The Beta- and Gamma-Rays of Ga^{72}

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The beta- and gamma-ray spectra of Ga^{72} (14.1 hours) have been measured in a magnetic lens spectrometer. Measurement of the energies of photoelectrons produced in a thin lead radiator gave lines corresponding to gamma-rays of energies 0.631, 0.835, 1.05, 2.18, and 2.50 Mev, and indications of weaker lines at 1.30, 1.47, 1.57, and 1.81 Mev. An internal conversion line, produced by a gamma-ray of 0.691-Mev energy, was also found.

The beta-ray spectrum was found to be highly complex. It is possible to resolve the spectrum into seven groups with end-point energies at 3.17, 2.57, 1.74, 1.45, 1.00, 0.74, and 0.56 Mev.

I. INTRODUCTION

THE beta- and gamma-ray spectra of gallium 72 (14.1 hours) have been investigated with the help of a magnetic lens spectrometer.[1] Gallium exists as two stable isotopes, Ga^{69} and Ga^{71}, from which two radioactive species, Ga^{70}, half-life 20 min., and Ga^{72}, half-life 14.1 hours, have been shown to be formed by neutron capture.[2–4]

Some preliminary results on the spectrum of Ga^{72} have been known for some time,[5, 6] but no detailed study has been made until recently. The distribution of Compton electrons produced by the gamma-rays in a metallic radiator was studied by Mandeville.[7] He used a small 180° type spectrometer and concluded that the spectrum consists of two equally intense gamma-rays of energies 1.17 ± 0.02 and 2.65 ± 0.06 Mev. Siegel and Glendenin[8] found, by absorption techniques, beta-group end points of 0.8 and 3.1 Mev, and one gamma-ray of 2.1 Mev energy. Recently Mitchell, Jurney, and Ramsey[9] made a study of the radiations from Ga^{72} by the use of coincidence counting methods. The beta-ray end point was determined by absorption to be 2.3 Mev. The most energetic gamma-ray, determined by coincidence absorption of the Compton electrons, appeared to have an energy of 2.4 Mev. Finally, measurement of gamma-gamma coincidences showed that there are several gamma-rays per disintegration. Measurements on beta-gamma coincidences as a function of the range of the beta-particles indicated that the beta-ray spectrum is complex and that a strong group of beta-rays with an end-point energy of approximately 0.8 Mev is also present. Later Mandeville and Scherb[10] made a similar study using these techniques with essentially the same results.

A determination of the gamma-ray spectrum, with the help of a magnetic lens spectrometer, was made by Miller and Curtiss,[11] who found gamma-rays at 0.64, 0.84, and 2.25 Mev. Finally, while the present authors' work was nearing completion, a report of an investigation of both the beta- and gamma-ray spectra was published by Haynes[12] with results quite similar to those to be given here.

II. APPARATUS AND PREPARATION OF SOURCES

The apparatus used in this investigation was a magnetic lens spectrometer of conventional design. The general details of the instrument have been described elsewhere[13] and need not be repeated here. An end window counter served as the detector of beta-particles in the instrument

[1] A. C. G. Mitchell, B. D. Kern, and D. J. Zaffarano, Phys. Rev. **73**, 1220 (1948).
[2] E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segré, Proc. Roy. Soc. **A149**, 522 (1935).
[3] R. Sagane, Phys. Rev. **53**, 212 (1938); Phys. Rev. **55**, 31 (1939).
[4] J. J. Livingood and G. T. Seaborg, Phys. Rev. **54**, 51 (1938).
[5] R. Sagane, S. Kojima, and G. Miyamoto, Proc. Phys.-Math. Soc. Jap. **21**, 728 (1939).
[6] J. J. Livingood and G. T. Seaborg, Rev. Mod. Phys. **12**, 30 (1940).
[7] C. E. Mandeville, Phys. Rev. **64**, 147 (1943).
[8] J. M. Siegel and L. E. Glendenin, Rev. Mod. Phys. **18**, 513 (1946); Plutonium Project Reports **9B**, 7.1 (1946).
[9] A. C. G. Mitchell, E. T. Jurney, and M. Ramsey, Phys. Rev. **71**, 324 (1947).
[10] C. E. Mandeville and M. Scherb, Phys. Rev. **72**, 520 (1947).
[11] L. E. Miller and L. F. Curtiss, Phys. Rev. **70**, 983 (1946).
[12] S. K. Haynes, Phys. Rev. **73**, 187 (1948).
[13] B. D. Kern, D. J. Zaffarano, and Allan C. G. Mitchell, Phys. Rev. **73**, 1142 (1948).

and throughout these experiments it was fitted with a mica window of 4 mg/cm^2 surface density.

