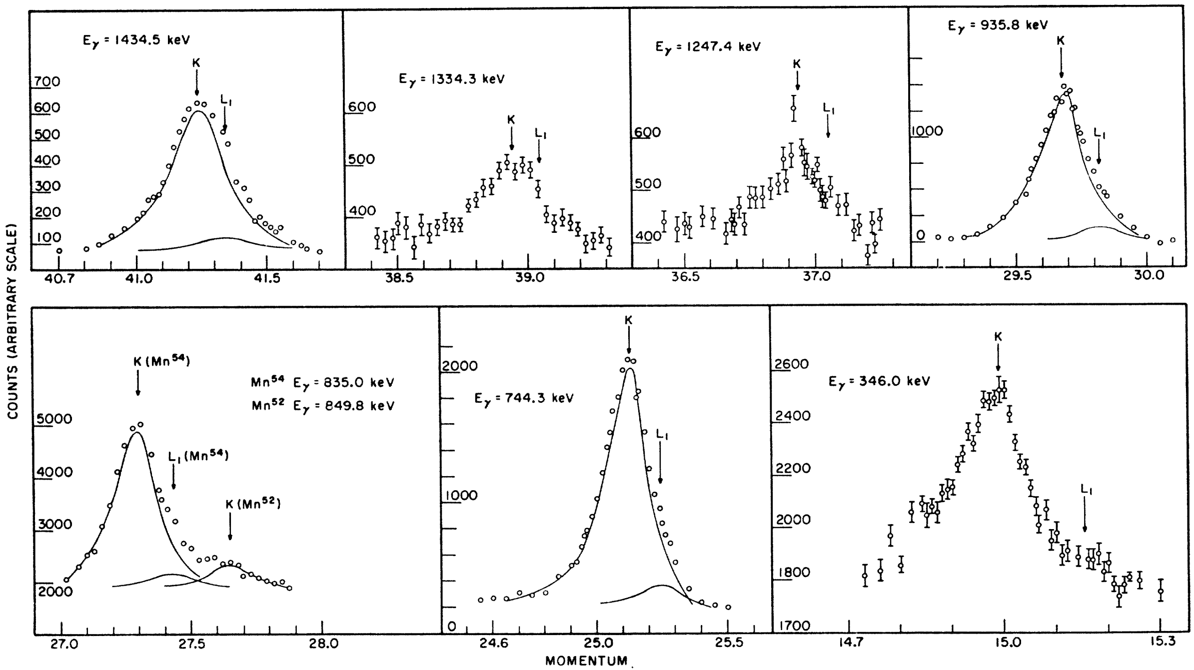

FIG. 5. Conversion lines of Mn^{52}. Ordinate scale shows counts for an arbitrary period of time, varying for different plots. Abscissa scale is potentiometer setting.

Ni foil, over a $\frac{1}{4}$-in.-diam area. A significant amount of manganese activity carried through this procedure with the cobalt, sufficient to permit electron spectrometry of the Mn^{52} prominent lines.

B. Beta Spectrometry

Since a complete survey of the electron spectrum from ~0.1–1.6 MeV was carried out by Wilson *et al.*[6] and was exhibited in their Fig. 7 we examined the spectrum in detail only at each of the conversion lines and at doubtful regions. The Argonne iron-free toroidal beta spectrometer[26] was used at a transmission of 16% and an instrumental resolution of 0.62%.

Even at this high-transmission setting, the background continuum under the conversion lines was less than half as high, relative to the conversion peaks, as in the double focusing spectrometer of Wilson *et al.*,[6] at the same resolution, 0.6%. This background is due to scattered annihilation radiation from positrons which irradiate the walls of the large vacuum chamber on the source side of the toroidal focusing field.

Calibration was referred to the Ba^{137} K line at 3381.03 ± 0.26 $H\rho$.[27] A small correction ($\sim1:10^4$) was made to account for the measured axial displacement of the source with respect to the standard. About one-half the uncertainty in transition energies is due to the standard.

In addition to examining each of the conversion lines of Ref. 6, and surveying the region of the 1.465- and 1.214-MeV K lines at which we found no suggestions of conversion lines, we looked in the neighborhood of 599 keV, but found nothing. At this energy a marked fluctuation in the counting rate is visible in Fig. 7 of Ref. 6, at ~0.800 "peaking strip amperes."

