Short-Lived Isomers of As^{75} and As^{77}†

ALOIS W. SCHARDT
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 10, 1957)

Sources of Se^{75} and Ge^{77} have been investigated by delayed-coincidence techniques for short-lived isomeric levels in the daughter nuclei As^{75} and As^{77}, respectively. The 0.305-Mev level of As^{75} has a half-life of 17 milliseconds and is depopulated by a 0.025-Mev $M2$ transition (90%) in competition with a 0.305-Mev $E3$ transition (10%). The 0.475-Mev level of As^{77} has a half-life of 116 microseconds and is depopulated by a 0.210-Mev $M2$ transition. An upper limit of 2% of the isomeric decays was placed on the intensity of any possible 0.475-Mev ground-state transition. In the beta decay of Ge^{77} to As^{77}, gamma rays of the following energies were found to feed the metastable state: 0.153, 0.709, 1.08, and 1.50 Mev and probably also 0.92 and 1.96 Mev. The data obtained have been incorporated in a recently proposed decay scheme of Ge^{77}. The previously discovered isomeric transition in As^{73}, as well as those in As^{75} and As^{77}, are probably all $M2$ transitions between 9/2+ and 5/2− levels, with transition probabilities of 0.9, 1, and 0.6%, respectively, of the shell-model single proton transition probability.

INTRODUCTION

THE level structure of As^{75} has been studied by measurement of the radiations from the decay of Ge^{75} and of Se^{75} [1,2] and from Coulomb excitation.[3] The level scheme[1] which appeared to fit these data best failed to account for the absence of coincidences[2] between the 97-kev gamma ray and other gamma rays appearing in the decay of Se^{75}. However, this observation could be explained if the proposed 305-kev level was assumed to be metastable.[1] DeBenedetti and McGowan[4] looked for isomerism in the microsecond range but found none in the Se^{75} decay. Vegors and Axel[5] observed a gamma activity (283±15 kev) with a half-life of 12±3 msec, produced by high-energy x-ray irradiation of arsenic; however, the mode of activation did not permit an assignment of the energy of the isomeric state or of the arsenic isotope responsible. Subsequently, the 305-kev level of As^{75} was shown to be isomeric[6] with a half-life of 18±1.5 msec, as observed by delayed-coincidence techniques in the decay of Se^{75}. Further work[7] on the x-ray excitation of arsenic has shown that the same activity was being observed in both cases. The As^{75} isomer has also been excited by inelastic scattering of neutrons, and a half-life of 21±2 msec was reported.[8*]

The existence of isomerism in[9] As^{73} and in As^{75} raised the possibility that a similar situation could exist in As^{77}. The results of a recent investigation[10] of the decay of Ge^{77} indicated the existence of a metastable level; no coincidences were found between gamma rays feeding the 475-kev level and those following its decay. The work reported here was undertaken to clarify the level scheme of As^{77} and to check with improved techniques the earlier results on As^{75m}. In particular, an attempt was made to establish the mode of formation and decay of the metastable states. Delayed-coincidence techniques in conjunction with scintillation counting and pulse-height analysis were employed using Se^{75} and Ge^{77} as sources of the isomers. This approach has the advantage that existing information on the decay schemes of these nuclei is an aid in identifying the isomeric levels. On the other hand, accidental coincidences are a problem because the half-lives are relatively long.

EXPERIMENTAL EQUIPMENT

For delayed coincidence work in the 100-μsec to 10-msec region, it is especially important to optimize the ratio of the coincidence rate to the accidental rate. This means that there must be high detection efficiency, discrimination against radiations not connected with the isomeric state, and low natural background. These requirements were met by placing the radioactive source at the center of a well-type NaI(Tl) crystal ($2\frac{7}{8}$ in. high and $2\frac{1}{2}$ in. in diameter) and by selecting the desired gamma rays with single-channel analyzers bracketing the respective photopeaks. In this arrangement, the gamma ray leading to the isomer, as well as the radiation by which it decays, was detected in the same crystal. Since the two events were not simultaneous, they could be identified by pulse-height analysis. The natural background was reduced by enclosing the crystal and photomultiplier in a 4-in. lead shield lined with $\frac{1}{2}$ in. of iron to absorb the lead K x-rays.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] A. W. Schardt and J. P. Welker, Phys. Rev. **99**, 810 (1955). Refer especially to note added in proof, p. 819.

[2] Lu, Kelly, and Wiedenbeck, Phys. Rev. **97**, 139 (1955); also W. H. Kelly and M. L. Wiedenbeck, Phys. Rev. **102**, 1130 (1956).

[3] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).

[4] S. DeBenedetti and F. K. McGowan, Phys. Rev. **74**, 728 (1948).

[5] S. H. Vegors, Jr., and P. Axel, Phys. Rev. **100**, 1238(A) (1955); **101**, 1067 (1956).

[6] A. W. Schardt, Bull. Am. Phys. Soc. Ser. II, **1**, 85 (1956).

[7] S. H. Vegors, Jr. (private communication).

[8] E. C. Campbell and P. H. Stelson, Oak Ridge National Laboratory Report ORNL-2076, (unpublished), p. 32.

* *Note added in proof.*—This value of the half-life has been revised to 18±2 msec; P. H. Stetson and E. C. Campbell, Oak Ridge National Laboratory, Report ORNL 2302 (unpublished) p. 25.

[9] R. W. Hayward and D. D. Hoppes, Phys. Rev. **101**, 93 (1956).

[10] Burson, Jordan, and LeBlanc, Phys. Rev. **96**, 1555 (1954).