The sources were prepared by bombarding gallium oxide (Ga_2O_3) targets with 11.5 Mev deuterons in the Indiana University cyclotron. Bombardments ranging from 150–450 micro-ampere hours were used.

The source was purified chemically in the following manner. The oxide was dissolved off the copper target plate with 12*N* HCl and the solution evaporated to dryness. A small amount of copper carrier was added, the solution was diluted to 100 cc, the hydrogen ion concentration adjusted to 3 normal, and the copper was precipitated as copper sulfide by H_2S. The filtrate was evaporated to a small volume and an ether extraction was made of the $GaCl_3$. The source was finally brought down as $Ga(OH)_3$ and converted to Ga_2O_3 by heating. The period of the active source was measured and only the 14.1 hour period of Ga^{72} was found. The twenty-minute period had, of course, disappeared by the time the chemistry was completed.

When the gamma-rays of gallium were to be investigated, the gallium oxide was placed in a cylindrical copper capsule, 1 cm outside diameter, with walls and end just thick enough to stop all beta-rays. If the distribution of photoelectrons was to be observed, a lead radiator, 1 cm in diameter and of 26 mg/cm^2 surface density (in some cases 75 mg/cm^2) covered the end of the capsule. If, on the other hand, the distribution of Compton electrons was to be studied, no additional radiator was used. The preparation of the beta-ray sources will be described later.

III. THE GAMMA-RAY SPECTRUM

The distribution of photoelectrons ejected from a thin lead radiator by gamma-radiation from Ga^{72} was examined in the lens. A number of strong lines appeared corresponding to gamma-ray energies of 0.631, 0.835, 2.18, and 2.50 Mev. In addition, a careful search showed a weak gamma-ray at 1.05 Mev and a number of irregularities in the distribution of the photoelectrons apparently caused by the presence of weaker gamma-rays. In order to investigate these weak lines, a lead radiator of 75 mg/cm^2

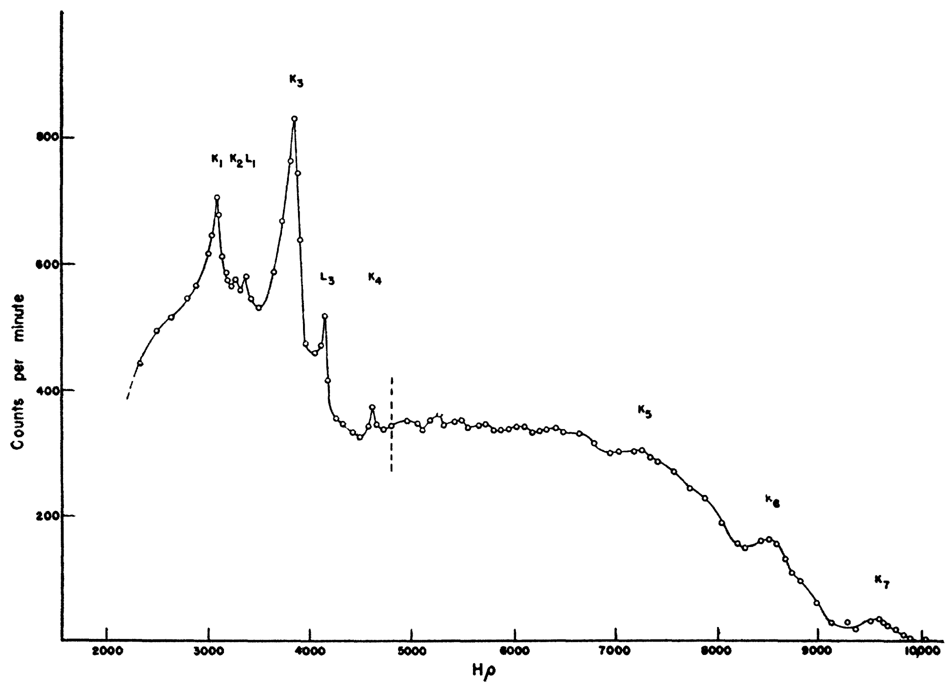

FIG. 1. Spectrum of photoelectrons ejected from lead by the gamma-rays of Ga^{72}. Below 4800 $H\rho$ the lead radiator used had a surface density of 26 mg/cm^2; above 4800 $H\rho$, 75 mg/cm^2. The gamma-ray energies are, respectively: K_1, L_1, 0.631 Mev; K_2, 0.676 Mev; K_3, L_3, 0.835 Mev; K_4, 1.05 Mev; K_5, 1.81 Mev; K_6, 2.18 Mev; K_7, 2.50 Mev.

