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Double Isomerism in As^{73}†

H. H. Bolotin
Argonne National Laboratory, Argonne, Illinois

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The levels in As^{73}, populated by the decay of Se^{73}, were studied. States at 0.425 and 0.066 MeV were found to decay by means of two cascade gamma rays with energies of 0.359 and 0.066 MeV, with no observed crossover transition. Half-lives of 5.0 ± 0.4 μsec and 6.1 ± 0.4 nsec were measured for the 0.425- and 0.066-MeV states, respectively. The 0.066-MeV transition, previously assigned as $M1$, was found to be retarded by a factor of 97 compared to single-particle estimates. This result tends to confirm the l-forbidden character of this transition. This retardation is compared with that for the 0.068-MeV transition in Ni^{61}, which proceeds between analogous states.

I. INTRODUCTION

ODD-A nuclei which have between 29 and 39 odd neutrons or protons are in a region in which many $M1$ transitions might be expected to show l-forbidden characteristics. In this region, the odd nucleons predominantly occupy the $p_{3/2}$ and $f_{5/2}$ orbitals. The configurations of the low-lying states may be complicated and often ambiguous. However, many $M1$ transitions between levels that are dominantly composed of nucleons in these orbitals would be expected. Such $M1$ transitions would be l forbidden and would proceed at a retarded rate through admixtures of other configurations in these levels. Retarded $M1$ transitions have been reported in this region (e.g., in Cu^{63}, Ge^{73}, As^{75}, and Rb^{85}), with retardation factors ranging from about 3 to 400 with respect to Moskowski's single-particle estimates.[1]

The possibility that the 66-keV transition from the first excited state to the ground state in As^{73} could be of this retarded type prompted the investigation reported here. The decay of Se^{73} has been reported by several groups.[2] The combined work of these investigators shows that the population and decay of the As^{73} levels correspond to a simple decay scheme Only two excited states are populated, with two transitions in cascade and no observed cross-over transition. These transitions have energies of 0.359 and 0.066 MeV and are of $M2$ and $M1$ character, respectively.[3,4] The 0.425-MeV second excited state receives about 99% of the population from the 7.1-h ground state of Se^{73} by means of 70% positron emission and 30% electron capture.[3,4] Hayward and Hoppes,[4] who have measured the lifetime of the 0.425-MeV second excited state by conventional delayed-coincidence methods, report a half-life of 6.0 ± 0.2 μsec. These workers also attempted to measure the lifetime of the 0.066-MeV level by the same method and reported an upper limit of $\leqslant 5$ nsec for the half-life of this level. The positron spectrum and internal-conversion spectrum of the transitions were investigated by Scott[3] and by Hayward and Hoppes[4] with comparable results. A weak (<1%) positron branch with an end-point energy 0.36 MeV higher than the main positron group was evidence that the 0.359-MeV transition precedes the 0.066-MeV one.

Scintillation γ-ray spectroscopy was used throughout the work reported here. Delayed-coincidence techniques were used to determine the lifetime of the first excited state and to remeasure that of the second excited state by methods somewhat more refined than those previously used to investigate these levels.

II. SOURCE PREPARATION

Sources of 7.1-h Se^{73} were produced by the reaction $Ge^{70}(\alpha,n)Se^{73}$ induced by $\approx$20-MeV alpha particles from the Argonne National Laboratory 60-in. cyclotron bombarding targets of naturally occurring elemental Ge having a purity of >99.999%. At this bombarding

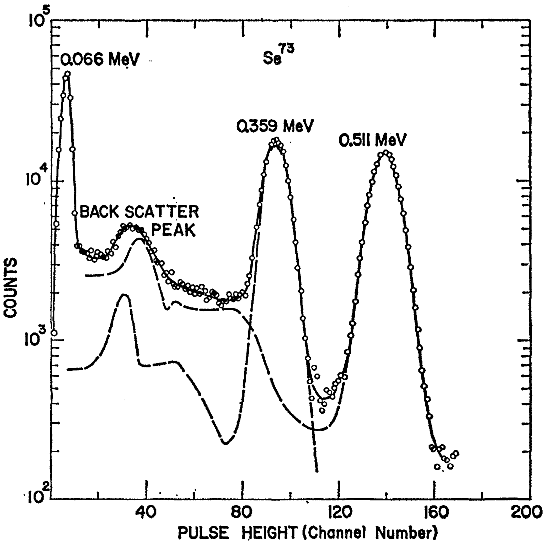

FIG. 1. Singles γ-ray spectrum of the decay of Se^{73} as viewed by a 3-in.×3-in. NaI(Tl) detector. Individual γ-ray contributions are represented by dashed lines.