The L line of the 0.346-MeV gamma was resolved from the K line, despite evident line broadening due to source thickness effects. For the other prominent lines, the L line could be readily unfolded as an obvious asymmetrical broadening on the K line. The line broadening effects were taken into account in deriving the conversion-line intensities. Comparison to the gamma intensities was made using 5.70 days for the half-life. At the time we examined the electron spectrum, about two weeks after irradiation, the K conversion line of the 835-keV gamma of Mn^{54} was 8 times the intensity of the K line of the 850-keV gamma in Mn^{52} decay.

The K conversion lines of the 1435- and 744-keV gammas were remeasured on the Mn^{52} contaminant in the thin volatilized Co^{55} source after the Co^{55} had decayed to insignificance. The energy difference between these measurements and those on the thick source (1.7 keV at 1435 and 2.1 keV at 744) determined a smoothly varying correction function applied to the

[26] M. S. Freedman, F. Wagner, F. T. Porter, J. Terandy, and P. Day, Nucl. Instr. Methods **8**, 255 (1960); Bull. Am. Phys. Soc. **8**, 526 (1963); and to be published.

[27] *Alpha, Beta, and Gamma Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), 2nd ed., p. 198; R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instr. Methods **24**, 81 (1963).

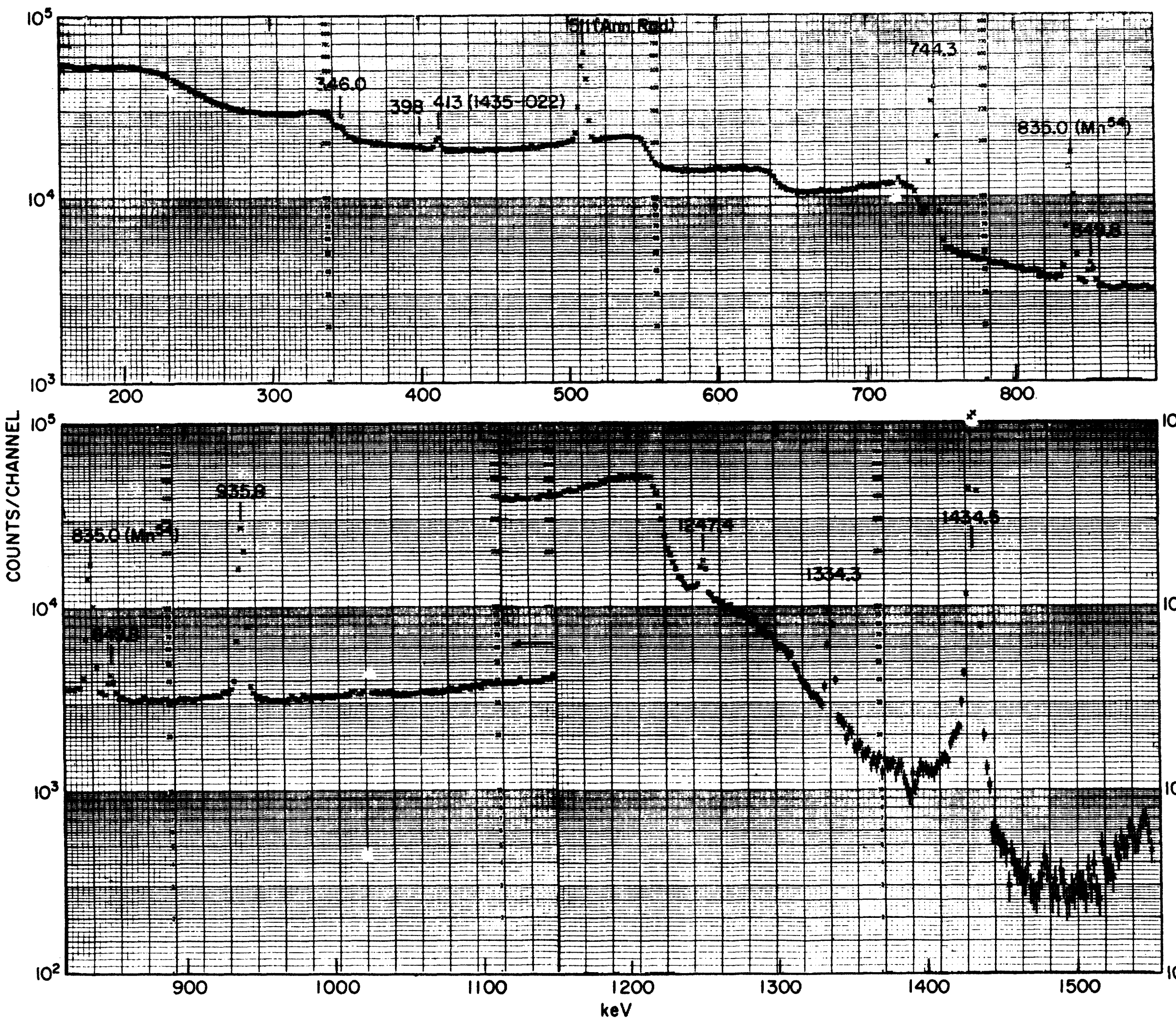

FIG. 6. Gamma-ray spectrum uncorrected for counting efficiency of Ge(Li) detector. Ordinate scale is counts for arbitrary time. Abscissa is energy in keV.

energies of all the lines obtained with the liquid-drop source to account for line shifts due to source thickness.

The results of the beta spectrometry are presented in Tables I, II, and III and in Fig. 5.

