Energy Levels of As^{75}†*

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The excited levels of As^{75} were investigated by studying the decay schemes of Se^{75} and Ge^{75}. Beta- and gamma-ray energies, internal conversion coefficients and relative transition intensities were measured. In addition, coincidence and gamma-gamma directional correlation experiments were performed. Se^{75} electron-captures to a level at 402 kev in As^{75}; eleven transitions of indicated energy and multipolarity follow the electron-capture process: 25, 66($M1+E2$), 81, 97($E2$), 121($M1+E2$), 136($M1+E2$), 199($M1+E2$), 265($M1+E2$), 280($E2$), 305, and 402($M1$) kev. Ge^{75} decays by emission of negative beta groups with end-point energies of 1.19, 0.98, 0.92, 0.72, and 0.55 Mev. Subsequently, six gamma rays with the following energies are emitted: 66, 199, 265, 427, 477, and 628 kev. A level scheme for As^{75} is proposed and plausible spin and parity assignments are discussed. The evidence indicates that most of the levels of As^{75} have spin 1/2 or 3/2 and are not single-particle shell-model states.

INTRODUCTION

A NUMBER of levels of As^{75} have been found at rather low excitation energies.[1] For instance, Jensen *et al.*[2] postulate the existence of six levels below 402 kev in order to account for the gamma spectrum of a Se^{75} source. Since such close level spacing cannot be explained in terms of the single-particle shell model, core deformation has to be assumed. At arsenic the $3p_{3/2}$ and $4f_{5/2}$ proton subshells and the $3p_{1/2}$ and $5g_{9/2}$ neutron subshells are being filled.[3] In each case the energy difference between the subshells is very small; therefore, conditions are favorable for the existence of close low-lying levels due to core excitation. The purpose of this investigation is to establish, as far as possible, a definite level scheme with spin and parity assignments and thus gain information as to the neutron-proton configurations of these levels. The disintegration schemes of Se^{75} and Ge^{75} have been investigated repeatedly[1] and a brief summary of some of the published results follows. An attempt is made to emphasize existing discrepancies and deficiencies.

Se^{75} (127 days)[1] decays by electron-capture to one or several excited states of As^{75}. The internal conversion-electron spectrum and the photoelectron spectrum have been measured several times[1] and good agreement exists as to the gamma-ray energies (66, 97, 121, 136, 199, 265, 280, 305, and 402 kev). However, Cork *et al.*[4] observed internal conversion-electron lines from gamma rays of energies 24.7 and 80.8 kev though no evidence for these transitions was found by other investigators.[2,5] On the other hand, a strong 76.6-kev gamma ray, which was not seen by Cork *et al.*, has been reported.[2,5] Jensen and co-workers[2] have proposed a decay scheme for Se^{75} based on gamma-ray energies, approximate transition intensities and some preliminary coincidence observations with G.M. tubes. The level scheme proposed by Cork *et al.* on the basis of gamma-ray energies differs from that of Jensen and co-workers because the 24.7- and 80.8-kev transitions are included. Temmer and Heydenburg[6] induced by Coulomb excitation transitions of 68, 199, and 283 kev with relative yields of 0.02, 0.4, and 0.3, respectively. Only Cork's disintegration scheme is consistent with the Coulomb excitation results.[7]

To date no decay scheme has been proposed for Ge^{75} (80 min).[1] Smith *et al.*[8] found two negative beta groups having end-point energies and relative abundances of 1.137 Mev (85 percent) and 0.614 Mev (15 percent). The 1.137-Mev beta group decays to the ground state of As^{75} since no 1.137-Mev beta, gamma coincidences could be found. Internal conversion-electron lines at 408 and ~520 kev were seen superimposed on the beta spectra. The electron spectrum from a uranium converter was investigated and a photoelectric line from a 265-kev gamma ray, together with Compton electrons from a transition at ~600 kev, were observed. Weak gamma rays at 418 and 572 kev, in addition to the 265-kev line, were seen on a scintillation spectrometer. A 250-kev gamma ray, approximately 10 percent abundant, was observed by Reynolds.[9] This gamma-ray energy was obtained by aluminum absorption measurements and therefore it is not surprising that weaker lines were missed. The

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[1] See Hollander, Perlman, and Seaborg, "Table of Isotopes," Revs. Modern Phys. **25**, 469 (1953).
[2] Jensen, Laslett, Martin, Hughes, and Pratt, Phys. Rev. **90**, 557 (1953).
[3] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).
[4] Cork, Rutledge, Branyan, Stoddard, and LeBlanc, Phys. Rev. **79**, 889 (1950).
[5] Ter-Pogossian, Robinson, and Cook, Phys. Rev. **75**, 995 (1949).
[6] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1954).
[7] Since the completion of this manuscript Lu, Kelly, and Wiedenbeck published [Phys. Rev. **97**, 139 (1955)] a decay scheme for Se^{75} based on an investigation of the normal and "summed" gamma-ray spectra. The scheme proposed by these authors is a compromise between the schemes of Jensen *et al.* and Cork *et al.* and includes a 77-kev transition of appreciable intensity.
[8] Smith, Caird, and Mitchell, Phys. Rev. **88**, 150 (1952).
[9] S. A. Reynolds (private communication).

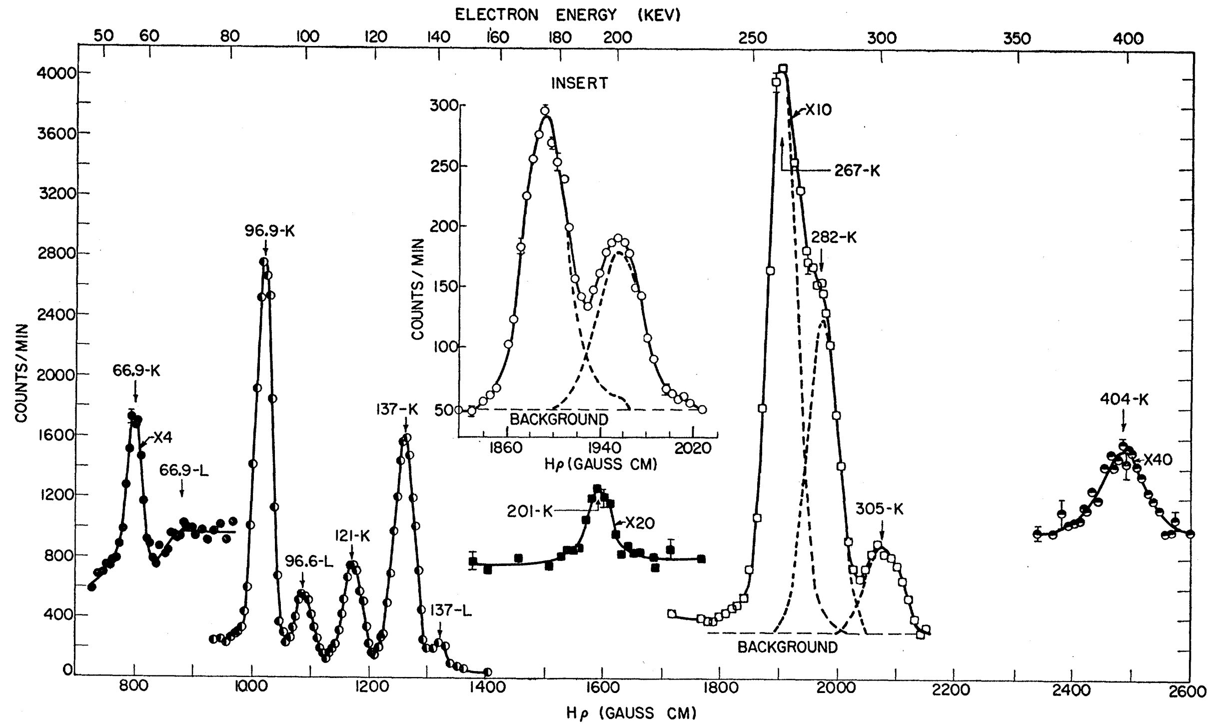

FIG. 1. Internal conversion-electron spectrum from a 0.5-mg/cm² Se^{75} source. Both G.M. counters were used and the data internormalized. Different scale factors are used for various portions of the curve. Dashed curves represent Gaussian distributions fitted to individual photopeaks. The Insert was obtained using 2.4 percent resolution.

difference in end-point energies of the two beta groups observed by Smith *et al.* points to the existence of an As^{75} level at 523 kev. No single gamma ray or gamma-gamma cascade of sufficient intensity to account for the decay of this level has been reported.

EXPERIMENTAL PROCEDURES AND RESULTS

Source Preparation

The Se^{75} sources were prepared by irradiating natural metallic selenium[10] with slow neutrons.[11] The other selenium activities made on slow-neutron irradiation are short-lived[1] with the exception of Se^{79}; a negligible amount of this activity is produced because of the relatively small capture cross section of Se^{78} and the long half-life ($\lesssim 6.5\times 10^4$ years)[1] of Se^{79}. No radiochemical purification of the irradiated material from nonisotopic activities was necessary. When thin, uniform sources were required the activity was distilled in vacuum onto a cold finger covered with an aluminum foil of suitable thickness.

An additional Se^{75} source was made by bombardment of germanium with 40-Mev α particles. The selenium plus arsenic activities were isolated by a distillation procedure,[12] several milligrams of selenium carrier were added and metallic selenium was precipitated several times in the presence of arsenic hold-back carrier. The gamma-ray spectrum of this Se^{75} source, as seen on a scintillation counter, was identical with that of the pile-irradiated sources.

The Ge^{75} sources were prepared by irradiating germanium dioxide powder[13] with slow neutrons. Irradiation times were of the order of minutes and the sources were used only during the first half-life of Ge^{75}. When the radiations from sources enriched and nonenriched in Ge^{74} were compared on a scintillation spectrometer no significant differences were observed. Small amounts of nonisotopic activities such as Na^{24} were present in all sources used. When beta sources were required, the germanium dioxide powder was spread onto a thin cellophane backing and covered with 1 percent Zapon.

Conversion-Electron Spectra of Se^{75}

In order to obtain conversion-coefficient data on which to base multipolarity assignments, the relative intensities of both the internal and external conversion-electron lines from a Se^{75} source were determined. The measurements were made on a conventional magnetic lens spectrometer set for a momentum resolution of 3.2

[10] The selenium metal was purchased from the Johnson Matthey Company.

[11] The authors are indebted to the Metals Testing Reactor group for producing a sample of high specific activity.

[12] J. Irvine, J. Phys. Chem. **46**, 910 (1942).

[13] The nonenriched germanium dioxide was purchased from the Johnson Matthey Company. Germanium dioxide enriched in Ge^{74} (95.8 percent) was supplied by the Y-12 plant, Carbide and Carbon Corporation, through the Isotopes Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

TABLE I. Se^{75}: Gamma-ray, internal conversion-electron and transition intensities.