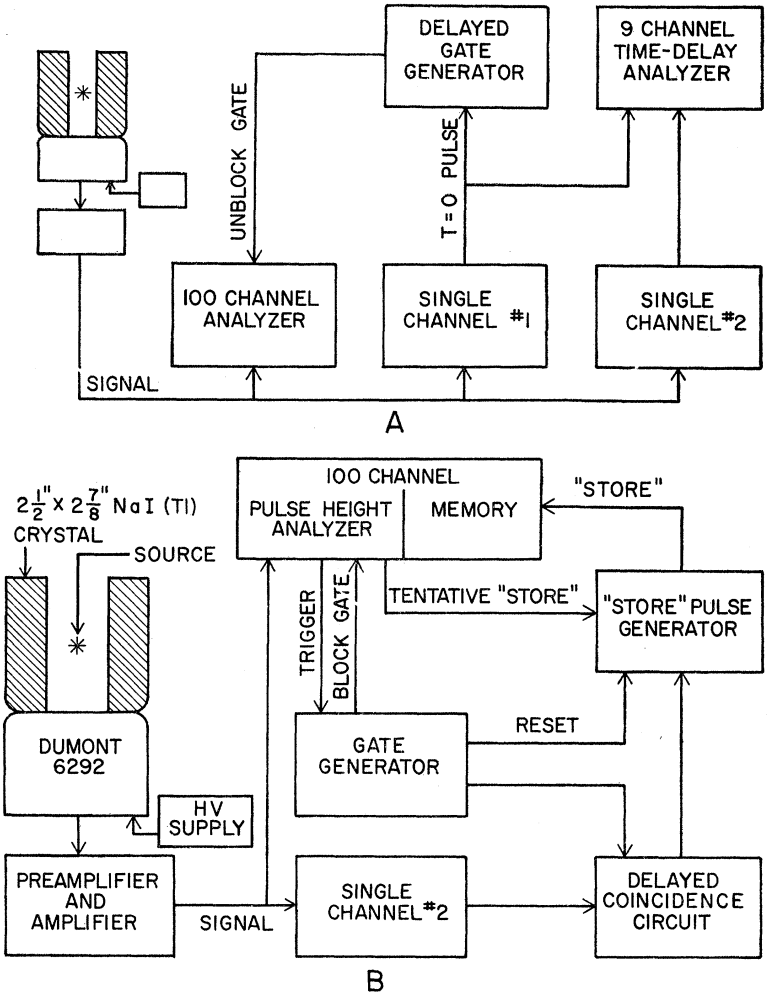

FIG. 1. Block diagram of delayed coincidence circuits. Diagram *A*—Arrangement for measuring isomeric half-life and the scintillation pulse-height spectrum of the gamma rays leaving the isomeric state. Diagram *B*—Arrangement for measuring the pulse-height spectrum of the gamma rays feeding the isomeric state.

To provide a complete picture of the formation and decay of the isomeric state, it was necessary to measure the isomeric half-life and to observe the scintillation spectra of the gamma rays feeding the isomer as well as of those by which it decayed. These observations were made with the electronic equipment[11] shown in diagram form in Fig. 1. The pulses from the photomultiplier were amplified and fed into one 100-channel and two single-channel pulse-height analyzers. The channel of Analyzer No. 1 was set to include pulses predominantly due to gamma rays leading to the isomeric state; similarly, Analyzer No. 2 was set to discriminate in favor of pulses produced by the isomeric decay.

In the half-life measurement, the first time gate of the 9-channel time-delay analyzer was opened by the $t=0$ pulse from Analyzer No. 1 (Diagram *A*, Fig. 1). Any subsequent pulse from Analyzer No. 2 within the range of the time-delay analyzer was then recorded in the appropriate time channel. The lengths of the time channels were calibrated with a 100-kc crystal oscillator. This calibration was checked by triggering the time-delay analyzer with a pulser and feeding pulses of a known repetition rate into the other input; thus it was shown that the nine channels were equal in length and stable to $\pm 0.5\%$ for several days.

In the determination of the background of the different time channels it was necessary to take into account a nonrandom component. This effect arose in the following manner: the fact that the $t=0$ pulse from Analyzer No. 1 triggered the time-delay analyzer implied that no similar pulse had occurred since the end of the last cycle. Consequently, the population of the isomeric state just before $t=0$ was, on the average, less than in the random case, roughly by that fraction of the events forming the isomer which was being detected. As a result, the part of the random background

[11] The time-delay analyzer and the special gating circuits were designed and put into operation by J. P. Glore, and are described in the Los Alamos Scientific Laboratory Report, LA-2152. Another report will describe the Los Alamos Model 2A, 100-channel analyzer. With the exception of these circuits, standard amplifiers, analyzers, etc., could be used. The whole system was stable to better than 1% over periods of a week with regard to both pulse height and gate length.

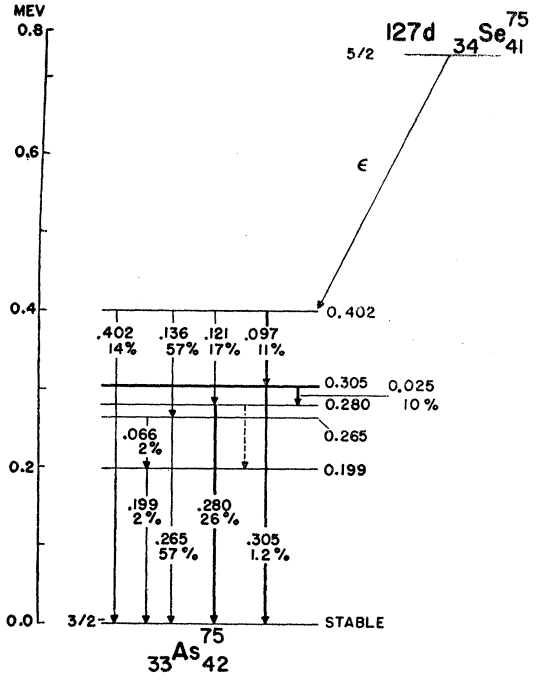

FIG. 2. Decay scheme of Se^{75}. Level and transition energies are given in Mev. Transitions involving the isomeric state at 0.305 Mev are shown with heavy lines.

due to gamma rays following the isomeric decay was reduced in the first time channel. The background increased towards its random value in later channels because Analyzer No. 1 pulses occurring during a cycle of the time-delay analyzer did not retrigger it. The difference between the actual and random background was estimated for the As^{75m} data; it amounted to 7% in time-channel 1 and 0.5% in channel 9. This change in background had less than a 0.5% effect on the final isomeric half-life. The true random background of the time-delay analyzer data was determined by supplying the $t=0$ pulses from a pulser rather than Analyzer No. 1 and counting Analyzer No. 2 pulses in the different channels for the same number of $t=0$ pulses as in the original experiment. In cases where source decay during the experiment was appreciable, a close approximation to the actual background during the experiment was obtained by averaging the background as measured before and after the experiment. This procedure was exact to the degree that the counting rates of Analyzers No. 1 and No. 2 decayed exponentially and that source decay during the background measurements could be neglected. The errors resulting from these approximations were calculated for the As^{77m} data because normally the experiment lasted one half-life of Ge^{77}. The discrepancy was less than 1.5% of the random background.