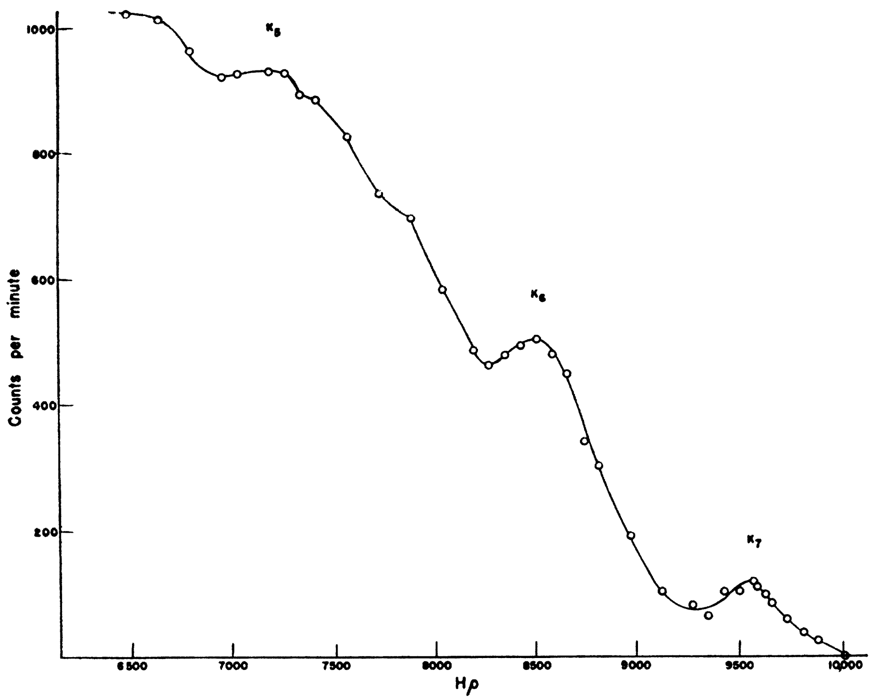

FIG. 2. Spectrum of photoelectrons ejected from lead by the higher energy gamma-rays of Ga^{72}. The lead radiator used had a surface density of 75 mg/cm^2. The gamma-ray energies are, respectively: K_5, 1.81 Mev; K_6, 2.18 Mev; K_7, 2.50 Mev.

surface density was used and the region from approximately 1 Mev to 3 Mev was carefully studied. This study brought to light a weaker line at 1.81 Mev. A composite curve of the photoelectron distribution is shown in Fig. 1, in which the various peaks are labelled. Figure 2 gives the enlarged view of the distribution at the high energy end. The peaks caused by gamma-rays at 1.81, 2.18, and 2.50 Mev can be clearly seen.

Returning to Fig. 1, it is evident that the strongest and most easily identifiable peaks on the curve, in the low energy region, are the K peak from the 0.631-Mev line and the K and L peaks from the 0.835 Mev line. Between the K peak from the 0.631 Mev line and that from the 0.835-Mev line will be seen two small peaks. The higher energy one of these two corresponds to the L peak of the 0.631-Mev line and the other, barely distinguishable, corresponds to a K peak for a line at 0.676 Mev. Farther out on the curve the lines at 1.05, 1.81, 2.18, and 2.50 Mev are clearly seen.