(1) Transition energy (kev)	(2) Relative gamma-ray intensity: Lens spectrometer[a]	(3) Relative gamma-ray intensity: Scintillation spectrometer	(4) Relative gamma-ray intensity: Final	(5) Relative internal conversion-electron intensity[c]	(6) Total conversion coefficient, scintillation spectrometer	(7) Final conversion coefficient[c,e]	(8) Transition intensity, percent of Se^{75} disintegrations[f]
402		0.17 ±0.02	0.248 ±0.025	13.3 ± 1.5 (K)	0.00243	0.0024 ±0.0005 (K)	14.0
305	0.020 ±0.005		0.020 ±0.005	14.5 ± 1.2 (K) }		0.03 ±0.01 (K)	1.2
280	0.457 ±0.04 }	1.00	0.457 ±0.04	197 ±20 (K) }	0.0186 ±0.005	0.019 ±0.005 (K)	26.2
265	1.00 }		1.00	369 ±30 (K) }		0.016 ±0.005 (K)	57.0
199		~0.02	~0.03	23.5 ± 2.5 (K)		~0.03 (K)	1.8
136	1.00 }	0.84 ±0.09	0.94 ±0.12	{1550 (K)		{0.07 ±0.02 (K)	56.7
				{190 ±20 (L)		{0.009 (L)	
121	$0.301^{+0.08}_{-0.02}$ }		$0.28^{+0.06}_{-0.03}$	640 (K)		0.10 ±0.03 (K)	17.3
97	0.052 ±0.016	0.045 ±0.01	0.066 ±0.015	{2640 (K)		{1.8 ±0.8 (K)	11.5
				{430 ±50 (L)		{0.3 (L)	
81				~30[d] (K)			~0.13[d]
77		≤0.002		<30			≤0.2[g]
66		0.012 ±0.007	0.018 ±0.01	250 ±30 (K)		0.6 ±0.3 (K)	1.6
K x-ray		0.55 ±0.08[b]	0.81 ±0.12				80[h]

[a] The intensities of the 305- and 280-kev gamma rays are reported relative to that of the 265-kev gamma ray; the intensities of the 121- and 97-kev gamma rays are reported relative to that of the 136-kev gamma ray.
[b] The intensity of K x-rays relative to 121-kev plus 136-kev quanta was measured.
[c] (K) or (L) refers to the electron shell of arsenic in which the conversion occurs.
[d] It was estimated from the photographic record of a permanent magnet spectrograph experiment that $81(K)/66(L)$ is slightly less than unity. The intensity values were then calculated using the theoretical K/L value of the 66-kev transition (reference 39) and the theoretical $E2$ K-conversion coefficient of the 81-kev transition (reference 21).
[e] In order to calculate these final coefficients, the total conversion coefficients measured with the scintillation spectrometer were corrected for the contribution due to L conversion.
[f] Taking into account the decay scheme given in Fig. 11, the total disintegration rate of Se^{75} was calculated from the gamma-ray intensities [data of column (4)] corrected for conversion using column (7).
[g] A $77(K)$ line was not present in the photographic record of the permanent magnet spectrograph experiment. Using a conservative estimate of the minimum line intensity detectable above the film background and the theoretical $E1$ K-conversion coefficient (reference 21), an upper limit of 0.6 percent can be placed on the intensity of this transition.
[h] To obtain the number of K holes, the K x-ray intensity has been corrected for the fluorescence yield (57 percent). This fluorescence-yield value was obtained from the curve of Broyles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953). See also reference 32.

percent. Geiger-Müller counters were used as detectors; one counter had a 0.5-mg/cm² nylon window, the other an approximately 2.0-mg/cm² mica window. Over the range, ~250 to ~400 kev, counter-efficiency corrections for the mica-window counter were measured relative to the thin-window counter. Absorption corrections taken from the curves of Saxon[14] for the 0.5-mg/cm² window were applied; nevertheless, the intensity data for energies below 50 kev are inaccurate. Coincidence loss corrections were made in the usual manner.[15]

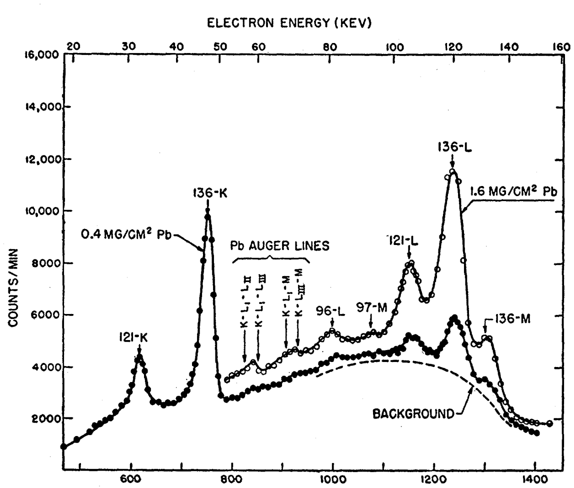

FIG. 2. Photoelectron spectra of Se^{75} obtained with the nylon-window counter. ○ 1.6-mg/cm² lead converter. ● 0.4-mg/cm² lead converter.

[14] D. Saxon, Phys. Rev. **81**, 639 (1951).
[15] G. Friedlander and J. W. Kennedy, *Introduction to Radiochemistry* (John Wiley and Sons, Inc., New York, 1949), p. 213.

The internal conversion-electron spectrum from a 0.5-mg/cm² thick Se^{75} source is shown in Fig. 1 and the relative intensity data are summarized in Table I, column (5). The photoelectron spectra from a Se^{75} source (Figs. 2 and 3) were obtained by using lead converters of suitable thickness. The Compton background curve shown in Fig. 2 was calculated on the assumption that the background is not increased by the presence of the lead converter; in this way, a lower limit for the background was obtained. Maximum values of the background at various points were estimated by interpolation between the count rates on either side of a photopeak. The errors listed in Table I, column (2) were arrived at by considering these extreme background values. The relative intensities of the 265-, 280-, and 305-kev gamma rays were calculated from the ratio of the peak heights of the K-conversion lines. Similarly, the relative intensities of the 136-, 121-, and 97-kev gamma rays were obtained from the ratio of the peak heights of the L-conversion lines.

Conversion electrons from the 76.7-kev gamma ray found by other investigators[2,5] should appear in the region of the lead Auger lines (Fig. 2). According to the intensities quoted by Jensen *et al.*,[2] the 76.7-kev gamma ray is two-thirds as intense as the 136-kev gamma ray. Therefore, the $76.7-L$ photoelectric line should be more intense than the $136-L$ line. However, the conversion-electron line intensities in this region are completely accounted for by the Auger lines of the lead K x-ray series.

The internal conversion spectrum of Se^{75} was also investigated with a 100-gauss permanent magnet spectrograph. Both the K-, L-, and M-conversion lines of a

24.4-kev transition were observed and the experimental energy differences ($K-L=10.23\pm0.15$ kev, $L-M=1.31\pm0.15$ kev) agree with the arsenic $K-L$ and $L-M$ differences. A very weak K-conversion line corresponding to an 81.2-kev transition was also found, but the identification of this line is not definite since the L-conversion line was not observed. The following transition energies were measured with an accuracy of ±0.3 percent: 24.4, 66.3, 81.2, 96.9, 121.1, and 136.1 kev. These results are in excellent agreement with the values of Cork *et al.*[4] The Se^{75} gamma-ray energies used in the rest of this paper are those of Cork and coworkers since they measured accurately the energy of every gamma ray.

Relative Transition Intensities

The relative gamma-ray intensities were measured with a scintillation spectrometer consisting of NaI(Tl) crystals, DuMont 6292 photomultipliers, a Beva 1.5-kev power supply, a nonoverload amplifier[16] with a gain of 1000, and an Atomic Instrument single-channel analyzer. Most of the measurements were made with a 1.5-inch diameter by 1-inch high crystal. The area under a photopeak corrected by a photopeak-efficiency factor is taken as a measure of the gamma-ray intensity. The photopeak efficiency is equal to the product of an intrinsic efficiency factor[17] and a peak-to-total term. The latter was evaluated from measurements of the ratios of the photopeak to Compton-plus-photopeak count rates for sources which emit one gamma ray.[18] The relative intensities of nuclear gamma rays of energy less than 150 kev were measured with a 0.2-cm thick, 2-cm diameter NaI(Tl) crystal. The necessary efficiency factors were calculated for this size crystal. In order to evaluate the count rate in each photopeak, the background due to higher energy transitions has to be subtracted. The intensity of the continuous spectrum accompanying each major transition was evaluated by normalization of the observed pulse-height distribution of a gamma ray of essentially the same energy.[19] Figure 4 serves to illustrate the procedure used. Curve (a) represents the summed Compton contributions from the 402-, 280-, and 265-kev Se^{75} gamma rays. Curves (b) and (c) represent the contributions of the 136- and 121-kev gamma rays, respectively. The latter two curves were obtained by normalization of the Tc^{99m} pulse-height distribution to the 136- and 121-kev photopeaks, respectively. The ratio of the 121- to 136-kev gamma-ray intensities was taken from the lens-spectrometer results. The sum of curves (a), (b), and (c)

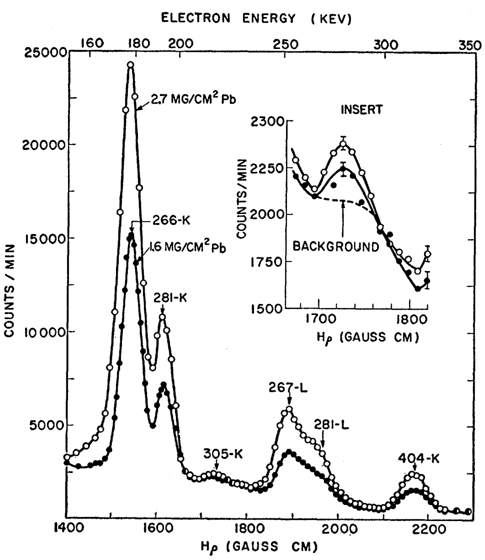

FIG. 3. Photoelectron spectra of Se^{75} obtained with the mica-window counter. ○ 2.7-mg/cm² lead converter. ● 1.6-mg/cm² lead converter. The 305—K line is shown on an enlarged scale in the Insert.