The spectrum of gamma rays by which the isomer decays was recorded by a 100-channel pulse-height analyzer with delayed coincidence gating (Diagram *A*, Fig. 1). This analyzer was normally blocked by the delayed-gate generator. Pulses from Analyzer No. 1 (gamma rays feeding isomer) triggered this unit. After a given time delay, it in turn generated a gate pulse which unblocked the 100-channel pulse-height analyzer. Only for the duration of this gate were pulses from the scintillator recorded. The pulse-height spectrum observed in this way was due to delayed gamma rays superimposed on accidental background. The gamma rays associated with the isomer could be distinguished from the others by observing the change of the 100-channel analyzer spectrum with change in time delay between the $t=0$ pulse and the unblocking pulse. The isomeric half-life could be determined also from this data, but this method is in general less accurate than the time-delay analyzer method.

The gamma rays feeding the isomeric state were investigated with the gating arrangement shown in Diagram *B*, Fig. 1. At the time when a gamma ray was detected in the scintillator, it was not yet known whether it led to the metastable state; this identification could be made only after the detection of the gamma ray by which the isomeric state decayed, and hence all photomultiplier pulses had to be analyzed for pulse height. This information was recorded in the 100-channel analyzer memory only if a pulse from Analyzer No. 2 occurred within a specified time

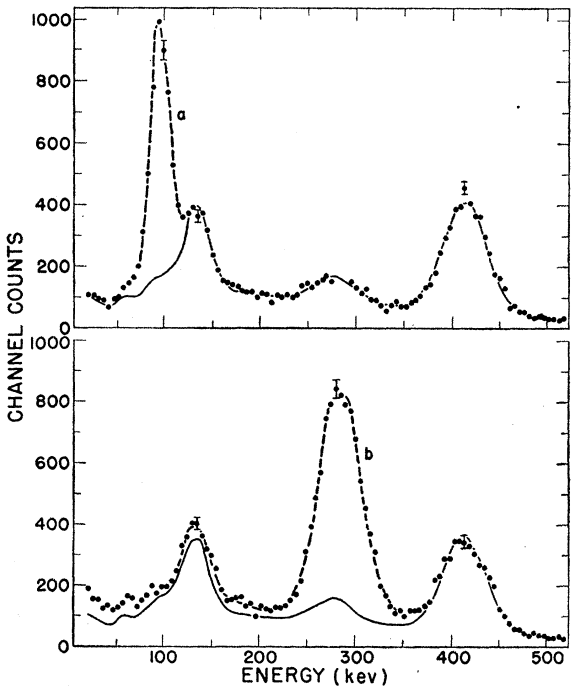

FIG. 3. Pulse-height spectrum of a Se^{75} source at the center of a well-type NaI(Tl) crystal. Solid curves, ungated spectra normalized to give accidental background under gated spectra. Curve *a*—15-msec delayed coincidence spectrum superimposed on accidental background displaying gamma rays feeding the isomeric state. Curve *b*—Gated spectrum displaying gamma rays due to isomeric decay.

interval. For the duration of this process, the 100-channel analyzer input was blocked in order to prevent a second pulse from destroying the pulse-height information which was temporarily stored in the pulse-height scaler. At the end of each cycle, the "store" pulse generator was reset to ready it for the next count. Pulses which fell into the channel of Analyzer No. 2 were prevented from recording themselves by requiring a minimum delay of 5 μsec between the original pulse and the delayed coincidence pulse from Analyzer No. 2. This delay was just a little longer than the time between input and output pulses of the single-channel analyzer. Accidental coincidences were determined as before by triggering the delayed coincidence circuit with a pulser.

As^{75m} (17.0 msec)

According to the decay scheme of Se^{75} (reference 1), as shown in Fig. 2, delayed coincidences are to be expected between the 97- and 280-kev gamma rays. With the techniques of this experiment, the 25-kev transition cannot be observed, and the 305-kev gamma ray is so weak relative to the 280-kev gamma ray that it cannot be identified separately. Se^{75} decays to the 402-kev level of As^{75}, and with a highly efficient crystal only full-energy pulses will appear, regardless of whether the level is depopulated by one gamma ray or by a gamma-gamma cascade; however, if a metastable state prevents prompt coincidences the individual gamma-ray energies

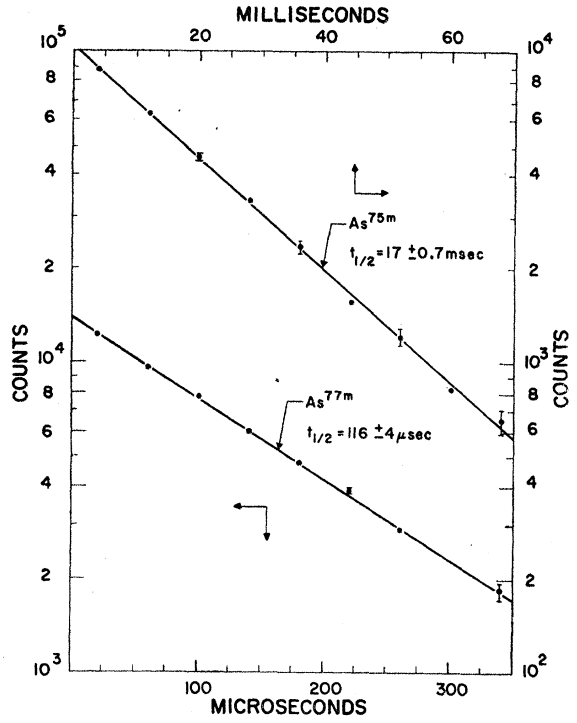

FIG. 4. Gamma-ray decay curves of As^{75m} and As^{77m} (accidental coincidence background has been subtracted). The As^{75m} curve is to be read on the right and upper scales; the As^{77m} curve is to be read on the left and lower scales.