In order to get confirmation of the existence of these lines and to obtain an estimate of their relative intensities, the distribution of the Compton electrons from a copper radiator was studied. Figure 3 shows the results of this investigation. Here the number of counts per minute is plotted as ordinate against Hρ (gauss-cm) as abscissa. The results confirm the existence of the gamma-rays at 2.50, 2.18, and 1.81 Mev, together with most of those of lower energy. In addition, there is some evidence for the existence of a gamma-ray at 0.691 Mev, and additional lines at 1.57, 1.47, and 1.30 Mev. The line at 0.69 Mev, if present, is quite weak. An estimate of the relative intensities of the stronger lines was obtained by using a method developed by Siegbahn.[14] In this method an "empirically-determined shape" is fitted to the data in Fig. 3. The higher energy components are fitted first, and the lower energy ones are then determined by subtraction. The areas under the individual curves are then calculated by integration and the intensities estimated by applying a correction for the efficiency of production of Compton elec-

[14] K. Siegbahn, Proc. Roy. Soc. **A188**, 541 (1947).

trons as a function of energy. The weak lines are taken together in one group. These results are shown in Table I. Since the intensities of the lower energy lines are determined by subtracting off the contributions from the higher energy lines, they are subject to rather large errors.

IV. THE BETA-RAY SPECTRUM

For the measurement of the beta-ray spectrum sources of high specific activity were used. In general, these required a bombardment of about 400 microampere hours of 11.5–Mev deuterons. The beta-ray sources were prepared by dissolving the active purified $Ga(OH)_3$ in HCl and evaporating a small drop of this solution on a thin Zapon film, approximately 0.1 mg/cm^2 surface density, or on an aluminum foil of surface density 1 mg/cm^2. These sources were approximately circular and varied in size from 0.5 cm to 1.0 cm in diameter. The surface density of the sources varied from 0.15 to 5.0 mg/cm^2.

Several determinations of the beta-ray spectrum were made. A plot of the spectrum is shown in Fig. 4. Here the number of counts per minute, corrected for decay, is plotted as ordinate against $H\rho$ (gauss-cm) as abscissa. Many points were taken, close together, and each point

TABLE I. Energies and relative abundances of beta- and gamma-rays from Ga^{72}.

$H\rho$ of electrons	Energy of gamma-ray	Gamma-rays Percent abundance	Evidence
9620	2.50 Mev	6 percent	K photo line
8520	2.18	13	K photo line
7260	1.81	4	K photo line
5970	1.57	9	Compton electrons; weak
5510	1.47		
5060	1.30		
4610	1.05	6	K photo line
3833	0.835	39	K photo line
3245	0.676*	2	K photo line; very weak
—	0.691*	—	Internal conversion
3075	0.631	21	K photo line

Beta-rays Group end-point energy	Percent abundance
3.17 Mev	8 percent
2.57	8
1.74	3
1.45	7
1.00	26
0.74	23
0.56	25

Internal conversion electrons $H\rho$ of electrons	Energy of electrons	Energy of gamma-ray
3585	0.680 Mev	0.691 Mev

* Probably both are due to the same gamma-ray (0.691 Mev); the internal conversion electron determination is more accurate.