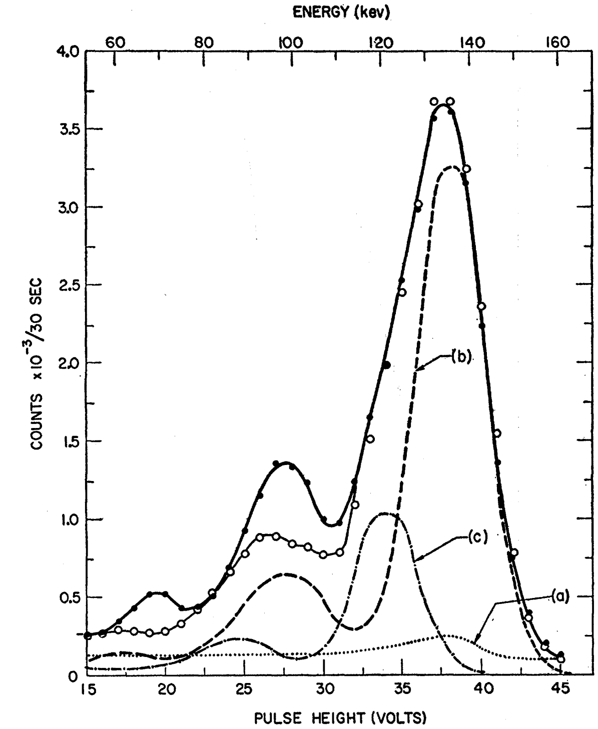

FIG. 4. Gamma-ray pulse-height spectrum from a Se^{75} source 2 cm above a 1.9-mm thick NaI(Tl) crystal. ● Se^{75} source, experimental points; ○ Sum of curves (a), (b), and (c). Curve: (a) Sum of Compton contributions from the 402-, 280-, 265-kev transitions. (b) Contribution of the 136-kev transition. (c) Contribution of the 121-kev transition.

[16] W. A. Higinbotham, Brookhaven National Laboratory Report BNL 234 (T-36) (unpublished).

[17] The authors are greatly indebted to P. R. Bell for making available to them his graphs of intrinsic efficiency *vs* gamma-ray energy for a 1.5-inch diameter by 1-inch high crystal.

[18] The following gamma-ray sources were used: Tc^{99m} (140 kev), Hg^{203} (279 kev), Cr^{51} (320 kev), Au^{198} (411 kev), Cs^{137} (661 kev).

[19] The pulse-height spectra of the following sources were used: Cs^{137} for the 628-kev Ge^{75} transition; Au^{198} for the 402-kev Se^{75} transition; Hg^{203} for the 280-kev Se^{75}, 265-kev Se^{75} and 265-kev Ge^{75} transitions; Tc^{99m} for the 136- and 121-kev Se^{75} transitions.

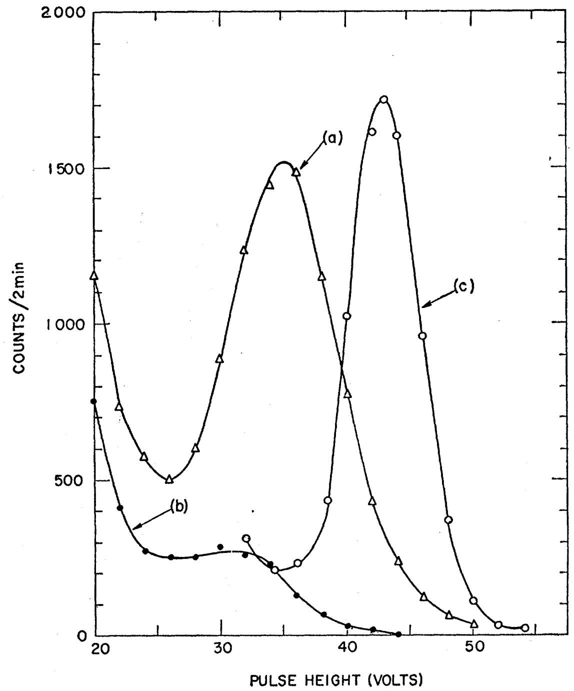

FIG. 5. Internal conversion-electron spectra obtained with an anthracene detector. (a) Se^{75} source, composite conversion-electron line of the 265- plus 280- plus 305-kev transitions. (b) Background to (a) obtained by insertion of an aluminum absorber. (c) Cs^{137} source, conversion-electron line of the 661-kev transition.

then matches the observed Se^{75} spectrum except at the photopeaks of the 97- and 66-kev gamma rays. An additional background at ~64 kev, not shown in Fig. 4, is due to the escape peak of the 98-kev transition; a correction for this effect[20] was applied.

The scintillation-spectrometer measurements of the relative intensities of the Se^{75} gamma rays are summarized in Table I, column (3). The gamma-ray intensities [column (2)] obtained from the lead L-conversion lines were normalized to those obtained from the lead K-conversion lines by use of the scintillation-spectrometer intensity measurements [column (3)]. The final gamma-ray intensities reported in column (4) are given relative to the 265-kev gamma-ray intensity.

The total conversion coefficient of the 402-kev Se^{75} gamma ray and the average of the total conversion coefficients of the 265-, 280-, and 305-kev Se^{75} gamma rays were measured relative to the total conversion coefficient ($\alpha=0.118$)[21] of the 661-kev Cs^{137} transition. The relative intensities of the gamma rays emitted by the two sources were measured with a 1.5-inch diameter by 1-inch high NaI(Tl) crystal. The relative yields of the internal conversion-electron lines (Fig. 5) were obtained using an anthracene scintillator. Unfortunately, some of the conversion electrons are scattered back out of the anthracene crystal and thus do not contribute to the full-energy peak. The fraction of scattered electrons increases with decreasing energy, thus the data of Table I, column (6) may be low. The final conversion coefficients for the Se^{75} gamma rays reported in Table I, column (7) were obtained from the data of columns (4), (5), and (6).

The energies[22] and relative intensities of the gamma rays associated with the decay of Ge^{75} are given in Table II, columns (1) and (2). Positive identification of these gamma rays with the Ge^{75} decay was made on the basis of their half-life together with the results of coincidence experiments described in the next section. Even though some of the Ge^{75} gamma rays are very weak (0.2 percent transition intensity), it was possible to measure their relative intensities. For example, a 10:1 ratio of photopeak to background count rate was obtained for the 628-kev gamma ray. A further difficulty arose because the photolines of the 427- and 477-kev gamma rays are only partially resolved from each other. The relative yields of these two transitions were estimated by fitting Gaussian distributions of the correct peak heights and resolution to the experimental pulse-height distribution. Unfortunately, this analysis is subject to errors due to the possible presence at the same pulse height of other weak photopeaks which may or may not be associated with Ge^{75}. Since a 402-kev photoline can also not be resolved from the 427-kev photopeak, an upper limit on the branching to the 402-kev level was determined by measurement of the (136, 265)-kev coincidence rate per 265-kev quantum. The result of this experiment, together with the data of Table I, column (3), may then be used to calculate the relative intensities of the gamma-ray transitions arising from the 402-kev level. So few coincidences were observed from the Ge^{75} source that they can be ac-

TABLE II. Ge^{75}: Transition intensities and coincidence data.

(1) Selected event, transition energy (kev)	(2) Gamma-ray intensity relative to 265-kev quanta	(3) Transition intensity, percent of Ge^{75} disintegrations[c,d]	(4) Gamma ray in coincidence with selected event (kev)
628± 5	1.8 ±0.3	0.20±0.03	none
477±10	2.3 ±0.7	0.26±0.08	none
427± 5[a]	2.5 ±0.7	0.28±0.08	199
402[b]	<0.03	<0.0034	...
264± 5	100	11.2 ±0.12	none
199	12 ±1.2	1.35±0.14	427, 66
121 and 136[b]	<0.15	<0.017	...
66	~2.2	~0.38	199

[a] This is the energy of the gamma ray observed in coincidence with the 199-kev transition.
[b] These gamma rays were not observed in the Ge^{75} decay; see text.
[c] The gamma-ray intensity of the 66-kev transition was corrected for the amount of internal conversion. The internal conversion coefficients for the other gamma transitions are at most a few percent.
[d] The results given in this column were obtained by normalizing the data of column (2) by means of the result, 11.2 percent, for the intensity of the 265-kev transition.

[20] P. Axel, Brookhaven National Laboratory Report BNL 271 (T-44) (unpublished).

[21] Rose, Goertzel, Harr, Spinrad, and Strong, Phys. Rev. **83**, 79 (1951); Rose, Goertzel, and Swift, *Low Energy K-Shell Coefficients* (privately circulated tables).

[22] Cs^{137}, Na^{22}, Se^{75}, and Hg^{203} were used as gamma-ray energy standards.

counted for by the presence of a small amount of Na^{24} activity.

The beta-branching ratio to the 265-kev level in As^{75} was determined by measurement of the number of beta, 265-kev gamma coincidences per beta particle. An anthracene scintillator was used to detect the negative beta particles and the bias setting was such that virtually all betas were counted. The absolute detection efficiency of the NaI(Tl) crystal for 265-kev quanta was obtained by means of a coincidence experiment in which the prominent Se^{75} gamma-gamma cascades were employed. The channel widths were sufficiently wide to include the somewhat broad photopeaks of these cascades and it was assumed that the detection efficiencies are the same for the 265- and 280-kev quanta. The fact that the 280-kev level is also populated by the 25-kev transition has no effect on the result. The solid angles subtended by the detectors were large, thus directional correlation effects could be neglected. The beta branching to the 265-kev level is 11.4 ± 1.1 percent of the Ge^{75} disintegrations. The beta-branching ratios to the other levels [Table III, column (4)] were determined from the decay scheme (Fig. 11) and the relative gamma-ray transition intensities.

Identification of Gamma-Gamma and Beta-Gamma Cascades

Coincidence studies were undertaken with both Se^{75} and Ge^{75} sources in order to establish the existence of various gamma-gamma cascades; in addition, the end-points of the beta groups in coincidence with the different gamma rays of Ge^{75} were measured in order to help establish the level scheme for the excited states of As^{75}. The coincidence investigations were carried out with the previously described scintillation spectrometer used in conjunction with a gray-wedge coincidence analyzer.[23] The photopeak or internal conversion-electron line of the gamma ray of interest was selected by means of a single-channel analyzer and the spectra of electromagnetic radiations, conversion electrons or beta particles in coincidence with it were displayed on the gray-wedge screen. A coincidence resolution time of 10^{-7} sec was used. The geometrical arrangement of the detectors and sources and the nature of the absorbers used were varied to suit the individual experiments. The results obtained for the Ge^{75} and Se^{75} sources are summarized in Table II, column (4) and in Table IV, respectively.

Considerable care has to be taken in interpreting the coincidence results because, in general, pulses due to other gamma rays than the one of interest also fall in the channel of the pulse-selecting detector. For example, with a Se^{75} source it was observed that a broad channel centered at 66 kev (Fig. 4) includes approximately equal numbers of counts due to 66-kev quanta and due to the continuous pulse-height spectra from the 121-, 136-, 265-, and 280-kev quanta. The 136- and 265-kev photopeaks, present in the Se^{75} gamma-ray spectrum (Fig. 6), appear also in the coincidence spectrum obtained by channeling at 66 kev (Fig. 7). The presence of these photopeaks in Fig. 7 is to be expected because of the existence of the (121, 280)-kev and (136, 265)-kev cascades. In addition to the true coincidence peak at 199 kev, peaks at $\sim$30 and $\sim$50 kev were observed (Fig. 7). The $\sim$30-kev peak is attributable to iodine K x-rays which escape from the pulse-selecting detector into the display crystal; the line at $\sim$50 kev is due to a scattering process. In all cases where the possibility of scattering between the de-

TABLE III. Ge^{75}: Beta groups and $\log ft$ values.