TABLE I. Comparative lifetimes of the isomeric transitions in As^{73}, As^{75}, and As^{77}.

(1) Isotope	(2) Transition energy (kev)	(3) Partial half-life (sec)	(4) Experimental gamma-ray transition probability[b] / Theoretical transition probability E2	M2	E3	M3
As^{73}	359[a]	6.0×10^{-6}[a]	4×10^{-4}	9×10^{-3}	3×10^{2}	3×10^{3}
As^{75}	25	1.9×10^{-2}	2×10^{-4}	1×10^{-2}	2×10^{3}	4×10^{4}
As^{75}	305	0.19	3×10^{-8}	6×10^{-7}	2×10^{-2}	3×10^{-1}
As^{77}	210	1.16×10^{-4}	2×10^{-4}	6×10^{-3}	4×10^{2}	4×10^{3}

[a] These values are taken from R. W. Hayward and D. D. Hoppes, reference 9.

[b] The theoretical single-proton transition probabilities were calculated with the formulas given by S. A. Moszkowski, reference 13. The experimental half-lives were corrected for internal conversion. When available, the experimental conversion coefficients were used; otherwise, the theoretical conversion coefficients were employed [Rose, Goertzel, and Swift (privately circulated tables)]. The theoretical conversion coefficients of a 25-kev transition are 390, 165, 5100, and 3700 for *E2*, *M2*, *E3*, and *M3* multipolarity assignments, respectively.

are detected. As can be seen from the ungated spectrum of Se^{75} (curve shown as a solid line in Fig. 3) a large fraction of the counts occurred at 415 kev.[12] With a 15-msec delayed-coincidence requirement, spectra were taken both of the gamma rays feeding the isomer and of those following its decay (Fig. 3). As expected, only the 97- and 280-kev transitions were found. If the 15-msec gate was delayed with respect to the 97-kev transition, the coincidence peak at 280 kev decreased; for a 70-msec delay, it was barely discernible above the accidental background.

The half-life of As^{75m} was measured with both 8- and 4-msec channels of the time-delay analyzer. The sum of all 8-msec data is shown in Fig. 4. The background, amounting to about 23% of the total number of counts in the first time channel, has been subtracted. The best value of the half-life is 17.0±0.7 msec. The quoted uncertainty corresponds to a possible 10% error in the subtracted background. In Table I are given the partial half-lives of the 25- and 305-kev transitions, together with the ratios of the experimental transition probability to the theoretical transition probability of a shell model calculation.[13] For the 25-kev transition, only an *M2* assignment results in a reasonable ratio. Both *E3* and *M3* assignments to the 305-kev gamma rays give reasonable transition probabilities, but *M3* can be ruled out on the basis of the *K*-conversion coefficient.[1] These multipolarities fix the spins of the 305- and 280-kev levels as 9/2+ and $\frac{5}{2}-$, respectively.

The above results remove the difficulty originally associated with the level scheme of Fig. 2. Additional confirmation has come from the study of gamma rays produced by inelastic scattering of neutrons on arsenic.[14] In this work, no 97-, 121-, or 136-kev gamma rays were

[12] The sum peak does not appear exactly at the sum of the transition energies because of the nonlinear response of the NaI(Tl) crystal. Refer to D. Engelkemeir, Rev. Sci. Instr. 27, 589 (1956).

[13] S. A. Moszkowski, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 13.

[14] D. A. Lind and R. B. Day (private communication).

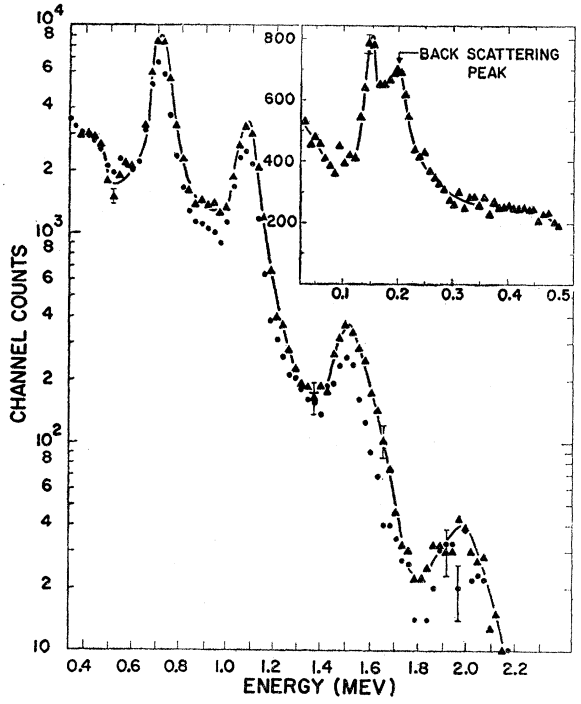

FIG. 5. Gated scintillation spectrum of gamma rays in the Ge^{77} decay which feed As^{77m} (accidental coincidence background has been subtracted). ▲ source surrounded by $\frac{1}{4}$-in. Lucite beta absorber. ● source surrounded by tin absorber to reduce 153-kev peak. Insert, low-energy region taken with Ge^{77} source in Lucite absorber.

found until the neutron energy was sufficient to excite the 402-kev level. By subtracting pulse-height spectra of gamma rays excited with neutrons having energies just below and just above 402 kev, it was possible to show that the spectrum of gamma rays, by which the 402-kev level decays, is indistinguishable from the scintillation spectrum of a Se^{75} source. Although the previously proposed level scheme[1] has been confirmed, the spin assignments[1,2] have to be changed in view of the new results. The half-life of the 402-kev level can now be bracketed between 1×10^{-10} sec[15] and 2×10^{-9} sec,[16] corresponding to a partial half-life of the 97-kev transition falling between 1×10^{-9} sec and 2×10^{-8} sec. The experimental K-conversion coefficient[1] and the relatively short half-life indicate that the 97-kev transition is $E2$. This multipolarity, together with the 9/2+ character of the 305-kev level, requires a spin and parity of $\frac{5}{2}+$ for the 402-kev level. With such an assignment, the conversion coefficients[1] of the 402-, 136-, and 121-kev gamma rays have to be explained on the basis of $E1-M2$ mixtures. Although such mixtures would normally not be expected, they are consistent with the partial half-lives of these transitions. The spin and parity of the 265-kev level is then determined as $\frac{3}{2}-$ on the basis of the logft value of the beta branching in the Ge^{75} decay, the character of the 402-kev level, and the multipolarity of the 136-kev transition. The isotropic directional correlation of the (136, 265)-kev cascade[1,2] and the anisotropic fluorescence gamma-ray angular distribution[15] can be interpreted on the basis of the above spin assignments if proper multipolarity mixing of the gamma rays is assumed. However, the required $E2$ admixture to the 265-kev gamma ray is larger than might be expected from the half-life, $\sim1.5\times10^{-11}$ sec,[15] of this level.

