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Electric Monopole Transitions in Ge^{70} and Zr^{90}†

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The electric monopole crossover transition from the 1.215 Mev 0+ second excited state to the ground state of Ge^{70} has been observed with an intermediate-image beta-ray spectrometer arranged for electron-electron coincidence measurements. Internal conversion electrons in delayed coincidence with Ga^{70} beta rays correspond to a 1.215-Mev transition intensity of 0.0025% per disintegration. Total beta-ray branching to the 1.215-Mev state is 0.18%, mostly followed by a (0.173 ± 0.002)–(1.042 ± 0.005) Mev gamma-ray cascade through the first excited state. Beta-ray branching to the 1.042-Mev level in Ge^{70} is 0.30%. Beta-conversion-electron delayed coincidence measurements taken at the peak of the 0.173-Mev K-line give a half-life value of $(3.0\pm0.5)\times10^{-9}$ sec for the 1.215-Mev state. It follows that the partial half-life for K-conversion of the 0–0 transition is $(2.4\pm1.2)\times10^{-7}$ sec which compares with 1.6×10^{-7} sec expected if the matrix element were the same as for the 0–0 transition in Ge^{72}. Using similar techniques on Y^{90} the half-life of the 1.75 Mev 0–0 transition in Zr^{90} has been found to be $(6\pm1.5)\times10^{-8}$ sec.

INTRODUCTION

THE matrix elements of electric monopole transitions[1] are useful in the study of nuclear structure. Although such transitions can take place between any two states of the same spin and parity it is only the 0+ -0+ transitions which have been observed thus far. In O^{16}, Ca^{40}, Ge^{72}, and Zr^{90} a 0+ first excited state occurs while in the heavy nuclei Po^{214},[2] U^{234},[2] and Pu^{238} [3] 0–0 transitions have been established even though 3 to 5 energy levels lie between the 0+ level and the ground state. There is also evidence for a 0–0 transition from a fourth excited state in Cd^{114} as observed by Motz[4] in the $Cd^{113}(n,\gamma)Cd^{114}$ reaction.

Only a few examples of 0+ second excited states in even-even nuclei have been found, namely in C^{12}, Ge^{70}, and Pd^{106}, and in none of these has the monopole de-excitation of the 0+ state been established previously. In C^{12} the monopole strength parameter is estimated from the cross section for electron scattering.[5]

The decay scheme of 21.1-min Ga^{70} has been studied by Bunker, Mize, and Starner[6] who were the first to show that weak gamma radiation is associated with this activity. Their scheme, established by means of scintillation techniques, consists of a 0.3% beta-ray branch of 0.61-Mev end-point energy to a 1.04-Mev level in Ge^{70} and a 0.5% beta-ray branch of 0.44 Mev to a 1.21-Mev level, the latter de-exciting by a 0.174–1.036 Mev gamma-ray cascade. 99.2% of the disintegrations go to the ground state via a 1.65-Mev beta ray. From angular correlation measurements they found that the 0.174–1.036 Mev cascade must correspond to a 0–2–0 sequence and hence the 1.21-Mev state is probably 0+. Beta-ray branches in coincidence with gamma rays fixed the order of gamma-ray emission which is consistent with the 1.02-Mev 2+ first excited state of Ge^{70} observed both in the decay of As^{70} and in Coulomb excitation.[7] Their search for the 1.21-Mev crossover transition showed that a gamma ray of this energy is <0.5% as strong as the 1.04-Mev gamma ray and that the conversion line of a monopole transition is <4% as strong as the 0.174-Mev gamma ray. From coincidence measurements they found that the half-life of the 1.21-Mev state is $<4\times10^{-9}$ sec.

Using scintillation techniques, Kendall[8] has measured the half-life of the 1.21-Mev state as $(2.8\pm0.6)\times10^{-9}$ sec, a value 100 times less than expected on the basis of the Weisskopf single-particle model. Even with so short a half-life one should still expect the monopole crossover transition to compete with the 0.174-Mev gamma-ray to the extent of a few percent if the monopole matrix element were comparable to that of the 0–0 transition in Ge^{72}.

In the decay of 64-hour Y^{90} Johnson, Johnson, and Langer[9] showed that a weak beta-ray branch takes place to a 1.75-Mev level in Zr^{90}. They assigned this state as 0+ by observing in a beta-ray spectrometer an internal conversion electron line having an intensity of 0.005% per beta ray and from the absence of corresponding 1.75-Mev gamma radiation. The existence of the transition was confirmed by Yuasa, Laberrique-Frolow, and Feuvrais[10] who measured the branching as 1.6×10^{-4} conversion electron per beta ray and by Greenberg and Deutsch[11] who showed that nuclear pairs

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† Under contract with the U. S. Atomic Energy Commission.