(1) Beta group (kev)	(2) Gamma ray in coincidence with β^- group (kev)	(3) Level in As^{75} (kev)	(4) Fraction of Ge^{75} activity (percent)[b]	(5) $\log ft$[d]
1188 ± 20	none	ground state	87	5.2
975 ± 20	199	199	0.69	7.0
919 ± 20	265	265	11.4	5.6
784	...	402	<0.022[c]	>8.1
720^{+20}_{-60}	477	477	0.26	6.9
553[a]	199, 427, 628	628	0.48	6.2

[a] This beta group was not observed directly; however, its existence can be deduced with certainty from the results of experiments involving the 199-, 427-, and 628-kev gamma rays (see Table II).
[b] The results given in this column were calculated using the decay scheme of Fig. 11 and the transition intensities of Table II, column (3).
[c] As beta branching to the 402-kev level was not observed, only an upper limit can be given for the intensity of the 784-kev beta group.
[d] The comparative half-lives were calculated with the aid of the graphs given by S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

TABLE IV. Se^{75}: Results of coincidence experiments.

Selected event (kev)	Events observed in coincidence with selected event	Remarks
K x-rays	402, 280, 265, 199, 136, 121, 97, 66	The 81- and 305-kev radiations were not observed because of their low intensities; the 25-kev gamma ray was not observed because it is highly internally converted.
66	199	Whether or not other transitions are also in coincidence could not be determined from this coincidence experiment (see text).
97	either 280 or 305, or both(?)	These coincidences are probably real but not positively established.
121	280	
136	66, 265	
199	66	It was not possible to establish the presence or absence of coincidences with 136-kev quanta from this coincidence experiment.
265	136	
280	97(?), 121	
305	97(?)	
402	K x-rays only	No coincidences with any other gamma rays were observed.

[23] The gray-wedge analyzer is described by Bernstein, Chase, and Schardt, Rev. Sci. Instr. **24**, 437 (1953). The specific equipment used in this experiment is described by R. L. Chase, Brookhaven National Laboratory Report BNL 263 (T-42) and by A. W. Schardt, Brookhaven National Laboratory Report BNL 237 (T-37).

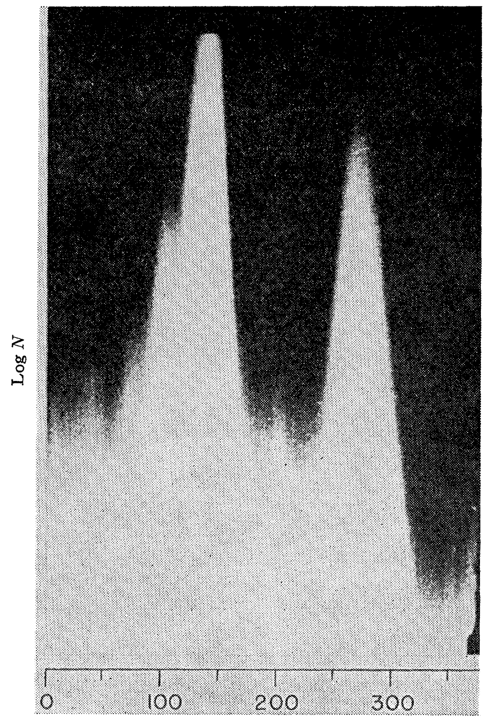

FIG. 6. Gray-wedge analyzer picture of Se^{75} gamma-ray spectrum (0 to 350 kev) as detected by a 3-cm diameter by 2-cm high NaI(Tl) crystal.

tectors existed, great care was taken to identify any spurious peaks produced in this way.

It was readily proven that coincidences exist between Se^{75} quanta included in the 97- plus 121- plus 136-kev composite photopeak and quanta included in the 265- plus 280- plus 305-kev composite photopeak. The existence of the (121, 280)-kev and (136, 265)-kev cascades could also be established since the coincidence rate per channel count depends markedly on which of the gamma rays predominated in the narrow channels used. On the other hand, the results of coincidence experiments involving the 97- and 305-kev radiations were inconclusive because of the low intensities of these transitions. Coincidences between K x-rays and 97-kev quanta were also observed but it was not determined whether these x-rays had their origin in the electron-capture process or whether they resulted from internal conversion of other gamma rays.

The spectra of the beta groups emitted by Ge^{75} were investigated with an anthracene detector. The energy response of anthracene was taken to be linear[24] and the pulse-height scale was calibrated with the 624-kev Cs^{137} and 976-kev Bi^{207} internal conversion-electron lines. The Au^{198} beta spectrum was measured; the experimental beta-endpoint energy, 0.972 Mev, is in good agreement with the accepted value, 0.963 Mev.[1] In order to correct the Ge^{75} beta spectra for the effects of crystal resolution and backscattering, correction factors, which were necessary to linearize the Au^{198} Fermi plot, were computed as a function of energy below the endpoint. Figure 8 shows corrected Fermi plots of the composite Ge^{75} spectrum and of the beta spectra in coincidence with the 199-, 265-, and 477-kev gamma rays, respectively. The approximate nature of the applied corrections could account for the fact that the composite beta spectrum [curve (a)] cannot be resolved into its components. Since a considerable fraction of the count rate at the photopeak of the 477-kev gamma ray was due to the Compton background from Na^{24} radiations, spectrum (d) is undoubtedly perturbed by the presence of Na^{24} betas. As no correction could be made for this effect, it is impossible to determine the exact endpoint of spectrum (d). On the other hand, Fermi plots (b) and (c) are not perturbed by the presence of a background spectrum; thus, the difference in endpoint energies, 56 kev, is accurate to ± 20 kev. The beta-group energies and intensities are summarized in Table III.

Lifetime Measurements

The theoretical half-life of the 280-kev transition, which is characterized as $E2$ from the conversion-coefficient (Table VII), is 10^{-8} sec.[25] Similarly, a lifetime might be expected for the decay of the 305-kev level. A knowledge of the actual half-lives of the 265-

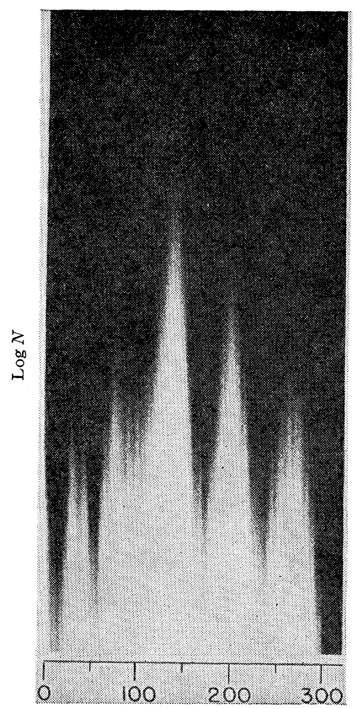

FIG. 7. Gray-wedge photograph of the Se^{75} pulse-height spectrum in coincidence with pulses which fall in a channel centered at 66 kev. The photopeak at 265 kev and at least part of the photopeak at 136 kev are due to coincidences with the background pulses on which the 66-kev photoline is superimposed. Different gain settings were used for Figs. 6 and 7.

[24] J. I. Hopkins, Rev. Sci. Instr. 22, 29 (1951).

[25] J. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. XII, p. 627.

and 280-kev levels is also desirable in order to decide whether or not the directional correlations of the (136, 265)-kev and (121, 280)-kev Se^{75} cascades can be perturbed by local fields.[26] Previous investigations[27,28] searched for isomeric transitions from a Se^{75} source and found none in the time range, 10^{-8} to 10^{-3} sec.

In the present experiments a fast coincidence circuit[29] of resolving time, $\tau = 2\times10^{-9}$ sec, was used in conjunction with 5819 photomultipliers and stilbene crystals. The coincidence rate between the internal conversion electrons of the 121- plus 136-kev Se^{75} transitions and the internal conversion electrons of the 265- plus 280-kev transitions was measured as a function of time delay over a two-hundred-fold diminution in count rate. It was concluded that both the 265- and 280-kev levels have a half-life which is less than 8×10^{-10} sec. An experiment was also performed in which the pulse-height selectors were set so that an appreciable fraction of the observed coincidence rate was due to coincidences between the internal conversion electrons of the 97-kev gamma ray and those of the 280- plus 305-kev transitions. The results indicate that the half-life of the 305-kev level is either shorter than 10^{-9} sec or longer than 5×10^{-8} sec; a half-life greater than the latter figure would not have been observed because of the presence of other coincidences. The multipolarity of the 305-kev gamma ray is therefore not greater than $E2$ unless a half-life longer than 5×10^{-8} sec was missed in the earlier investigations.[27,28]

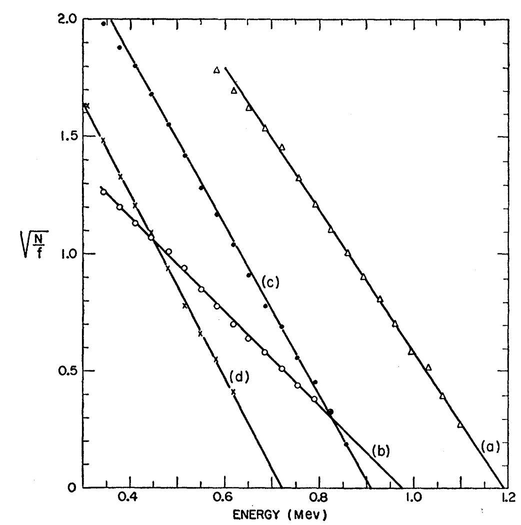

FIG. 8. Corrected Fermi plots of Ge^{75} beta spectra. (a) △ Composite beta spectrum. (b) ○ Beta spectrum in coincidence with 199-kev gamma rays. (c) ● Beta spectrum in coincidence with 265-kev gamma rays. (d) × Beta spectrum in coincidence with 477-kev gamma rays.

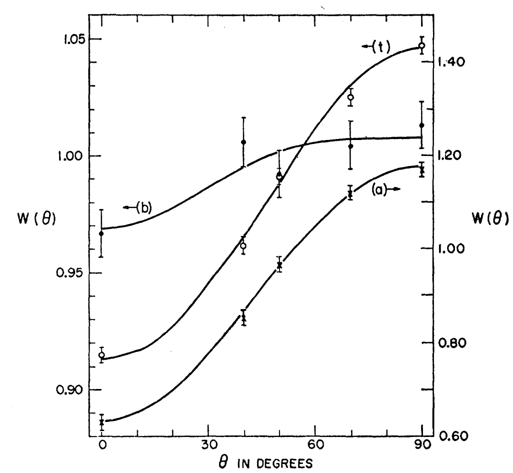

FIG. 9. Experimental directional distributions. The experimental values were normalized by dividing by a_0 (Table V). Each curve represents a least-squares fit to the data. Curve (a) and the × points refer to case a, Table V. Curve (b) and the ● points refer to case b. Curve (t) and the ○ points refer to case t. The arrows refer to the ordinate scale.