[15] Franz Metzger (private communication). An unsuccessful attempt to excite the 402-kev level with fluorescent radiation made it possible to place a lower limit of 1×10^{-10} sec on the half-life.

[16] Robert B. Day (private communication). No delayed gamma rays were found in the millimicrosecond region from an arsenic sample excited by a pulsed neutron beam.

As^{77m} (116 μsec)

The Ge^{77} decay scheme proposed by Burson and coworkers[10] indicates that the 0.475-Mev level in As^{77} is fed by 0.709- and 1.08-Mev gamma rays and decays by a 0.210-, 0.265-Mev gamma-gamma cascade. However, these investigators found no prompt coincidences (1.6-μsec resolving time) between the two groups of gamma rays. In the work reported here, the isomeric nature of the 0.475-Mev level was confirmed. The half-life of this state was measured with the single-channel Analyzer No. 1 covering the photopeak of either the 0.71- or the 1.08-Mev quanta and with Analyzer No. 2 set to count both the 0.210- and 0.265-Mev photopeaks. Similar results were obtained in both cases. Figure 4 shows data taken with 40-μsec time gates; a time-independent background amounting to about 12% of the counts in the first time channel has been subtracted from the number of counts in each channel. The best value of the isomeric half-life is 116±4 μsec; the quoted uncertainty corresponds to a possible 10% error in the subtracted background.

Spectra were taken of the quanta feeding the 475-kev level (Fig. 5) and of those by which it decays (Fig. 6), by requiring 110-μsec delayed coincidences. In the spectrum of quanta feeding the isomer (Fig. 5) photopeaks are found at 153±5, 709±7, 1080±10, 1500±15, and 1960±30 kev; in addition, a weak peak at 920±40 kev appears to be hidden in the valley between the 709- and 1080-kev peaks. Some of these photopeaks could be due to coincidence addition in the NaI(Tl) crystal since many gamma-gamma coincidences[10] occur in the decay of Ge^{77} (refer to Fig. 7). By observing the same delayed-coincidence spectrum (Fig. 5) with a tin absorber surrounding the source, it was shown that none of the observed peaks was due to coincidence addition with the 0.153-Mev gamma ray, because the absorber would have reduced the intensity of the addition peaks by a factor of 3 relative to the 0.709-Mev photopeak. Coincidence addition is also to be expected between the 0.709- and 0.800-Mev and between the 0.92- and 1.080-Mev gamma rays (Fig. 7). The intensity of the addition peaks at 1.5 and 2.0 Mev

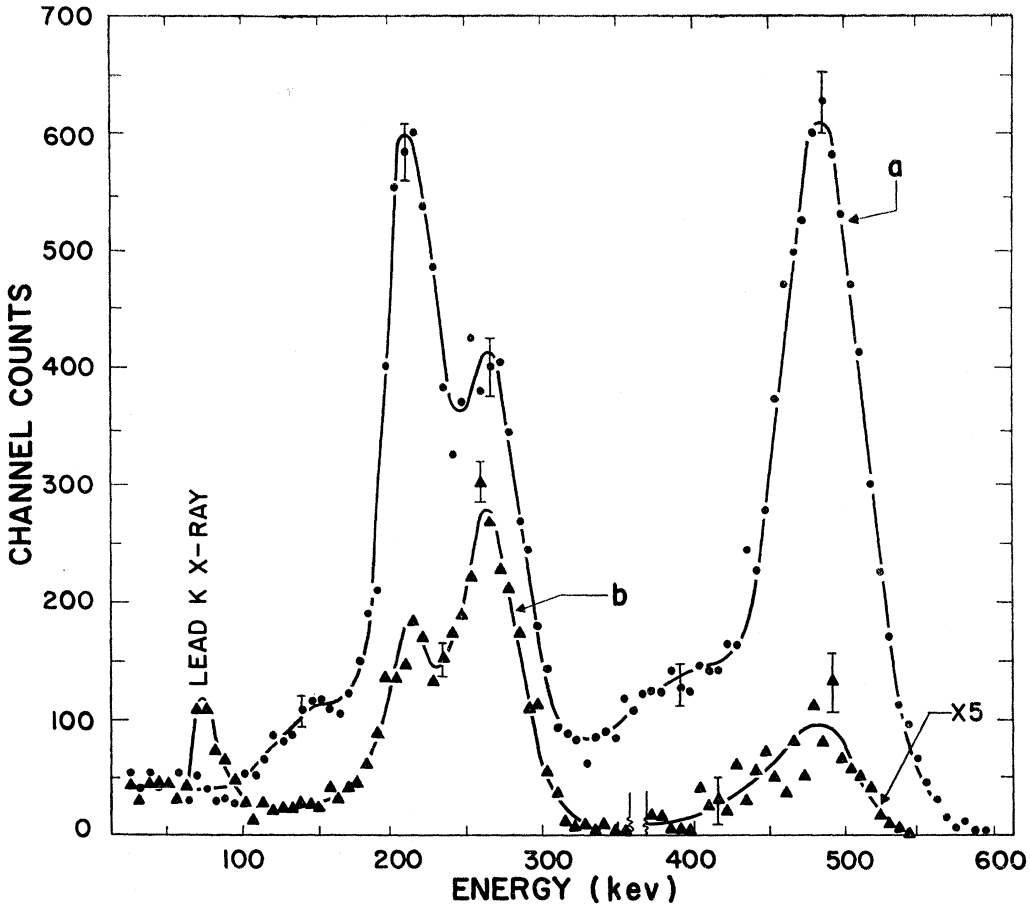

FIG. 6. Gated scintillation spectrum of As^{77m} decay (background has been subtracted). Curve *a*—Source in $\frac{1}{4}$-in. Lucite beta absorber. Curve *b*—Source in 0.24-cm lead absorber to reduce the addition peak of the 210- plus 265-kev gamma rays.

was calculated by use of the absolute crystal efficiency[17] and the relative gamma-ray intensities (Table II, column 2) as observed in the ungated Ge^{77} spectrum. This calculation showed that roughly one half of the counts at 1.50 and at 1.96 Mev are due to coincidence addition. The relative gamma-ray intensities deduced in this way are given in column 3, Table II.