C. Gamma-Ray Spectroscopy

The sample used for the gamma-ray spectroscopy was the same as that which was used for the β-ray spectrometer measurements, enclosed in a plastic shield sufficient to stop the positrons locally. For a gamma-ray spectrometer we used a lithium-drifted germanium [Ge(Li)] crystal 14 mm in diameter with the lithium drifted to a depth of approximately 6 mm.

The energy dependence of the full energy-peak counting efficiency of the Ge(Li) counter was determined by counting a number of standards (Co^{60}, Sc^{46}, Hg^{203}, Sb^{124}, Cs^{137}) each at the same distance (25 mm) from the face of the detector. The absolute disintegration rates of the standards had been determined by counting on a 3 in.×3 in. NaI scintillation counter at 10 cm from the face of the crystal. The data of Heath[28] were used for the NaI counting efficiencies. These data were normalized to give absolute counting efficiencies for this experiment by counting a carefully calibrated Cs^{137} source in the identical position used for the Mn^{52} samples.

The area under the full energy peaks was "hand integrated," that is, the data were plotted and the graphically estimated background subtracted channel by channel. The resultant counts in each channel are then summed. Figure 3 shows this experimentally determined full energy efficiency function for the germanium crystal.

[28] R. L. Heath, Atomic Energy Commission Research and Development Report IDO-16880-1, 2nd ed. (unpublished).

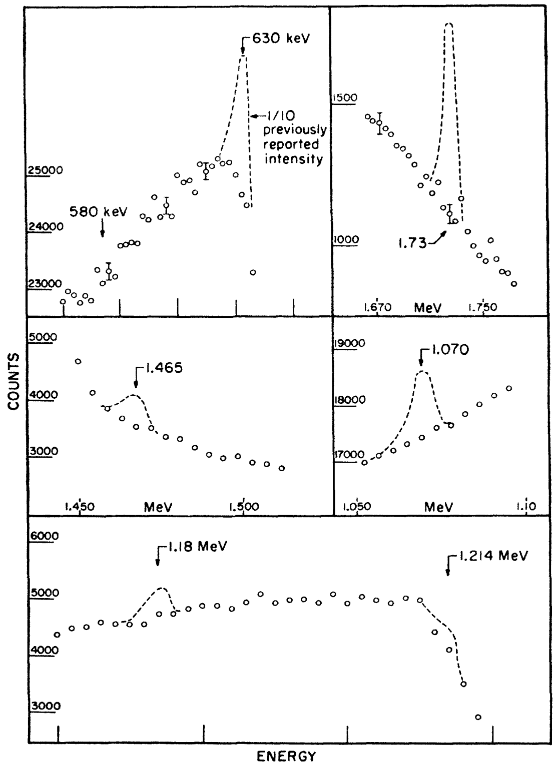

FIG. 7. Gamma-ray spectrum in energy ranges of previously reported gamma rays not found in this investigation. Dotted lines indicate previously reported intensities for the lines.