Gamma-Gamma Directional Correlation Studies

The directional correlations of the (121, 280)-kev and (136, 265)-kev Se^{75} cascades were investigated in order to obtain further information about the multipolarities of these gamma-ray transitions and the spins of the levels involved. The apparatus used for measuring the directional correlations has been described previously.[30] The gamma rays were detected with NaI(Tl) crystals placed in lead collimators and Atomic Instrument single-channel pulse-height analyzers were used to select the photopeak of the desired gamma ray. A fast (0.1-μsec) coincidence requirement was imposed on the unselected pulses; subsequently, a 5-μsec triple coincidence requirement was imposed on the output pulses of the fast coincidence circuit and the two single-channel analyzers. The sources, which consisted of from 2 to 10 milligrams of irradiated selenium-metal powder, were placed in an aluminum holder. The dimensions of the source holder were minimized in order to reduce perturbations due to scattering effects[26]; the holder had an outside diameter of 0.085 inch and a $\frac{1}{16}$-inch hole, $\frac{3}{8}$ inch deep. Measurements were made at the detector-to-detector angles of θ and 360° minus θ, where θ was given the following values, 90°, 110°, 130°, 140°, and 180°. An equal number of measurements was made at each angle and the results for angles symmetrical with respect to 180° were then averaged. The order of angle coverage was random.

Directional correlation data were obtained using wide channels centered on the composite photopeaks of the 121- plus 136-kev and 265- plus 280-kev gamma rays, respectively. In addition, data were taken with narrow channels set so that either the (121, 280)-kev

[26] H. Frauenfelder, Ann. Rev. Nuc. Sci. 2, 129 (1953).
[27] S. DeBenedetti and F. K. McGowan, Phys. Rev. 74, 728 (1948).
[28] F. K. McGowan, Oak Ridge National Laboratory Report ORNL 952 (unpublished).
[29] The authors are greatly indebted to Mr. R. L. Chase for designing and testing this circuit.
[30] J. J. Kraushaar and M. Goldhaber, Phys. Rev. 89, 1081 (1953).

TABLE V. Experimental results of the directional correlation measurements with Se^{75}.[a]

Channel position	A_2 Coefficient of $P_2(\cos\theta)$[b]	A_4 Coefficient of $P_4(\cos\theta)$[b]	Gamma-ray mixing ratio in channel, Detector A, 121 kev α_{01}	Detector A, 136 kev α_{02}	Detector B, 280 kev α_{13}	Detector B, 265 kev α_{23}	β[d]	a_0 sec/count $\times10^{-5}$	(N_1+N_2)[f] counts/sec $\times10^{+5}$
(121, 280)-kev cascade favored (case a)	-0.359 ± 0.014	-0.011 ± 0.014	0.84 0.66[c]	0.16 0.34[c]	0.68 0.61[c]	0.32 0.39[c]	25 6.7[c]	0.365 ± 0.003[e] 0.365 ± 0.003[e]	2.31[g] 1.79[c,g]
(136, 265)-kev cascade favored (case b)	-0.022 ± 0.0095	-0.0095 ± 0.0095	0.044	0.96	0.10	0.90	0.0113	0.485 ± 0.003	2.60
Channels set to include all of composite photopeaks (case t)	-0.090 ± 0.003	0.003 ± 0.003	0.23	0.77	0.32	0.68	0.31	0.440 ± 0.001	2.26
Case t computed from Table VI	-0.101 ± 0.019	···	0.23	0.77	0.32	0.68	0.31		

[a] The notation used in this table is defined in the Appendix.
[b] The rms statistical errors are given; the actual errors are somewhat larger. No correction has been applied for the finite resolution of the detectors.
[c] These values were computed from the results of additional coincidence experiments at 180° (refer to Appendix).
[d] To compute β the ratio, $N_2/N_1=2.20$, was used (see Table I).
[e] This a_0 was measured with a source 2.27 ± 0.05 times as strong as the one used for the other experiments.
[f] Either N_1 or N_2 was computed depending on whether $\alpha_{01}\alpha_{13}$ or $\alpha_{02}\alpha_{23}$ is larger; the source strength (N_1+N_2) was then obtained by use of the experimental ratio, $N_2/N_1=2.20$. A value of $(2.57\pm0.26)\times10^{+5}$ counts/sec for (N_1+N_2) was computed from the results of experiments in which the (136, 265)-kev cascade was favored more strongly than in case b (see Appendix).
[g] In order to facilitate comparison with the other entries in this column, the actual source strength was divided by 2.27.

or the (136, 265)-kev cascade predominated. The discrimination between cascades was accomplished by channeling on the sloping portions of the composite photolines; as a result the count rate in the channel was very sensitive to small shifts in pulse height. Slow drifts, such as those resulting from variations in room temperature, were compensated for by manually changing the channel position. In order to minimize the effects of erratic, uncompensated drifts, the coincidence rate (after subtraction of the accidental rate) was divided by the product of the channel-count rates (refer Appendix). A complete compensation for these effects is not obtained since a shift in channel position is also accompanied by a change in detection sensitivity for the gamma rays of the two cascades.

In several instances, the rms error was computed from the deviations as a check on the consistency of the data. For example, for the fourteen measurements made at 180° with the channels set to favor the (136, 265)-kev cascade, the rms error computed from the deviations is 7 percent while the statistical rms error on each measurement is 4 percent. These errors are 6.6 and 5.6 percent, respectively, for the same measurements with the channels set to favor the (121, 280)-kev cascade. The results, that the rms error computed from the deviations is always greater than the statistical rms error, is undoubtedly due to uncompensated drift errors.

The curves fitted to the experimental points are shown in Fig. 9 and the coefficients of the Legendre polynomials are given in Table V. The formulas needed to calculate the directional distribution functions of the individual cascades from these coefficients are derived in the Appendix. The ratio of the number of 121- to 136-kev pulses and the ratio of 280- to 265-kev pulses at each channel setting also enter into the calculations. (In future these ratios will be referred to as gamma-ray mixing ratios.) The mixing ratio of two gamma rays in a channel of known width and position can be determined from an analysis of the composite photopeak. For example, Fig. 10 shows the contributions of the 265- and 280-kev gamma-ray pulses; the relative intensities of the individual gamma rays were taken from Table I, column (2). In the case of the distribution measured with the channels set to favor the (121, 280)-kev cascade, the gamma-ray mixing ratios could also be evaluated from the results of some additional coincidence experiments (see Appendix). The directional correlation function for the (121, 280)-kev cascade, computed with the mixing ratios obtained from the coincidence measurements, is in 10 percent agreement with the function calculated using the other mixing ratios. The directional distribution functions of the individual cascades (Table VI), together with the

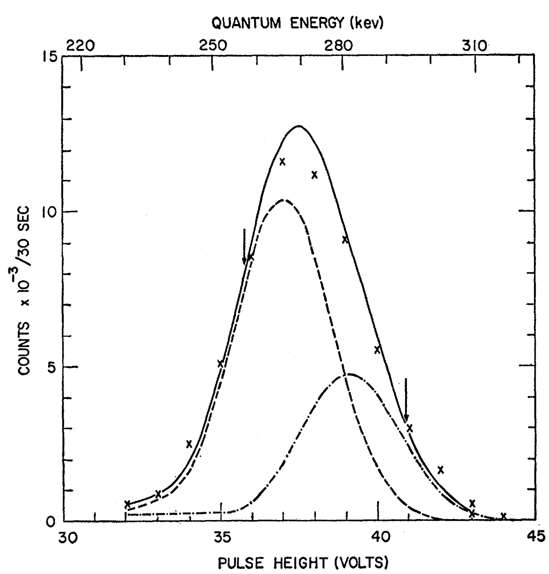

FIG. 10. Composite photopeak of the 265- plus 280-kev gamma rays. × represent experimental points, ↓ designate centers of two-volt channels.

gamma-ray intensity ratios obtained with the lens spectrometer, can be used to calculate the directional correlation to be expected if the entire composite photopeaks are included in the channels. The agreement with the experimental distribution is satisfactory (Table V).

It should be noted that the final directional correlation coefficients listed in Table VI have been corrected for the finite angular resolution of the detectors.[31] The solid angle subtended by the detectors was determined by measuring the coincidence rate of annihilation quanta as a function of angle; the resulting angular resolution curve exhibited a half-width at half-maximum of 10.5°.

DISCUSSION AND INTERPRETATION OF RESULTS

A level scheme (Fig. 11) for As^{75} can be constructed on the basis of the data presented. The level arrangement is identical with that proposed by Cork and co-workers[4] except for the addition of levels at 477 and 628 kev. The endpoints of the beta groups in coincidence with the different gamma rays of Ge^{75} show the existence of levels at 199, 265, and 477 kev. Since the 402-kev Se^{75} and the 628-kev Ge^{75} transitions are not in coincidence with any other gamma rays, it can be concluded that levels exist at these energies. All the gamma-gamma cascades of Table IV can then be accounted for by the presence of two additional levels at 280 and 305 kev. Unfortunately, it was not possible to determine directly the order of emission of the gamma rays of the (121, 280)-kev and the (97, 305)-kev cascades, thus the 280- and 305-kev levels could be placed at 121 and 97 kev, respectively. The latter scheme is unlikely since neither the 121- nor 97-kev gamma rays are excited by Coulomb excitation.[6] If the 121- and 97-kev transitions are not Coulomb excited and represent transitions to the ground state of As^{75}, then they would have to be pure magnetic multipoles. However, the conversion coefficient of the 121-kev gamma ray (Table VII) shows that this transition has a large $E2$ component. The 97-kev gamma ray, on the basis of its conversion coefficient, could be designated as a pure $M2$ with an expected half-life of $\sim 10^{-4}$ sec[25] but the fact that K x-ray, 97-kev coincidences were observed is incompatible with such an assignment. The 81-kev transition can also be included in the proposed scheme without postulating the existence of a new level. It should be noted that the measured transition intensities are consistent with the assumption that Se^{75} decays only to the 402-kev level. However, electron capture to other excited levels, amounting to as much as 10 percent of the Se^{75} decay, cannot be ruled out on the basis of the results presented in Table I. Similarly, an upper limit of 20 percent[32] can be placed on the electron-capture branching to the ground state of As^{75}.§

Plausible spins and parities can be assigned to the excited levels of As^{75} by means of logft evidence and gamma-ray multipolarities provided the ground-state spins and parities of As^{75}, Se^{75}, and Ge^{75} are known. The As^{75} ground-state configuration is $p_{3/2}$.[3] A spin of 5/2 has been measured for Se^{75},[33] but the parity has not as yet been determined. This 5/2 spin would not be expected from the shell model since the Ge^{73} nucleus,

TABLE VI. Directional correlation coefficients of the (121, 280)-kev and (136, 265)-kev cascades.