In Fig. 6 is shown the scintillation spectrum of the gamma rays which follow the isomeric level; photopeaks at 0.210 and 0.265 Mev, plus the addition peak at 0.485 Mev (reference 12), are easily identified. A true 0.475-Mev gamma ray corresponding to a ground-state decay of the isomer was looked for by measurement of the spectrum with the source placed inside a cylindrical lead absorber of 0.24-cm wall thickness. Within experimental uncertainties, the very much reduced peak at 0.48 Mev (Curve *b*, Fig. 6) can still be accounted for on the basis of coincidence addition[17]; an upper limit on the intensity of crossover transitions was estimated to be 2% of the isomeric decays.

As far as possible, the relative gamma-ray intensities (Table II) were determined by analyzing the gamma-ray spectrum following the Ge^{77} decay as observed with a 3×3 in. NaI(Tl) crystal.[18] The relative intensities are in some cases rather uncertain because the gamma rays are only partially resolved from one another. Although Burson and co-workers[10] assumed the existence of two gamma rays, 1.46 and 1.54 Mev, only one gamma ray of 1.50 Mev is necessary to explain the relative intensities as observed in the normal spectrum (Table II, Column 2) and in the delayed coincidence spectrum (Table II, Column 3). Therefore, the 1.46- and 1.54-Mev ground state transitions tentatively assigned by Burson *et al.* were omitted from the decay scheme proposed here (Fig. 7). The 0.92- and 1.96-Mev transitions were entered as dashed lines, since these gamma rays were too weak for positive identification. There is

[17] The absolute detection efficiency for sources at the center of the NaI(Tl) crystal was determined by coincidence counting, and the absorption of the lead absorber was determined for several gamma-ray energies. The intensity of the expected addition peak could then be calculated.

[18] The author is greatly indebted to N. H. Lazar for his graphs of intrinsic efficiency *vs* gamma-ray energy of a NaI(Tl) crystal 3 in. in diameter by 3 in. high.

TABLE II. Ge^{77} gamma-ray energies and transition intensities.

(1) Transition energy[a] (kev)	(2) Relative gamma-ray intensity: Normal spectrum	(3) Relative gamma-ray intensity: Delayed-coincidence spectrum	(4) Transition intensity, percentage of Ge^{77} disintegrations[b]
153±5		0.13±0.05	1.0
210±1	15 ±2		35[c]
215±3			28
265±1			57
368±5	2.2 ±0.3		18
416±5	3.5 ±0.4		28
563±5	2.5 ±0.3		20
632±8	1.5 ±0.3		12
709±7	1.5 ±0.3	1.3 ±0.2	10
800±15	1.0 ±0.3	0.3 ±0.1	8
917±10[d]	0.8 ±0.2	0.2 ±0.1	6 and 1.6
1080±10	1.00	1.00	8
1193±15	0.52±0.15		4
1366±20	0.51±0.10		4
1500±15	0.15±0.04	$0.10^{+0.05}_{-0.02}$	1.0
1740±30	0.06±0.03		0.5
1960±40	0.35±0.10	0.02±0.02	0.2
2025±40			2.5
2320±40	0.09±0.02		0.7

[a] The energies given were derived from those of Burson *et al.* (reference 10) plus present data.
[b] Taking into account the decay scheme of Fig. 7, the total disintegration rate of Ge^{77} was taken to be equal to the sum of the intensities of the 265-, 416-, 632-, 2025-, and 2320-kev gamma rays.
[c] The gamma-ray intensity has been corrected with the theoretical $M2$ conversion coefficient of 0.08.
[d] This peak consists of 2 different gamma rays (Fig. 7).

also some question as to the number of levels at about 2.37 Mev. The direct ground-state transition has an energy of 2.32±0.04 Mev, whereas the cascades add up to 2.37±0.03 and 2.42±0.03 Mev, respectively. In view of the energy uncertainties, there is no definite evidence indicating whether one or two levels are involved.

On the basis of the decay scheme of Fig. 7 and the relative gamma-ray intensities (Table II, Columns 2 and 3), absolute intensities for both the gamma transitions (Table II, Column 4) and the beta groups (Fig. 7) can be calculated. The intensities of the beta groups agree within experimental errors with those observed by Smith,[19] provided beta groups with close end-point energies are added together, because they were not resolved. The energy of the unresolved beta groups feeding the 0.475- and 0.632-Mev levels in As^{77} was measured by Smith to be 2.196 Mev. Since from the present work the calculated relative intensities of these groups are as 15 to 27, an approximate $Ge^{77}-As^{77}$ energy difference was determined by adding 2.196 Mev to the weighted average of 0.475 and 0.632 Mev, that is 0.575 Mev. Thus the beta energies and logft values given in Fig. 7 were calculated by using an energy difference of 2.77 Mev.

According to the proposed decay scheme (Fig. 7), the 210-kev transition determines the isomeric half-life. That this gamma ray is not $E1$ or $M1$ is confirmed by the relatively large conversion coefficient as determined from a comparison of the relative intensities of the internal conversion lines[19] with those of the gamma rays (Table II). A comparison of the isomeric half-life with the theoretical values for different multipole assignments (Table I) shows that the 210-kev gamma ray is most probably an $M2$ transition. The absence of a direct transition to the $\frac{3}{2}-$ ground state of As^{77} indicates that the spin of the isomeric state is at least 9/2. In view of the similarity with the isomeric states in As^{73} (reference 9) and As^{75}, the spins and parities of the 475- and 265-kev levels of As^{77} are most probably 9/2+ and $\frac{5}{2}-$, respectively. From the experimental $E3$ ground-state transition probability measured for As^{75m}, one would expect that about 1% of the As^{77m} disintegrations go directly to the ground state, a value consistent with the experimental upper limit of 2%. With the limited information available, the spins and parities of the other levels cannot be assigned. However, the logft values of the Ge^{77} beta groups would indicate spins of $\frac{5}{2}$, $\frac{7}{2}$, or 9/2 for the As^{77} levels reached.