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[1] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, in *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 71.

[2] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council Office, Washington 25, D. C., 1960).

[3] F. R. Scott, Phys. Rev. **84**, 659 (1951).

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

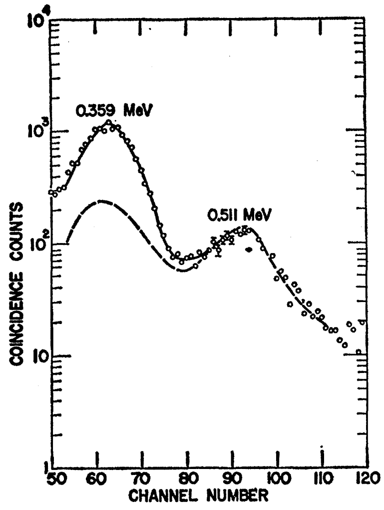

FIG. 2. Portion of the gamma-ray spectrum of Se^{73} in coincidence with the 0.066-MeV gamma ray (solid line). The dashed curve is the singles spectrum normalized to the 0.511-MeV peak.

energy, other contaminating activities were formed only in negligible proportions. Hayward and Hoppes,[4] using ≈28-MeV alpha particles, reported the presence of Se^{72} from $Ge^{70}(\alpha,2n)Se^{72}$.

A few milligrams of Se and As carriers were added to the target material which had been dissolved in aqua regia. The solution was evaporated to near dryness, taken up in 1*N* HCl, and hydroxylamine hydrochloride and 1*N* KI solution were added. After centrifuging, the precipitate was dissolved in aqua regia and the precipitation repeated. The final precipitate (elemental Se) was dissolved in hot concentrated HNO_3 and diluted to the desired specific activity by the addition of H_2O. The needed amount of sample was dried on a glass microscope-slide cover plate 0.2 mm thick.

III. SCINTILLATION STUDIES

A typical singles pulse-height spectrum recorded with a 3-in.×3-in. NaI(Tl) crystal is shown in Fig. 1. The spectrum reveals the presence of only two γ rays at 66 and 359 keV, in addition to the 511-keV annihilation-radiation peak, in agreement with the results of Hayward and Hoppes. There was no evidence for any other γ rays with energies below 2 MeV. The relative intensities of the radiations, as obtained from these scintillation studies, are in good agreement with previously reported values.[4] Figure 2 shows a portion of the spectrum coincident with the 66-keV gamma ray, displaying the relative lack of coincidences between this transition and the annihilation radiation, again in accord with the findings of Hayward *et al.* The coincidence circuitry was of the conventional fast-slow type with a fast resolving time of about 5×10^{-8} sec and slow triple-coincidence circuits of $\tau\approx2\times10^{-7}$ sec and $\tau\approx2\times10^{-6}$ sec. The striking lack of much annihilation radiation in coincidence with the 66-keV gamma ray reflects the fact that the ground-state decay of Se^{73} goes almost exclusively to the 425-keV level which has a long lifetime compared with the fast resolving time used.

IV. LIFETIME MEASUREMENTS

Delayed-coincidences between the 0.359 and 0.066-MeV gamma rays were studied by use of NaI(Tl) detectors and time-to-pulse-height conversion. The γ rays were selected by use of narrow differential pulse-height windows. The results are shown in Fig. 3. The "prompt" response curve was obtained by setting the windows on the Compton-electron spectrum of the annihilation quanta from a Cu^{64} source. The pulse-height regions were identical to those used in the As^{73} cascade. From the slope of the delayed-coincidence spectrum, the 0.066-MeV transition was found to be delayed relative to the 0.359-MeV transition with a half-life of $(6.1\pm0.4)\times10^{-9}$ sec, which disagrees with the upper limit of $\leqslant5\times10^{-9}$ sec reported by Hayward and Hoppes.[4] The time order of the transitions, previously supported only by the observation of a β^+ branch[3,4] with an intensity of about 1%, is confirmed by this result.