Cascade	A_2[a]	A_4[a]
(121, 280)-kev	-0.40 ± 0.03 -0.44[b]	-0.014 ± 0.017
(136, 265)-kev	$-0.019^{+0.01}_{-0.02}$[c]	-0.012 ± 0.012

[a] A correction of 7 percent to A_2 and 21 percent to A_4 has been made to take into account the finite angular resolution of the detectors. The indicated errors represent an attempt at estimating the accuracy of the coefficients.
[b] This value was obtained by use of the mixing ratios computed from the results of additional coincidence measurements made at 180°. These mixing-ratio values are given in Table V [see reference (c)].
[c] In subtracting the contribution of the (121, 280)-kev cascade its effect may have been underestimated; thus, the negative error is larger than the positive.

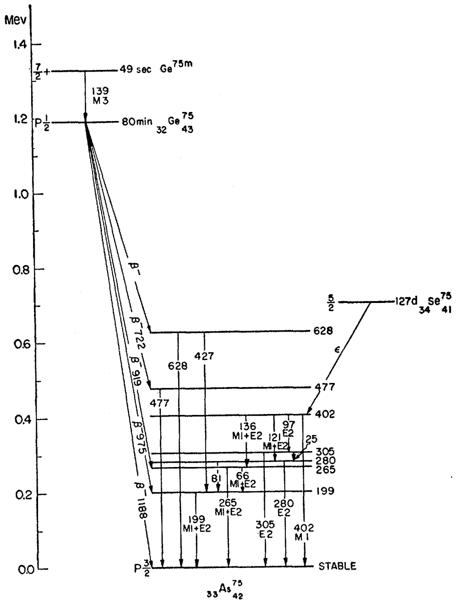

FIG. 11. Level scheme of As^{75}. Level and transition energies are given in kev.

[31] E. L. Church and J. J. Kraushaar, Phys. Rev. 88, 419 (1952).

[32] The K-hole yield of Table I must be corrected for the number of K holes ($\sim$23 percent) produced by internal conversion of the gamma rays. A correction for the amount of L-electron capture is also necessary; the L/K electron-capture probability is 10 percent according to M. E. Rose and J. L. Jackson, Phys. Rev. 76, 1540 (1949). The K x-ray yield is, however, insufficient to account for the transition intensities

§ *Note added in proof.*—The presence of a 280-kev photopeak in the "summed" spectrum[7] is compatible with the decay scheme of Fig. 11 since both the 97- and 25-kev transitions are highly converted. The pronounced 97-kev photopeak in the "summed" spectrum can be explained if the 305-kev level is an isomeric state. Unfortunately, this interpretation is in disagreement with the experimental results of De Benedetti and McGowan.[27]

[33] Aamodt, Fletcher, Silvey, and Townes, Phys. Rev. 94, 789 (1954); L. C. Aamodt and P. C. Fletcher, Phys. Rev. 98, 1224 (1955).

TABLE VII. Multipolarities of the gamma rays associated with the decay of Se^{75}.

Transition energy (kev)	Experimental K-conversion coefficient	Theoretical K-conversion coefficient[a] α_1	α_2	α_3	β_1	β_2	β_3	Multi-polarity[b]	$\lvert\delta\rvert = (E2/M1)^{\frac{1}{2}}$	Remarks
402	0.0024 ±0.0005	0.0012	0.0044	0.015	0.0023	0.0084	0.028	$M1$		
305	0.03 ±0.01	0.0025	0.0115	0.045	0.0045	0.019	0.077	$E2$		Higher order transition improbable because of competition with 25-kev transition.
280	0.019 ±0.005	0.00334	0.016	0.067	0.0057	0.026	0.11	$E2$	≥ 2	$M3$ admixture impossible since $t_{\frac{1}{2}} \leq 8\times10^{-10}$ sec.
265	0.016 ±0.005	0.0037	0.019	0.080	0.0064	0.030	0.13	$M1+E2$	$2.0^{+\infty}_{-1.2}$	This transition can be Coulomb excited.[c]
199	~0.03	0.0079	0.050	0.25	0.13	0.072	0.39	$M1+E2$		This transition can be Coulomb excited.[c]
136	0.07 ±0.02	0.026	0.23	1.5	0.036	0.27	2.1	$M1+E2$	$0.49^{+0.18}_{-0.21}$	
121	0.10 ±0.03	0.034	0.35	2.3	0.048	0.42	3.5	$M1+E2$	$0.45^{+0.14}_{-0.17}$	
97	1.8 ±0.8	0.073	0.77	6.4	0.090	0.97	9.4	$E2$		Higher order admixture or $M2$ impossible because of competition with 402-, 136-, 121-kev gamma rays. K/L ratio compatible with $E2$.[d]
66	0.6 ±0.3	0.21	2.8	40	0.27	3.7	50	$M1$ or $M1+E2$		

[a] See reference 21.
[b] $E1+M2$ admixtures were not considered because such transitions are highly improbable. The multipolarity assignments given are based on the K-conversion coefficient evidence in conjunction with the arguments listed under "Remarks."
[c] See reference 6.
[d] The theoretical K/L ratio for $E2$ is 4.5 (reference 39) and the experimental value is 6 (Table I).

which has the same number of neutrons as Se^{75}, has a $g_{9/2}$ ground-state configuration.[3] However, the 13.5-kev first excited level of Ge^{73} is probably a $(g_{9/2})^3$ state with a spin and parity of 5/2+.[34] It is conceivable that the addition of two protons to the Ge^{73} nucleus stabilizes the $(g_{9/2})^3$ over the $g_{9/2}$ configuration. The even-parity assignment to the ground state of Se^{75} is also supported by logft evidence. A lower limit of the logft value for the decay of Se^{75} to the As^{75} ground state was calculated on the basis of an energy-difference figure of 894±5 kev [35] and a maximum transition intensity of 20 percent. The logft value, ≥7.3, is consistent with a parity forbidden transition.[36] The ground-state configuration of Ge^{75} is expected to be $p_{1/2}$ from shell theory considerations[3] as this nucleus contains the same number of neutrons as Se^{77}. Other evidence also supports this $p_{1/2}$ assignment. The existence of an isomeric state of Ge^{75} at 139 kev has been reported.[8,37,38] The K-conversion coefficient value for the 139-kev gamma ray (~2)[37] is only consistent with an $E3$ or $M3$ transition.[21] However, the K/L ratio (~3)[38] and the half-life (49 sec) are only compatible with an $E3$ assignment.[25,39] Again by analogy with Se^{77},[40] an $E3$ transition between a 7/2+ and a $p_{1/2}$ level is to be expected. The logft value, 5.2, for the Ge^{75} beta decay to the $p_{3/2}$ ground state of As^{75} supports the fact that $p_{1/2}$ and not 7/2+, is the ground-state configuration of Ge^{75}.

The logft value [Table III, column (5)] and the gamma-ray multipolarities assigned with the aid of K-conversion coefficients (Table VII) form a basis for the following discussion of spins and parities. The logft values for the Ge^{75} beta transitions indicate that the 199-, 265-, 477-, and 628-kev levels have spins of either 1/2 or 3/2. In addition, the logft value (6.2) for the electron-capture decay of Se^{75} to the 402-kev level shows that this level must have either a 7/2, 5/2 or 3/2 spin. However, the choice is limited to 5/2− or 3/2− since the 402-kev gamma ray proceeds to the $p_{3/2}$ ground state of As^{75} by means of an $M1$-type transition. The $M1+E2$ character of the 199- and 265-kev ground-state radiations indicates that these levels also have negative parity. The spin and parity assignments made so far are consistent with the multipolarities given in Table VII for the 66- and 136-kev transitions. An $E2$ rather than an $M2$ multipolarity was chosen for the 97-kev transition because the theoretical 97-kev $M2$-transition probability is too small[25] to explain the competition with the other gamma rays which proceed from the 402-kev level.[41] Since the 305- and 97-kev gamma rays are in cascade, the 305-kev level must have negative parity if the 97-kev radiation is $E2$. Therefore, $E2$ is the most likely multipolarity for the 305-kev gamma ray. The experimental K-conversion coefficients for the 97- and 305-kev transitions are, however, considerably larger then the theoretical $E2$ values. Unfortunately, the conversion-coefficient measurements for the 97- and 305-kev radiations are the least accurate and the errors given in Table I may be too optimistic.

It is difficult without additional evidence to arrive at more definite spin and parity assignments since detailed arguments based on logft values and relative transition probabilities are of doubtful value when

[34] Welker, Schardt, Friedlander, and Howland, Phys. Rev. **92**, 401 (1953).
[35] C. C. Trail and C. H. Johnson, Phys. Rev. **91**, 474 (1953).
[36] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951); L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).
[37] A. Flammersfeld, Z. Naturforsch. **7a**, 295 (1952).
[38] Burson, Jordan, and LeBlanc, Phys. Rev. **96**, 1555 (1954).
[39] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[40] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[41] A less plausible interpretation would be that the 97-kev transition is pure $M2$ or an $M2+E3$ mixture and proceeds from a level the energy of which is within 1.5 kev of 402 kev. The observed K x-ray, 97-kev coincidences may be due to K x-rays which arise from internal conversion of the 25-kev transition (see Fig. 11).

many of the levels involved are not single-particle states. The directional correlation functions for the (121, 280)-kev and (136, 265)-kev cascades provide a further basis for spin assignments. However, since the K-conversion coefficient results show that the 121-, 136-, and 265-kev gamma rays are $M1+E2$ mixtures, the interpretation of the directional distribution results is in itself complicated.

Theoretical directional correlation distributions can be computed by use of Rose's[42] equations for mixed-gamma, mixed-gamma correlations. For the case where both gamma rays of a cascade are $M1+E2$ mixtures, the general equations can be simplified to give

$$A_2=\frac{(a+b\delta_1+c\delta_1^2)(d+e\delta_2+f\delta_2^2)}{(1+\delta_1^2)(1+\delta_2^2)}, \qquad \text{(I)}$$

$$A_4=\frac{g\delta_1^2\delta_2^2}{(1+\delta_1^2)(1+\delta_2^2)}. \qquad \text{(II)}$$

The capital letters, A_2 and A_4, are the $P_2(\cos\theta)$ and $P_4(\cos\theta)$ coefficients, respectively. The intensity ratio, $E2/M1$, is given by δ^2; subscripts 1 and 2 on δ refer to the first and second gamma rays of a cascade. The lower case letters represent numerical coefficients which are a function of the spin assignments; these coefficients can be evaluated by use of the papers by Rose and Biedenharn.[42,43] Equation (I) can be solved for δ_1 *vs* δ_2 for a given spin sequence and experimental value of A_2. Figures 12 and 13 show plots of δ_1 *vs* δ_2 for spin sequences consistent with the results and assignments discussed earlier in this section.