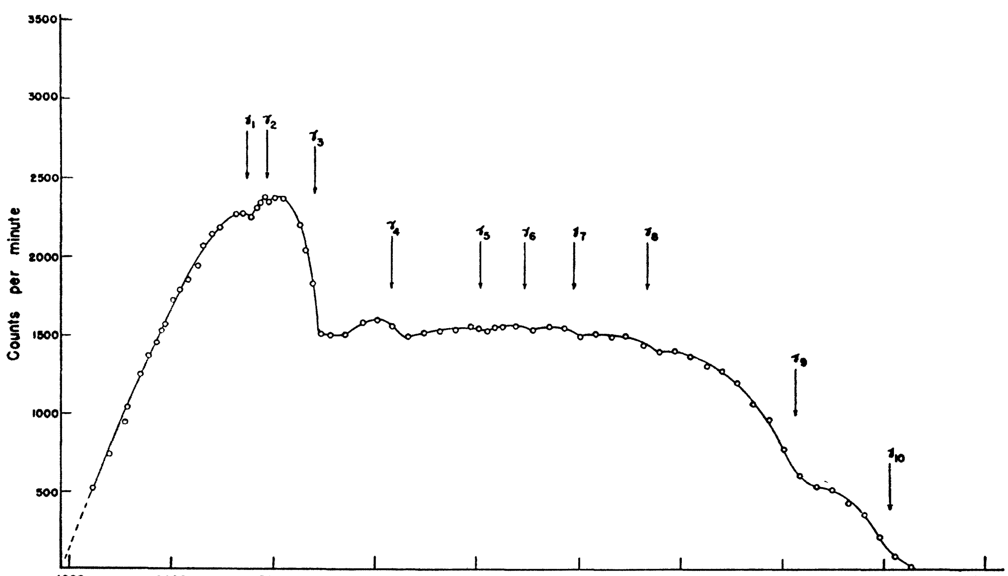

FIG. 3. Spectrum of Compton electrons ejected from copper by the gamma-rays of Ga^{72}. The gamma-ray energies are, respectively: γ_1, 0.631 Mev; γ_2, 0.691 Mev; γ_3, 0.835 Mev; γ_4, 1.05 Mev; γ_5, 1.30 Mev; γ_6, 1.47 Mev; γ_7, 1.57 Mev; γ_8, 1.81 Mev; γ_9, 2.18 Mev; γ_{10}, 2.50 Mev.

represents not less than 10,000 counts. From a casual inspection of this curve it is readily seen that the spectrum is highly complex. Even without the construction of a Fermi plot, it is evident that there are several groups of electrons. In addition, there is an internal conversion line at 3585 gauss-cm.

An analysis of the beta-ray data was made with the help of the Fermi theory. The data may be resolved into seven groups with end points and relative intensities as shown in Table I. Of the various groups, those at 1.74, 1.45, and 0.56 are probably the least certain; the first two because they are weak, the last because of the many subtractions which have to be made before arriving at this group. The groups at 3.17, 2.57, 1.00, and 0.74 Mev are more easily determined by virtue of either their position or intensity. The possibility of groups of lower energy than 0.56 Mev is not precluded.

The *ft*. values for each group have been calculated. The groups with end points at 3.17, 2.57, 1.74, and 1.45 Mev belong to the second forbidden class, and those with end points at 1.00, 0.74, and 0.56 Mev are first forbidden.

The internal conversion electrons which appear at 3585 gauss-cm have an energy of 0.680 Mev. If it be assumed that these electrons are produced by internal conversion in the K-shell of Ge^{72}, the energy of the gamma-ray which is internally converted is 0.691 Mev. The ratio of the number of internal conversion electrons to the total number of disintegration electrons is 0.005. It is not definitely known where this internally converted transition occurs in the disintegration scheme, hence it is not possible to calculate an internal conversion coefficient for this process.

Recently Bowe, Goldhaber, Hill, Meyerhoff, and Sala[15] have measured delayed coincidences between the internal conversion electrons men-

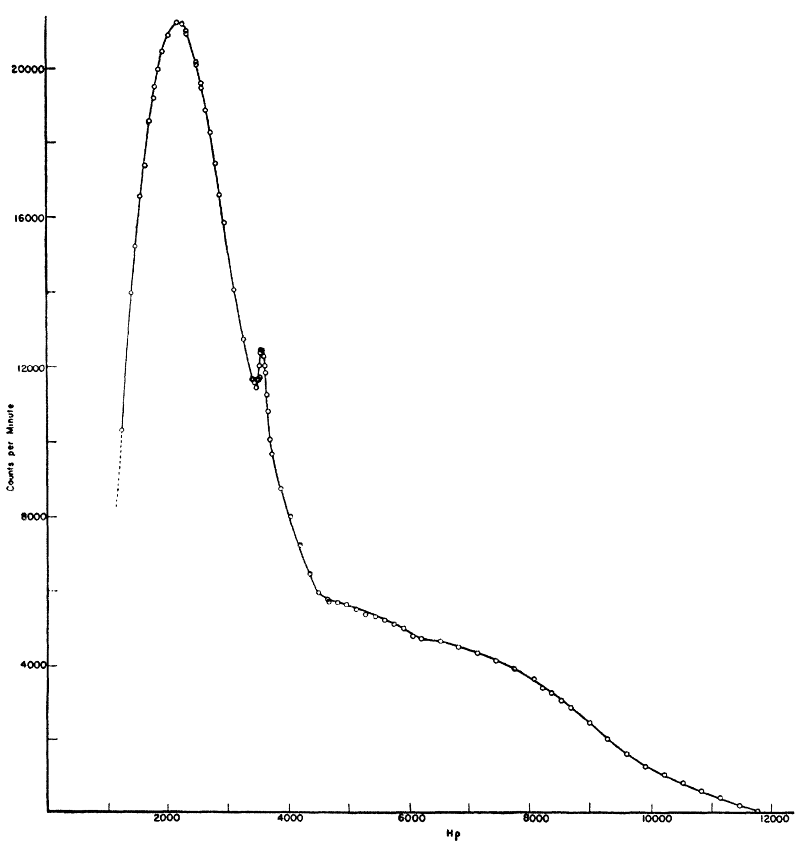

FIG. 4. The beta-ray spectrum of of Ga^{72}.