The lifetime of the 0.425-MeV state was remeasured with a 200-channel Radiation Instrument Development Laboratory pulse-height analyzer used as a direct time-delay analyzer of the "start-stop" type. The internal 2-Mc/sec oscillator in the analyzer provides an accurately controlled address advance of $\frac{1}{2}$ μsec per channel. In this case, the pulse-height output of a single-channel analyzer, which is set on the "early" 0.511-MeV annihilation radiation, is adjusted to be stored normally in channels 190 to 200 of the multichannel analyzer. The output pulse of a second single-channel analyzer, marking the appearance of the "late" 0.066-MeV gamma ray in a second detector, is delayed by about 15 μsec and is used to stop the address-advance oscillator of the multichannel analyzer so that a pulse is artificially stored in a channel corresponding to the time interval between the "early" and "late" pulses. If the

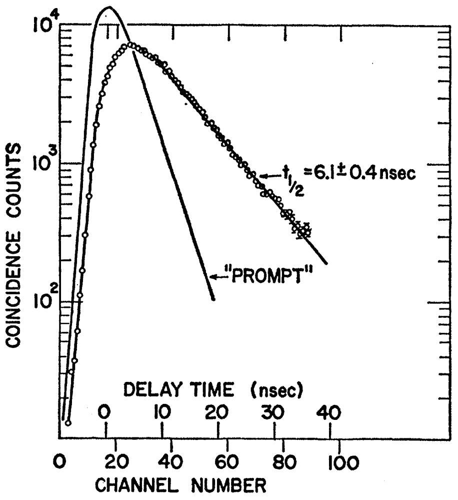

FIG. 3. Time spectrum of coincidences between the 0.066- and 0.359-MeV gamma rays. The delayed slope corresponds to the 0.066-MeV gamma ray being delayed. The prompt spectrum was obtained with a Cu^{64} source.

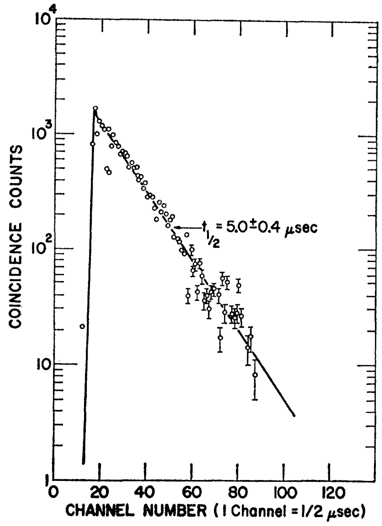

FIG. 4. Time spectrum of coincidences between the 0.066-MeV gamma ray and the 0.511-MeV annihilation radiation. The contribution from accidental coincidences has been subtracted.

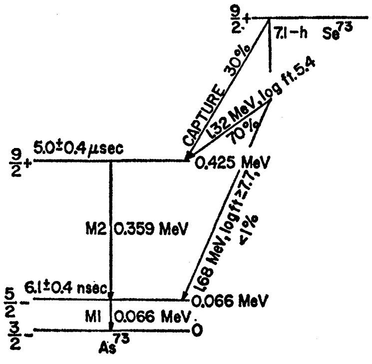

FIG. 5. Decay scheme of the Se^{73} ground state, summarizing both previous work and the half-life measurements reported in this paper.

"late" pulse does not arrive within about 100 μsec after the arrival of the "early" pulse, this pulse is stored in its normal pulse-height channels (190–200). This method of determining a relatively long lifetime in the microsecond region has been used previously.[5] The time spectrum of the 0.511-MeV annihilation radiation and the 0.066-MeV gamma ray is shown in Fig. 4. From the slope of the delay curve, the half-life of the 0.425-MeV level is 5.0±0.4 μsec, which differs somewhat from the value 6.0±0.2 μsec reported by Hayward and Hoppes who used conventional techniques. The absence of any significant "prompt" portion of this spectrum reflects the fact that positron emission goes almost exclusively to the 0.425-MeV level. Any direct population of the 0.066-MeV state ($t_{1/2}=6.1$ nsec) by positron emission would appear as a "prompt" component in Fig. 4. The same method was employed to determine the lifetime of the 0.425-MeV level by use of the 0.511-MeV annihilation radiation and the 0.359-MeV gamma ray. The results are in excellent agreement with those of Fig. 4.

V. DISCUSSION

Although the spins of the ground state and excited state of As^{73} have not been measured directly, the systematics of levels in this region of atomic weight, together with other β decay and internal-conversion work, strongly support the spin and parity assignments given in the decay scheme in Fig. 5. The ground state and first excited state have spin and parity assignments of $\frac{3}{2}-$ and $\frac{5}{2}-$, respectively.