Since the 265-kev level has a spin of either 3/2 or 1/2, the theoretical value of A_4 from Eq. (II) is zero, in good agreement with the experimental result for the (136, 265)-kev cascade (Table VI). Since the experimental value of A_2 for this cascade is very nearly zero, a 1/2 assignment for the 265-kev level is indicated. However, a spin of 3/2 for this level is also consistent with the experimental correlation data (Fig. 12). Spin assignments of 7/2, 5/2, or 3/2 are possible for the 280-kev level; the existence of an A_2 coefficient eliminates a 1/2 spin. Figure 13 shows plots of δ_1 *vs* δ_2 for the 5/2 and 3/2 cases for both possible spins of the 402-kev level, 5/2 and 3/2. The theoretical directional correlation for the spin sequence, $5/2(M1+E2)7/2(E2)3/2$, is also in agreement with the experimental values for δ_1 (Table VII) and A_2. An $E2+M3$ admixture for the 280-kev transition was not considered, as the measured half-life, $<8\times10^{-10}$ sec, of the 280-kev level is not compatible with such multipole mixing.[25]

A spin assignment of 5/2 for the 402-kev level appears improbable on the basis of the following argument. An examination of the δ_1 *vs* δ_2 plots for sequences in which a 5/2 spin is assigned to the 402-kev level (Figs. 12 and 13), in conjunction with the $|\delta_1|$ values given in Table VII, shows that both the 280- and 265-kev gamma rays are rather pure $E2$ transitions. The theoretical $E2$ K-conversion coefficient ratio ($\alpha_{280}/\alpha_{265}$) is 0.84,[21] while the experimental ratio is 1.17 ± 0.1. (The measured absolute K-conversion coefficients are considerably less accurate than the ratios because a normalization is involved.) The theoretical K-conversion coefficient of a 280-kev $E2$ transition is 0.016,[21] thus $\alpha_{265}=0.014$ and $|\delta_2|\approx1.2$ for the 265-kev radiation. It may be seen from Fig. 12 that for the 5/2, 3/2, 3/2 sequence such a low value of δ_2 is not reached within the limits set on δ_1. However, by combining the extreme values of A_2 and δ_1, it is barely possible to satisfy this condition for the spin sequence, $3/2(M1+E2)3/2(M1+E2)3/2$ (Insert, Fig. 12). Therefore, one may conclude that the spin of the 402-kev level is 3/2 and that the 265-kev level is probably 1/2 although the 3/2 assignment cannot be excluded. A choice of either 5/2 or 3/2 remains for the spin of the

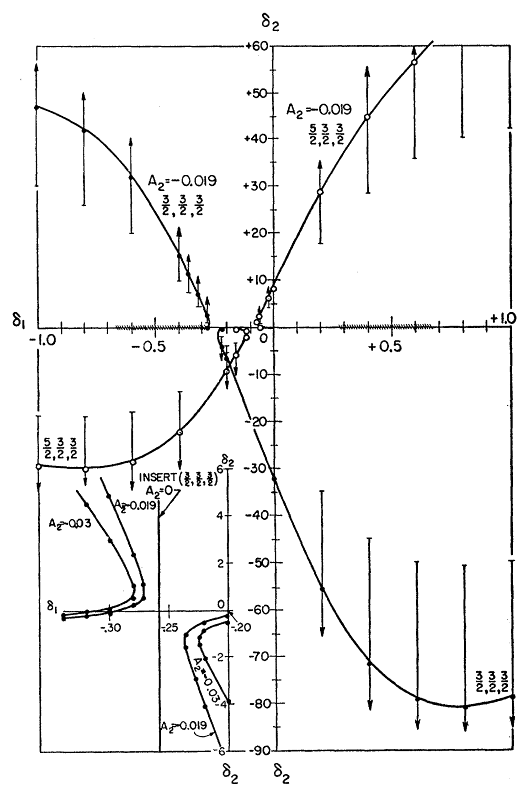

FIG. 12. Effect of $M1+E2$ mixing on the directional distribution of the (136, 265)-kev cascade. Values of δ_1 *vs* δ_2 are plotted for $A_2=-0.019$. The indicated errors are due to the errors assigned to A_2 (see Table VI). The arrows on the error symbols mean that δ_2 values up to infinity are consistent with the experimental correlation results. The shaded abscissa regions denote the values of δ_1 which are consistent with the measured K-conversion coefficient of the 136-kev gamma ray. The ○ points refer to a 5/2, 3/2, 3/2 spin sequence for the 402-, 265-kev levels and the ground state of As^{75}, respectively; the ● points refer to a 3/2, 3/2, 3/2 spin sequence. The Insert shows detail in the region of $\delta_1=-0.258$ for the 3/2, 3/2, 3/2 spin sequence.

[42] M. E. Rose, Phys. Rev. **93**, 477 (1954).

[43] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

280-kev level. In the former case $A_4 \approx -0.005(|\delta_1| = 0.45, |\delta_2| = 2.5)$, in the latter case A_4 vanishes. Both these values for A_4 are in agreement with the experimental result, $-(0.014 \pm 0.017)$.

All the spin and parity assignments which are consistent with the logft values, the gamma-ray multipolarities, and the above interpretation of the directional correlation results are given in Fig. 14. The spins not enclosed in brackets are those which are most compatible with the relative gamma-ray transition probabilities. For example, with a 7/2− assignment for the 305-kev level the competition between the 25-kev (probably $M1$) and 305-kev ($E2$) gamma rays is readily understood. On the other hand, if the 305-kev level has a spin of 5/2−, 3/2− or 1/2−, then the 305-kev transition would be a $M1$ with a very large admixture of $E2$. It is difficult to understand how a 25-kev transition involving no parity change could be ten times as intense as a 305-kev transition of such multipole order. A 5/2− assignment is preferred for the 280-kev level since the spin difference between the 305- and 280-kev levels can be, at most, one unit in order that the relative intensity of the 25- and 305-kev transitions be explained. The absence of negative beta decay from Ge^{75} to the 280-kev level is additional evidence for a 5/2− assignment. The 280-kev level

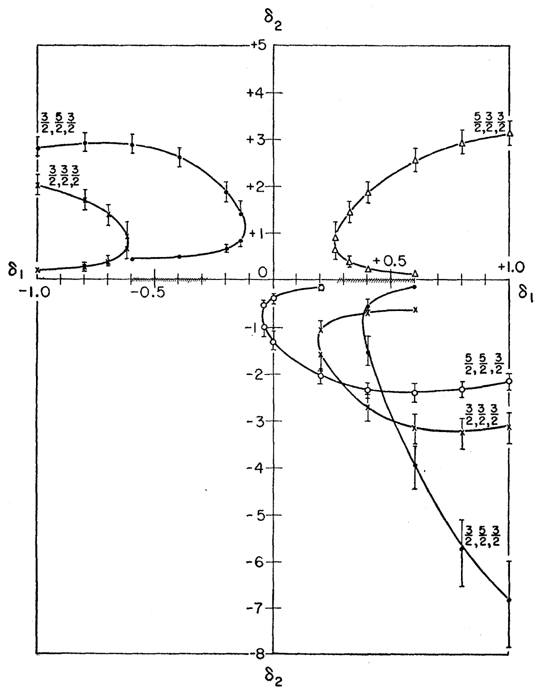

FIG. 13. Effect of $M1+E2$ mixing on the directional distribution of the (121, 280)-kev cascade. Values of δ_1 *vs* δ_2 are plotted for $A_2 = -0.40$. The indicated errors are due to the errors assigned to A_2. The shaded abscissa regions denote the values of δ_1 which are consistent with the measured K-conversion coefficient of the 121-kev gamma ray. The ○ points refer to a 5/2, 5/2, 3/2 spin sequence for the 402-, 280-kev levels and the ground state of As^{75}, respectively. Similarly, the △ points refer to 5/2, 3/2, 3/2, the ● points to 3/2, 5/2, 3/2 and the × points to 3/2, 3/2, 3/2.

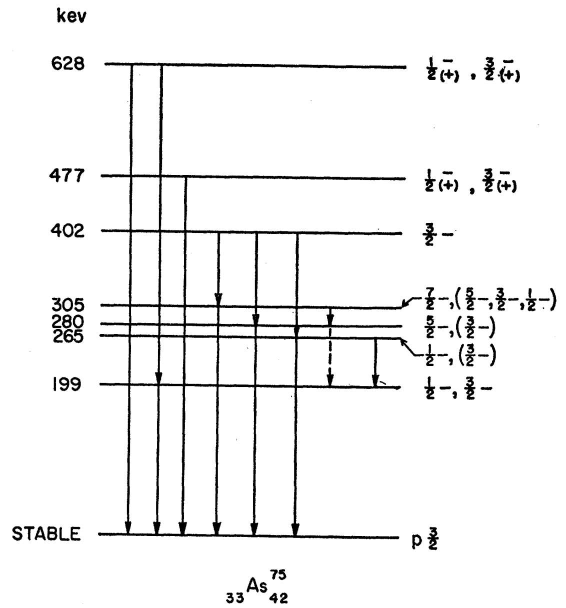

FIG. 14. Spin and parity assignments for levels of As^{75}. On the basis of transition-probability arguments, the bracketed assignments are less probable.

could very well have an $f_{5/2}$ configuration since from shell-model considerations[3] one would expect the $f_{5/2}$ state to occur at a low excitation energy. For example, in As^{77} the $f_{5/2}$ level occurs at 263 kev.[40]

The logft values for the Ge^{75} beta transitions to the 199- and 402-kev levels (7.0 and ≥8.1, respectively) indicate that these transitions are either l-forbidden[36] or that the configurations of the levels involved are unusually pure. An argument similar to that suggested by de-Shalit and Goldhaber[44] to explain the case of Kr^{85} may be applied here. The neutron configuration of the Ge^{75} ground state is $(p_{1/2})^1 (g_{9/2})^4$. The As^{75} ground-state neutron configuration may be either $(p_{1/2})^2 (g_{9/2})^2$ or $(p_{1/2})^0 (g_{9/2})^4$; the proton configuration could be $(p_{3/2})^1 (f_{5/2})^4$, $(p_{3/2})^3 (f_{5/2})^2$ or any other combination which gives a 3/2− spin. Since the nuclear magnetic moment of As^{75} falls between the Schmidt lines,[3] a large amount of configuration mixing in the ground state is indicated. Thus it is not surprising that the stabilizing effect of the odd $p_{3/2}$ proton on the $(p_{1/2})^2$ neutrons is insufficient in the ground-state configuration to produce an anomalously high logft value. On the other hand, if the 199-kev level is a fairly pure $p_{1/2}$ or $p_{3/2}$ proton state, then the $(p_{1/2})^2 (g_{9/2})^2$ neutron configuration may be stabilized sufficiently so that the logft value for the beta decay to this level is increased. Similarly, the configuration of the 402-kev level may also be unusually pure. Such configuration purity may be the reason for the absence of a gamma-ray transition between the 199- and 402-kev levels even though such a transition should compete favorably

[44] A. de-Shalit and M. Goldhaber, Phys. Rev. 92, 1211 (1953).

with the observed gamma-ray transitions from the 402-kev level (Fig. 11). A similar argument may be used to explain the fact that Se^{75}, which has a 5/2 ground-state spin, decays primarily to the 402-kev level, although the unobserved electron-capture transitions of Se^{75} to the other levels of As^{75} should be allowed or forbidden to the same degree.