[15] J. C. Bowe, M. Goldhaber, R. D. Hill, W. E. Meyerhoff, and O. Sala, Bull. Am. Phys. Soc. 22, No. 6, 6 (1947).

tioned above and the disintegration electrons. They concluded that the internal conversion electrons come from a metastable level of about 30 microseconds' half-life, which follows a low intensity beta-transition of energy 1.5 Mev. Moreover, they could find no delayed gamma-rays, from which they concluded that the gamma-ray associated with this transition must be almost completely internally converted. They suppose that the transition involved is one in which both the initial and final level have spin $i=0$.

V. DISCUSSION

It is probably not possible to give a complete decay scheme for Ga^{72} since this seems to be extremely complicated. Some of the gamma-rays are so weak as to make one skeptical of their existence. However, these weak gamma-rays are seen on each run and appear not to be caused by impurities.

The most striking feature of the spectrum is the high intensity of the line at 0.835 Mev. The intensity of this line is sufficiently high so that it may be assumed that practically all transitions lead through it to the ground state of Ge^{72}. The next most intense gamma-ray is that at 0.631 Mev, and it would appear that this line must be in series with several other gamma-rays. The line at 2.18 Mev is the third strongest line of the spectrum but, being a high energy line, its intensity probably comes about because it follows a beta-ray transition of rather high intensity. With these ideas as a foundation, a tenetative disintegration scheme is given in Fig. 5. In this diagram, the levels of Ge^{72} which are determined by the analysis of the beta-ray spectrum are shown slightly separated from and to the left of those determined with the help of the gamma-ray data. This is done purposely to show the order of magnitude of the discrepancies found. The worst discrepancy found seems to be of the order of 3 percent. The gamma-ray lines which appear to be certain are shown as solid lines, the others as dotted lines. Using the three better-known lines together with the associated beta-ray transitions as shown in the diagram, the energy of Ga^{72} above the ground state of Ge^{72} is found to be 4.01, 4.04, and 4.02 Mev, which shows that this part of the scheme is internally consistent to better than one percent. In addition, the energies of the two gamma-rays at 0.631 and 1.57 Mev add up approximately to that of the gamma-ray of energy 2.18 Mev. The 2.50-Mev line probably follows the 0.56-Mev beta-ray transition and leads to the 0.835-Mev level. The energy of Ga^{72} calculated via this route is $0.835+2.50+0.56=3.90$ Mev, which agrees with the other values for that energy to 2.5 percent. The remaining weak lines are placed in the scheme where they seem to fit from energy considerations. The line at 0.691 Mev is placed following the 1.74-Mev beta-transition and in a position in which it does not lead to the ground state, in spite of the fact that it is internally converted and has been shown by Bowe *et al.*[15] to be a delayed transition. From energetic considerations, there seems to be no other place in the scheme into which this line will fit.

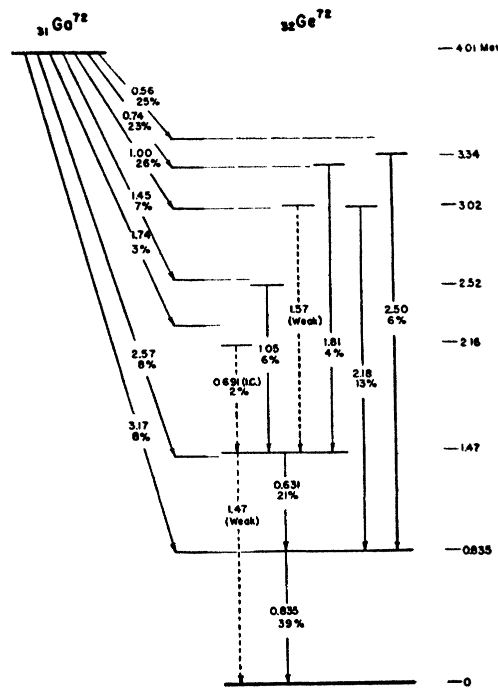

FIG. 5. Tentative energy level diagram for the disintegration of Ga^{72}.

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