We assign an uncertainty of 10–15% to the absolute efficiencies.[29]

Counts were accumulated in an 800-channel pulse-height analyzer with gains that resulted in energy dispersions of 1.1 to 2.1 keV per channel on several runs. The full energy peaks showed a full width at half-maximum (FWHM), ranging from approximately 3 keV at low energy to 6 keV at 1.5 MeV.

The count in each of the peaks was determined by plotting the line and graphically subtracting the underlying continuum (Compton scattered electrons from higher energy transitions). The line shape from the detector showed a low-intensity tail on the low-energy side. In unfolding the lines, the underlying continuum was drawn to preserve this line shape, as seen on lines (e.g., 1434, 936) free-standing on featureless regions of the background.

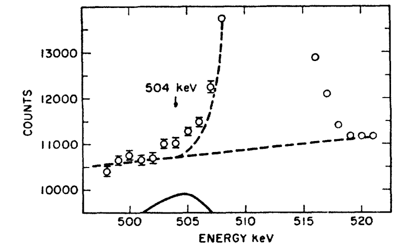

FIG. 8. Expanded view of the base of the 511-keV line. The dashed curve is the shape of the low-energy side of the 936-keV line normalized near the peak of the line on the low-energy side. The indicated difference in the low-energy tail occurs at an energy roughly that expected for the 504-keV transitions (see Fig. 2).

The decay of the gamma-ray spectrum was followed over a period of approximately 600 h, the decay of each gamma being separately plotted. All gammas of interest, those reported here as in the decay of Mn^{52}, (Table I) showed a half-life in good agreement with the published values (i.e., 137 h).[9] Several long-lived gamma rays were seen, some of which were identified with the decay of Mn^{54} and Cr^{51}. The entire spectrum is seen in Fig. 6.

Although the gamma-ray spectrum from 0 to 3 MeV was recorded and plotted, not all previously reported transitions were seen (see Table II). The feasibility of setting the indicated limits is, of course, dependent on the shape of the composite Compton continuum at the energy of interest. Figure 7 shows expanded plots of the several regions where gammas had previously been reported. The dashed lines show constructed gamma-ray lines of previously reported intensities superimposed on our data. The upper limit for intensity of the 2.65-MeV gamma is set by the total counts seen at this energy (background).

Figure 8 shows a comparison of the low-energy side of the 511-keV line and the 936-keV line. These have been normalized on the low-energy side near the peak (35 000 counts). The 936-keV line is narrower than the annihilation line (even though it is a higher energy line) because of the Doppler broadening of the 511-keV line.[30] The small difference in the low-energy tails is roughly at the energy expected for the transition from the 5+ (3618-keV) level to the 6+ (3115-keV) level. The intensity with obviously large uncertainties is given in Table I. The 935-keV line is used because it stands out strongly above a nearly flat background.

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[29] A considerable effort has been made to determine the absolute and relative full energy peak efficiency in two Ge(Li) detectors taking into account such factors as: source-crystal geometry, problems of integrating the peaks, and the nature of gamma intensity standards. A full description of these investigations is inappropriate here both because of its length and because many of the points need further study. We can summarize the somewhat disappointing results in the statement that the absolute efficiencies obtained from Ge(Li) detectors in this work have an uncertainty of 10–15% compared with estimates of 5–10% for NaI given by experienced workers.

This is surprising in the face of the expectations that the much better resolution of the Ge(Li) would yield a cleaner separation of the counts in the full energy peak from the underlying, generally complex backgrounds than is the case in NaI. The uncertainties stem mainly from attempts to apply efficiencies measured under a given set of conditions to data taken under a different set, e.g., geometry, rates, intrinsic windows, biasing voltages, gains, crystal thickness, and various methods for integrating peaks in Ge(Li) and NaI. In addition, evidence of inconsistency and nonreproducibility has been noted in measurements made under apparently identical conditions.