The 477- and 628-kev levels decay primarily to the ground state of As^{75}. A possible explanation is that these levels are formed by coupling the odd As^{75} proton to an even-even core which has been excited to a level comparable to the 2+ level in an even-even nucleus. The amount of excitation energy is approximately correct as, in this region of the periodic table the 2+ level of even-even nuclei is at ~600 kev;[45] in fact, it is 596 kev in the case of Ge^{74}. One can consider that the 477- and 628-kev levels are negative parity states and that they correspond to the ground and first excited states, respectively, of the odd As^{75} proton coupled to the excited even-even core.

The surprising feature of the As^{75} level structure is the occurrence of five excited levels within 402 kev, most of which have a spin of 1/2 or 3/2. Only two single-particle states, $f_{5/2}$ and $p_{1/2}$, are available.[3] However, in the case of arsenic, there is very little energy difference between the $p_{3/2}$ and $f_{5/2}$ proton subshells and between the $p_{1/2}$ and $g_{9/2}$ neutron subshells. The energy required to transfer a proton or neutron pair from one subshell to another may, therefore, be quite small. A confirmation of this process would be the occurrence of low-lying 0+ levels in neighboring even-even nuclei. Such levels have been found in Ge^{70} at 1.21 Mev[46] and in Ge^{72} at 0.68 Mev.[40] It would not be surprising if even less energy is required in the case of As^{75} as the energy needed to transfer a nucleon pair undoubtedly depends critically on the nuclear configuration. On the other hand, it is possible that the existence of so many low-lying levels is a result of different configuration-mixing ratios since a considerable amount of configuration mixing is to be expected for As^{75}.

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[45] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).
[46] Merle E. Bunker (private communication).

APPENDIX. TREATMENT OF DIRECTIONAL CORRELATION DATA WHEN TWO UNRESOLVED GAMMA-GAMMA CASCADES ARE PRESENT

Definitions

Subscripts: 0 refers to 402-kev level; 1 refers to 280-kev level; 2 refers to 265-kev level; 3 refers to ground state of As^{75}; a refers to channel positions set to favor cascade through level 1; b refers to channel positions set to favor cascade through level 2; t refers to wide channels set to include composite photopeaks at 121 plus 136 kev and 280 plus 265 kev, respectively.

N_1 denotes disintegrations per second from level 1 (280-kev gamma rays).

N_2 denotes disintegrations per second from level 2 (265-kev gamma rays).

N_{01} denotes count rate in channel of detector A due to transitions proceeding from level 0 to 1 (count rate of 121-kev gamma rays).

N_{02} denotes count rate in detector A channel due to 0 to 2 transitions (136-kev gamma rays).

N_{13} denotes count rate in detector B channel due to 1 to 3 trasitions (280-kev gamma rays).

N_{23} denotes count rate in detector B channel due to 2 to 3 transitions (265-kev gamma rays).

$\alpha_{01}=N_{01}/(N_{01}+N_{02})$, i.e., fraction of total counts in channel of detector A due to 0 to 1 transitions (121-kev gamma rays). Similarly,

$\alpha_{02}=N_{02}/(N_{01}+N_{02})$,
$\alpha_{13}=N_{13}/(N_{13}+N_{23})$,
$\alpha_{23}=N_{23}/(N_{13}+N_{23})$.

ϵ_{01}, ϵ_{02}, ϵ_{13}, and ϵ_{23} are efficiencies for detecting in channel transitions proceeding from the level indicated by first subscript to level indicated by second subscript; the appropriate branching factor is contained in ϵ_{01}.

$\beta=\alpha_{01}\alpha_{13}N_2/\alpha_{02}\alpha_{23}N_1$; a subscript on β refers to measurements made at a particular channel position.

$C(\theta)$ is coincidence rate between detector A and B as a function of θ.

$w(\theta)=C(\theta)/(N_{01}+N_{02})(N_{13}+N_{23})=\sum_{i=0}a_iP_i(\cos\theta)$, $a_i=0$ if i is odd.

$W_a(\theta)$, $W_b(\theta)$, $W_t(\theta)$, $W_1(\theta)$, and $W_2(\theta)$ are normalized directional distribution functions; subscripts refer to a particular channel position or cascade.

$A_{i,a}$, $A_{i,b}$, $A_{i,t}$, $A_{i,1}$, and $A_{i,2}$ are coefficients of Legendre polynomials in $W(\theta)$; A_i refers to the coefficient of $P_2(\cos\theta)$ for $i=2$ and the coefficient of $P_4(\cos\theta)$ for $i=4$.

Derivations of Equations

It follows from the definitions that

$$N_{01}=\epsilon_{01}N_1,\quad N_{02}=\epsilon_{02}N_2,\quad N_{13}=\epsilon_{13}N_1,\quad N_{23}=\epsilon_{23}N_2,$$

and that

$$C(\theta)=\epsilon_{01}\epsilon_{13}N_1\cdot W_1(\theta)+\epsilon_{02}\epsilon_{23}N_2\cdot W_2(\theta).$$

Hence,

$$w(\theta)=C(\theta)/(N_{01}+N_{02})(N_{13}+N_{23}),$$
$$=[\alpha_{01}\alpha_{13}/N_1]W_1(\theta)+[\alpha_{02}\alpha_{23}/N_2]W_2(\theta), \quad (1)$$
$$=[\alpha_{02}\alpha_{23}/N_2][\beta\cdot W_1(\theta)+W_2(\theta)]. \quad (1a)$$

Equate coefficients of corresponding Legendre polynomials to obtain the expression,

$$a_i=(\alpha_{02}\alpha_{23}/N_2)(\beta A_{i,1}+A_{i,2}), \quad \text{for} \quad i=0, 2 \text{ or } 4. \quad (2)$$

If $i=0$, $A_{0,1}=A_{0,2}=1$, and N_2 is given by the equation,

$$N_2=\alpha_{02}\alpha_{23}(1+\beta)/a_0. \quad (3)$$

Then,

$$A_{i,x}=a_i/a_0=(1+\beta_x)^{-1}(\beta_x A_{i,1}+A_{i,2}) \quad \text{for} \quad i=0, 2 \text{ or } 4; \quad (4)$$

subscript x refers to channel positions a, b or t. Solve (4) for $A_{i,1}$ and $A_{i,2}$ using cases a and b.

$$A_{i,1}=[(1+\beta_a)A_{i,a}-(1+\beta_b)A_{i,b}]/(\beta_a-\beta_b) \quad \text{for} \quad i=2 \text{ or } 4, \quad (5)$$

$$A_{i,2}=[\beta_b(1+\beta_a)A_{i,a}-\beta_a(1+\beta_b)A_{i,b}]/(\beta_b-\beta_a) \quad \text{for} \quad i=2 \text{ or } 4. \quad (6)$$

The coefficients of the individual cascades may be obtained from the experimental directional correlation distributions with the aid of Eqs. (5) and (6) provided the mixing ratios of the gamma rays in the detectors are known. The source strength may be calculated from Eq. (3) and the value of N_2 should be independent of whether the channels were set to favor the (121, 280)-kev or the (136, 265)-kev cascade. Thus one may obtain an overall check on the mixing ratios used.

The mixing ratios for case a can be determined from the results of additional coincidence experiments. Solve Eq. (1) for α_{23}.

$$\alpha_{23}=[w(\theta)N_2]/[\alpha_{02}W_2(\theta)] -[\alpha_{01}\alpha_{13}N_2W_1(\theta)]/[\alpha_{02}N_1W_2(\theta)]. \quad (7)$$

At one angle, 180°, $w(\theta)$ was measured with the detector channel for the 265- plus 280-kev radiations set as in case a and the other channel set so that α_{02} is large compared to α_{01}. Under these experimental conditions the first term of Eq. (7) is dominant; in fact, the magnitude of the ratio, α_{01}/α_{02}, is such that only a few percent error is incurred in the evaluation of α_{23} even if the second term of (7) is crudely estimated. The value of N_2 substituted into the first term of (7) was measured with the detector channels set to maximize α_{02} and α_{23}. This value of N_2 is more accurate than that obtained under the conditions of case b. Since $W_2(\theta)$ is almost isotropic, it does not have to be known accurately. Similarly, α_{02} for case a was determined. Equation (1) was solved for α_{02}, then $W(\theta)$ at 180° was measured with the detector channel for the 121- plus 136-kev gamma rays set as in case a and the other channel set so that α_{23} is large.

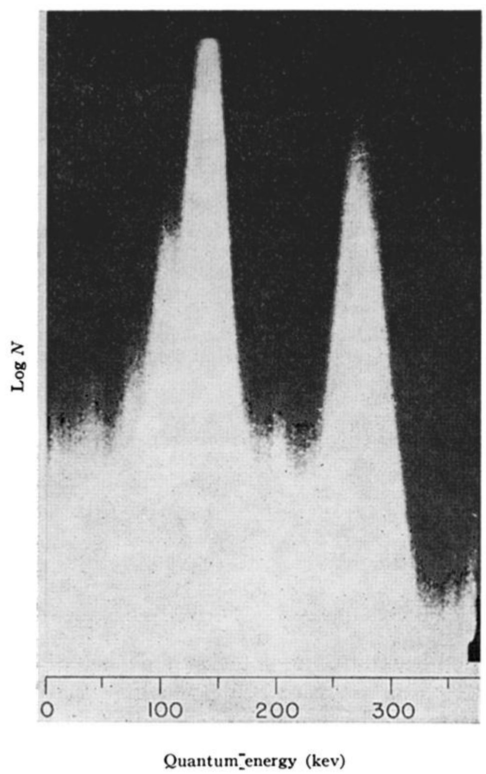

FIG. 6. Gray-wedge analyzer picture of Se^{75} gamma-ray spectrum (0 to 350 kev) as detected by a 3-cm diameter by 2-cm high NaI(Tl) crystal.

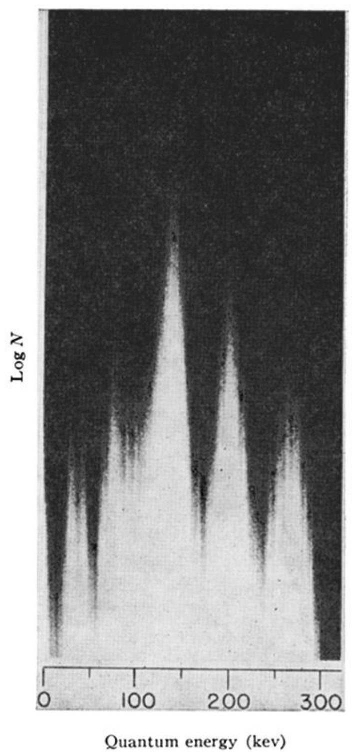

FIG. 7. Gray-wedge photograph of the Se^{75} pulse-height spectrum in coincidence with pulses which fall in a channel centered at 66 kev. The photopeak at 265 kev and at least part of the photopeak at 136 kev are due to coincidences with the background pulses on which the 66-kev photoline is superimposed. Different gain settings were used for Figs. 6 and 7.