As previously mentioned, As^{73} is in a region in which the $p_{3/2}$ and $f_{5/2}$ orbitals are expected to dominate the configurations of the low-lying levels. As^{73} has 33 protons and 40 neutrons. If only the 5 protons in excess of the closed $f_{7/2}$ shell are considered, the most plausible, but by no means certain or exhaustive, possibilities for the $\frac{3}{2}-$ ground state are the configurations $[(f_{5/2}{}^4)_0 p_{3/2}]_{3/2-}$, $[(f_{5/2}{}^2)_0(p_{3/2}{}^3)_{3/2}]_{3/2-}$, and $[(p_{3/2}{}^2)_0(f_{5/2}{}^3)_{3/2}]_{3/2-}$, either singly or in combination. On the same basis, the configurations making up or dominantly contributing to the $\frac{5}{2}-$ first excited state could be expected to be $[(p_{3/2}{}^4)_0 f_{5/2}]_{5/2-}$ and $[(p_{3/2}{}^2)_0(f_{5/2}{}^3)_{5/2}]_{5/2-}$. With one exception, all $M1$ transitions between these configurations are l forbidden. The exception, the $M1$ transition from $[(p_{3/2}{}^2)_0(f_{5/2}{}^3)_{5/2}]_{5/2-}$ to $[(p_{3/2}{}^2)_0(f_{5/2}{}^3)_{3/2}]_{3/2-}$, is also forbidden by orthogonality considerations. Thus, it is expected that the 0.066-MeV $M1$ transition between the first excited state and the ground state would be retarded. On the basis of the half-life obtained here for the 0.066-MeV level (with internal-conversion correction included), this transition is retarded by a factor of 97 over the single-particle estimate of Moskowski[1]—in agreement with what would be expected for an l-forbidden $M1$ transition.

The half-life of the first excited state in Ni^{61} at 0.068 MeV has been previously measured by Holland *et al.*[6] to be 5.2 nsec. Available evidence[7] indicates that this transition is $M1$ in character, going from a $\frac{5}{2}-$ first excited state to the $\frac{3}{2}-$ ground state in analogy to the 0.066-MeV transition in As^{73}. In Ni^{61}, there are 33 neutrons which would be expected to form states analogous to those of the 33 protons in As^{73}. It is significant, therefore, that the retardation (corrected for internal conversion) in the Ni^{61} case is 91—almost identical to that of the 0.066-MeV transition in As^{73}.

The absence of the crossover transition and the $M2$ character of the 359-keV transition tend to support the $\frac{9}{2}+$ assignment for the 0.425-MeV level. In addition, the 5-μsec half-life of this level is in good agreement with its $M2$ assignment. This transition is retarded by a factor of 63 compared with single-particle speed,[1] which is normal for an $M2$ transition. This level can be formed in a variety of ways, each of which reduces in effect to a single-particle $g_{9/2}$ proton with all other protons coupling in pairs to zero spin.

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[5] H. H. Bolotin, A. C. Li, and A. Schwarzschild, Phys. Rev. **124**, 213 (1961). Detailed specifications for the use of this method are given in this reference. However, footnote 28 of this reference should read "· · · imposed on pin 7 · · ·" instead of "· · · imposed on pin 8 · · ·."

[6] R. E. Holland, F. J. Lynch, and E. N. Shipley, Bull. Am. Phys. Soc. **5**, 424 (1960).

[7] R. H. Nussbaum, A. H. Wapstra, W. A. Bruil, M. J. Sterk, G. J. Nijgh, and N. Grobben, Phys. Rev. **101**, 905 (1956).

The allowed β decay[3,4] going almost exclusively to the 0.425-MeV state indicates that the ground state of Se^{73} would be a single-neutron $g_{9/2}$ configuration, as expected from the shell model. This transition from $g_{9/2}$ neutron to $g_{9/2}$ proton is in keeping with the above data.