DISCUSSION

The level schemes of both As^{75} and As^{77} are rather complex; yet the first few levels of these nuclei are in many respects similar (Fig. 8). It is plausible that the levels connected by dashed lines in Fig. 8 correspond to nuclear configurations which differ only by the presence of an additional neutron pair in the case of As^{77}. This similarity manifests itself in the following ways: the 402-kev level in As^{75} and the 632-kev level in As^{77} decay each by four different gamma rays; the

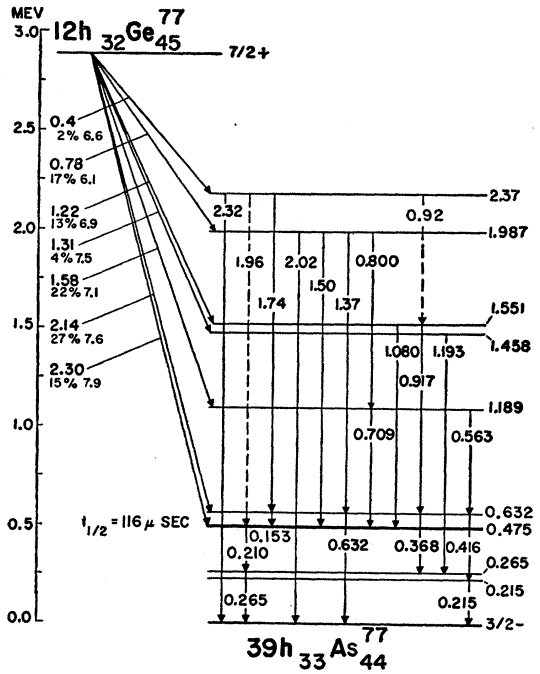

FIG. 7. Proposed decay scheme of Ge^{77}. Level and transition energies are given in Mev. The numbers associated with the beta groups represent transition energy, branching ratio, and logft value, respectively.

[19] Alan B. Smith, Phys. Rev. 86, 98 (1952).

reduced half-lives of the isomeric transitions are almost identical; and the logft values of the beta decay of the $p_{\frac{3}{2}}$ states in Ge^{75} and Ge^{77} to the 265- and 215-kev levels, respectively, are 5.6 and 5.7. No level corresponding to the 199-kev level of As^{75} has been found in As^{77}; such a level could have been missed in the Ge^{77} decay because in this case the beta transition selection rules favor higher spin states.

Two nuclear models appear promising for an explanation of the observed level schemes. In this mass range it is expected that the last odd nucleon may polarize the core.[20] The odd parity states could then be explained by a $p_{\frac{3}{2}}$ or $f_{\frac{5}{2}}$ proton coupled to the deformed core, and the even parity states by a similar coupling of a $g_{9/2}$ proton. The large number of levels in As^{75} that can be Coulomb-excited,[3] the large $E2$ transition probabilities, and the inhibited $E1$ transition probabilities should be explainable by this model, provided it is possible to identify the levels and to calculate the parameters involved. The single-particle shell model cannot account for the observed levels; however, with configuration mixing and the inclusion of interactions between equivalent particles, this situation may be changed. Configuration mixing may be significant in this region of the periodic table because the energy separations between the $p_{\frac{3}{2}}$, $f_{\frac{5}{2}}$, $p_{\frac{1}{2}}$, and $g_{9/2}$ states are relatively small.[21] Near closed shells, this model has been able to account for beta- and gamma-ray transition probabilities which were either unusually large or unusually small.[22] It remains to be seen whether an equally satisfactory explanation can be given for the transition probabilities occurring in the germanium and selenium decays.

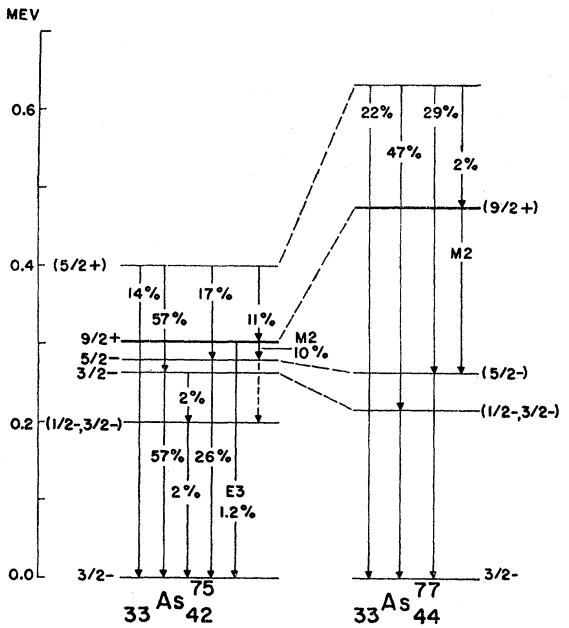

FIG. 8. Comparison of As^{75} and As^{77} level schemes. Transition intensities are given in percentage of the 402- and 632-kev level decays, respectively.

In the case of As^{75} and As^{77} the $g_{9/2}$ level should occur at an even lower energy than predicted by the shell model, because the odd $g_{9/2}$ proton is stabilized by the paired $g_{9/2}$ neutrons.[22] One might also expect to find even-parity states formed by several equivalent $g_{9/2}$ protons, because the anomalous magnetic moment of As^{75} already requires a pair of $g_{9/2}$ protons in the ground-state configuration.[23] For several equivalent $g_{9/2}$ neutrons, $\frac{5}{2}+$ (Ge^{73}, Se^{75}) and $\frac{7}{2}+$ (Se^{79}, Kr^{81}) states are known to occur,[24] and thus it appears likely that the $\frac{5}{2}+$ level in As^{75} is the equivalent proton configuration. These general arguments show that the proposed level assignments for As^{75} are not unreasonable, but an understanding of the configurations involved must await a detailed analysis and an explanation of the experimental transition probabilities of the different beta and gamma transitions.