[30] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **45**, 177 (1963).

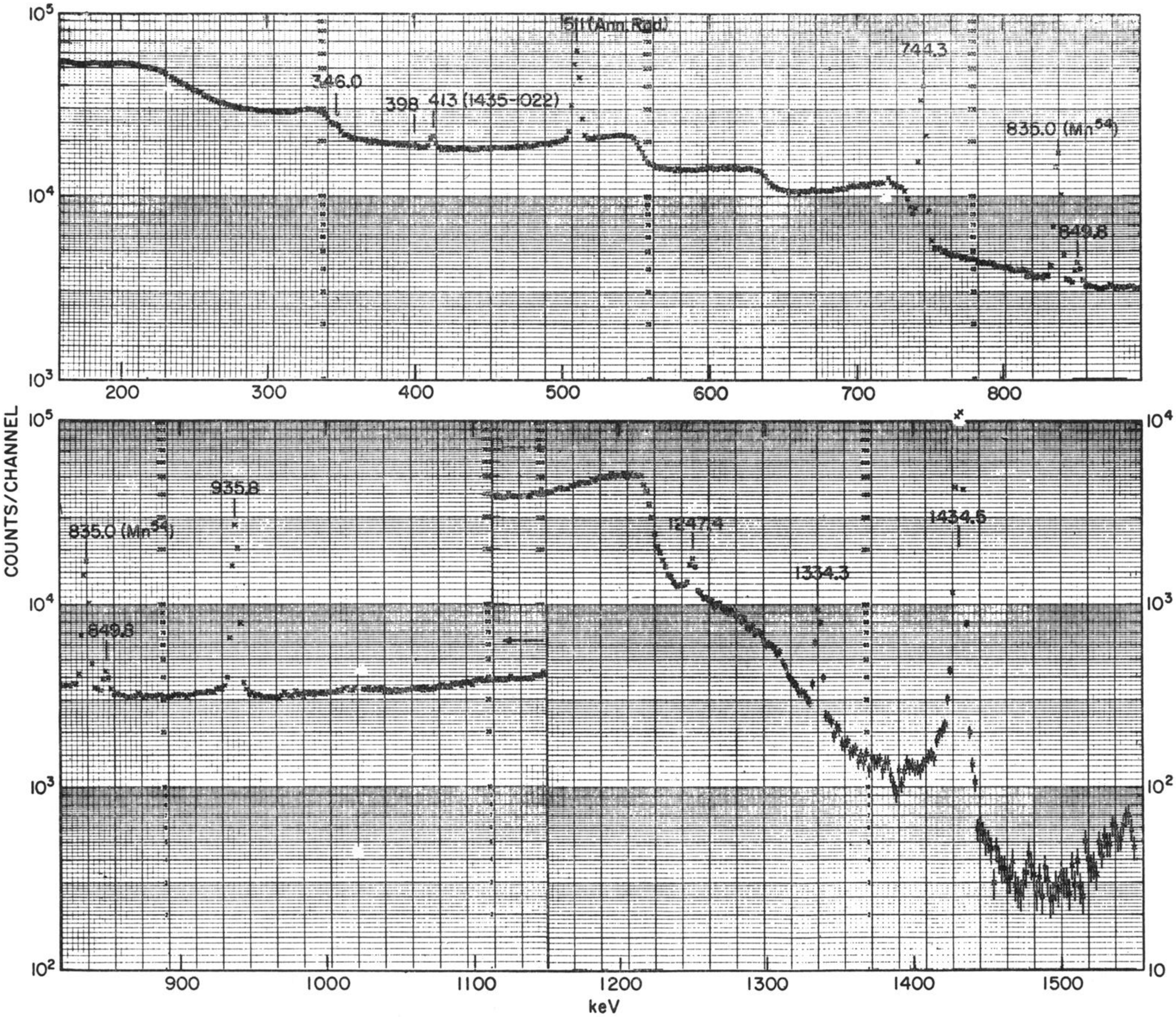

FIG. 6. Gamma-ray spectrum uncorrected for counting efficiency of Ge(Li) detector. Ordinate scale is counts for arbitrary time. Abscissa is energy in keV.