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Capture-Gamma Determination of Chromium-54 Structure

DONALD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California

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Gamma emission following thermal-neutron capture in separated chromium-53 has been studied at the Livermore 2-MW pool-type reactor using a fast coincidence scintillation spectrometer. A quartz-crystal thermal-neutron filter is described which produces a flux of 10^6 neutrons/cm^2 sec at the target with a cadmium ratio better than 10^4. Capture gammas are observed at 9.72, 8.88, 7.10, 6.88, 6.64, 6.28, 6.00, 4.86, 3.72, 2.60, 2.24, 2.00, 1.77, and 0.84 MeV. Cascade transitions were studied using coincidence, sum coincidence, and angular correlation methods. A "double-window" coincidence technique used in these measurements is described. This technique systematically subtracts coincident background and is particularly applicable to angular correlation measurements. Energy levels are established at 0.84, 2.61, 2.84, 3.08, 3.44, 3.72, and 4.86. MeV. The spins of the first four excited states are 2, 2, 0, and 2, respectively, as determined by angular correlation and cascade systematics. The results are discussed in terms of recent nuclear models.

I. INTRODUCTION

THE nucleus chromium-54 has two $p_{3/2}$ neutrons and four $f_{7/2}$ protons outside the closed shells. It is in the medium mass region and is particularly amenable to shell-model calculations involving coupling between nucleon groups in different shells.

Energy levels at 4.04, 1.83, and 0.84 MeV have been determined by Schardt and Dropesky[1] from β decay of vanadium-54. The 0.84 level has also been populated by manganese-54 K-capture[2] ($E=0.835\pm0.001$ MeV), by Coulomb excitation[3] ($\tau=1.7\times10^{-11}$ sec), and by inelastic proton scattering.[4] Deuteron stripping measurements were made by Elwyn and Shull[5] using separated Cr^{53} (spin $\frac{3}{2}^-$). They found Cr^{54} levels at 0.86, 1.31, 2.67, 3.19, and 3.79 MeV. El Bedewi and Tadros[6] used deuteron stripping on natural chromium and determined the isotopic contribution by consistency of the calculated Q values at different proton recoil angles. They found Cr^{54} levels at 0.81, 1.23, 2.60, and 3.03 MeV. In both experiments, all proton recoil distributions were characterized by angular momentum $l=1$, restricting the level spins to 0^+, 1^+, 2^+, and 3^+.

Natural chromium capture gammas above 3 MeV have been measured by Kinsey and Bartholomew[7] (hereafter referred to as KB) using a pair spectrometer. Groshev *et al.*[8] (hereafter referred to as GDLP) used a Compton recoil spectrometer to observe capture gammas above 0.5 MeV. Both instruments were especially suited to the high-energy region. The low-energy spectrum was investigated by Reier and Shamos[9] and by Braid[10] using a single-crystal scintillation spectrometer and a two-crystal Compton spectrometer. Although Cr^{53} is 9.55% abundant in the natural element, the neutron-capture gamma yield[2] is 55.9% owing to the 17.5-b Cr^{53} cross section. Ambiguities, nevertheless, arise in the assignment of the correct gammas from among the four capturing isotopes.

Trumpy[11] has made an angular correlation measurement on the 8.88–0.84-MeV cascade in natural chromium, finding the capture state to be purely 1^-. A measurement of the circular polarization of the 8.88- and 9.72-MeV gammas arising from capture of polarized

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[*] Work done under the auspices of the U. S. Atomic Energy Commission.

[1] A. W. Schardt and B. J. Dropesky, Bull. Am. Phys. Soc. **1**, 162 (1956).

[2] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1961).

[3] D. S. Andreyev, A. P. Grinberg, G. M. Gusinskii, K. I. Erokhina, and I. Kh. Lemberg, Izv. Akad. Nauk S.S.S.R., Ser. Fiz. **24**, 1474 (1960) [translation: Bull. Acad. Sci. U.S.S.R. Phys. Ser. **24**, 1466 (1961)].

[4] W. C. Porter, D. M. Van Patter, M. A. Rothman, and C. E. Mandeville, Phys. Rev. **112**, 468 (1958).

[5] A. J. Elwyn and F. B. Shull, Phys. Rev. **111**, 925 (1958).

[6] F. A. El Bedewi and S. Tadros, Nucl. Phys. **19**, 604 (1960).

[7] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[8] L. V. Groshev, A. M. Demidov, V. N. Lutsenke, and V. I. Pelekhov, *Atlas of γ-ray Spectra from Radioactive Capture of Thermal Neutrons*, translated by J. B. Sykes (Pergamon Press, Inc., New York, 1959).

[9] M. Reier and M. H. Shamos, Phys. Rev. **100**, 1302 (1955).

[10] T. H. Braid, Phys. Rev. **102**, 1109 (1956).

[11] G. Trumpy, JENER Publ. No. **13** (1957); Nucl. Phys. **2**, 664 (1956).