The isomeric transitions of the arsenic isotopes of mass numbers 73, 75, and 77 can be classified as $M2$ transitions between $9/2+$ and $\frac{5}{2}-$ levels. By comparison with other $M2$ transitions,[25] they form a very homogeneous group with a transition probability between 0.6% and 1% of that of the single proton (Table I). The same type of isomerism would be expected to occur in at least some of the odd bromine and rubidium isotopes, since the above arguments on level spacings may be expected to apply also to them. It is possible that in some of these isotopes the $\frac{5}{2}+$ or $\frac{7}{2}+$ level, presumably formed by coupling between equivalent $g_{9/2}$ protons, falls below the $9/2+$ level. In this case, isomerism would be found only if the $\frac{7}{2}+$ level occurs below the $\frac{5}{2}-$ level. Starting with yttrium, both the $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ subshells are filled and the well-known island of $p_{\frac{1}{2}}-g_{9/2}$ isomerism starts.[26] This $9/2+$ to $\frac{5}{2}-$ transition has already been found[24] in Rb^{85}; it, too, has a transition probability of 0.9% of that of a single proton. Short-lived isomers have been found also in bromine,[27] but available information is insufficient to determine whether they fall into this group.

ACKNOWLEDGMENTS

Much of the credit for the successful completion of this work should go to the electronics group of this

[20] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. 28, 432 (1956). Refer to discussion on p. 539.
[21] P. F. A. Klinkenberg, Revs. Modern Phys. 24, 63 (1952).
[22] A. de-Shalit and M. Goldhaber, Phys. Rev. 92, 1211 (1953).
[23] A. Arima and H. Horie, Progr. Theoret. Phys. (Japan) 12, 623 (1954).
[24] *Nuclear Level Schemes, A=40 — A=92*, compiled by Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).
[25] M. Goldhaber and A. W. Sunyar, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 16, Part II.
[26] M. Goldhaber and R. D. Hill, Revs. Modern Phys. 24, 179 (1952).
[27] S. H. Vegors, Jr., and R. B. Duffield, Bull. Am. Phys. Soc. Ser. II, 1, 206 (1956).

Laboratory and in particular to James P. Glore. Thanks are due to the reactor group for sample irradiations and to Bruce J. Dropesky for the preparation of the many gamma-ray calibration sources needed. The author is also indebted to Keith Zeigler for the statistical analysis of the decay data and discussions about statistical problems regarding the accidental background corrections. It is a pleasure to acknowledge many helpful discussions with Lawrence Wilets and Jere D. Knight, and to thank Franz Metzger, David A. Lind, and Robert B. Day for permission to quote their results before publication.

PHYSICAL REVIEW VOLUME 108, NUMBER 2 OCTOBER 15, 1957

Inelastic Scattering of 4-Mev Protons and Deuterons from Separated Isotopes of Dy^{161}, Dy^{163}, Yb^{171}, and Yb^{173}

B. ELBEK, K. O. NIELSEN, AND M. C. OLESEN
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received July 1, 1957)

The inelastic scattering of protons and deuterons from the odd isotopes of Dy and Yb has been measured at energies around 4 Mev in a heavy-particle spectrometer at a scattering angle of 145°. Isotopically pure targets were prepared in an electromagnetic isotope separator. Inelastic groups corresponding to the two lowest rotational states were observed in Dy^{161} at 44 kev and 102 kev, in Dy^{163} at 74 kev and 170 kev, in Yb^{171} at 67 kev and 76 kev, and in Yb^{173} at 78 kev and 181 kev. The reduced electric quadrupole transition probabilities for these levels were determined.

INTRODUCTION

WHEN a heavy element is bombarded with low-energy particles, the only inelastic events correspond to Coulomb excitation of low-lying nuclear levels.[1] In spite of the preponderance of elastic scattering it is possible to observe the groups of inelastically scattered particles in magnetic spectrometers of high resolution.[2]

This method of detection has several advantages as compared with other techniques used in Coulomb excitation experiments: The level order is directly established; the inelastic cross sections are easily obtained by comparison with the Rutherford scattering, and it is possible to use minute quantities of the target material. In the experiments reported here, only about 15 μg of each isotope were used for the target.

Until recently the Coulomb excitation of the odd isotopes of dysprosium and ytterbium has been studied only by means of natural elements.[1] Separated targets of these isotopes have been produced in the isotope separator at this Institute and their low-lying levels have been studied by means of the inelastic scattering technique.

APPARATUS

Protons and deuterons were accelerated in a 4-Mev electrostatic generator. Energy analysis was performed in a 90° deflecting magnet of 50-cm radius. The settings of the entrance slit (0.8 mm) and the exit slit (0.3 mm) were such that the energy spread in the analyzed beam at 4 Mev was less than 6 kev. The analyzed beam current reaching the target was around 0.1 microampere.

After energy analysis the beam was made to strike the target in the heavy-particle spectrometer used for the detection of the scattered particles. This spectrometer is of the uniform-field type described by Hafner, Donoghue, and Snyder,[3] and others.[4] It has a maximum radius of 36 cm and a minimum radius of 20 cm. A range of energies covering more than a factor of 3 is thus simultaneously recorded on photographic plates extending 40 cm along the focal line. The photographic plates used are Ilford C2 with an emulsion thickness of 25 or 50 μ. By means of a screw, the plateholder can be shifted laterally in the spectrograph, so that three different exposures can be made on the same set of plates without breaking the vacuum. The number of tracks in the plates is counted in a microscope as a function of the distance along the plates.

The spectrograph field is measured by means of a nuclear-induction magnetometer. Calibration of the spectrograph was carried out in a way similar to that described by Browne and Buechner,[5] using the known momenta of Bi^{212} and Po^{210} alpha particles.

A more complete description of the present installation will be given elsewhere.

[1] See Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).
[2] B. Elbek and C. K. Bockelman, Phys. Rev. **105**, 657 (1957).
[3] Hafner, Donoghue, and Snyder, Brookhaven National Laboratory (privately circulated report).
[4] D. J. Prowse and W. M. Gibson, J. Sci. Instr. **33**, 129 (1956).
[5] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1955).