[1] A recent discussion with references is given by E. L. Church and J. Weneser, Phys. Rev. **103**, 1035 (1956).

[2] B. S. Dzhelepov and L. K. Peker, "Decay Schemes of Radioactive Isotopes," Academy of Sciences U.S.S.R. (1957). (Translated and issued as report AECL 457 by the Atomic Energy of Canada, Limited, 1957.)

[3] I. Perlman, *Proceedings of the International Conference on Nuclear Structure, Rehovoth, Israel, September, 1957* [North Holland Publishing Company, Amsterdam (to be published)].

[4] H. T. Motz, Phys. Rev. **104**, 1353 (1956).

[5] L. I. Schiff, Phys. Rev. **98**, 1281 (1955); see Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **107**, 508 (1957) for a discussion of this state.

[6] Bunker, Mize, and Starner, Phys. Rev. **105**, 227 (1957).

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

[8] H. W. Kendall, Phys. Rev. **109**, 861 (1958).

[9] Johnson, Johnson, and Langer, Phys. Rev. **98**, 1517 (1955).

[10] Yuasa, Laberrique-Frolow, and Feuvrais, Compt. rend. **242**, 2129 (1956); J. phys. radium **17**, 558 (1956).

[11] J. S. Greenberg and M. Deutsch, Phys. Rev. **102**, 415 (1956).

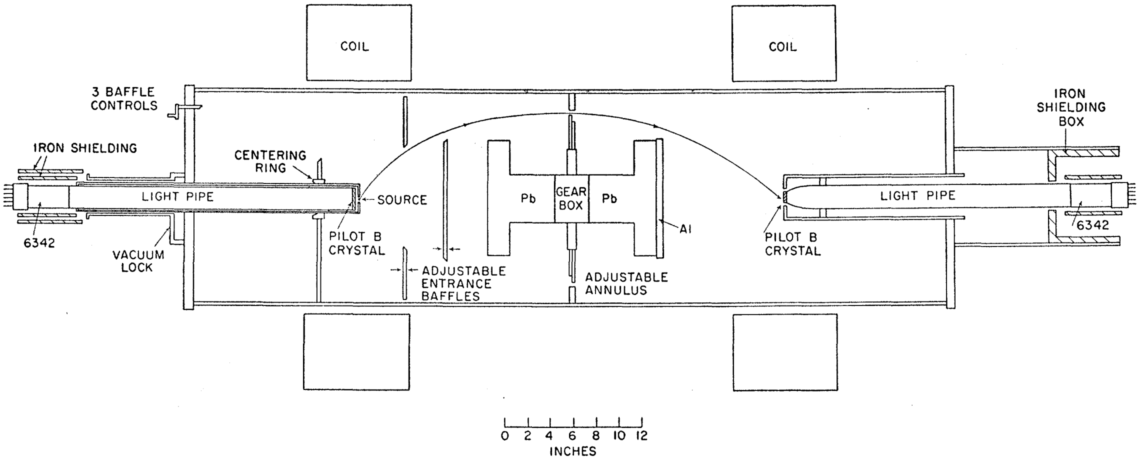

FIG. 1. Intermediate-image beta-ray spectrometer arranged for beta-conversion-electron coincidence measurements.

are produced in this transition in the amount of 3.6×10^{-5} per beta ray. (These branches are summarized in Fig. 4.)

Two direct measurements of the half-life of the 1.75-Mev level in Zr^{90} have been made. Deutsch,[12] using crystal detectors and observing delayed coincidences between beta rays to the 1.75-Mev level and the annihilation radiation resulting from the nuclear pairs, obtained a half-life of 6×10^{-9} sec. A much longer half-life of 5×10^{-8} sec was reported by Kloepper, Day, and Lind.[13] They excited the state with a pulsed neutron source and measured the time distribution of delayed annihilation radiation. The latter measurement is confirmed by the work described below.

EXPERIMENTAL METHODS AND RESULTS ON THE Zr^{90} MONOPOLE TRANSITION

At the start of these investigations the intent was to search for the electric monopole crossover transition in Ge^{70} after using Y^{90} activity, which has similarities in respect to energies and very weak branching, as a means of testing the sensitivity of the beta-conversion-electron coincidence spectrometer shown in Fig. 1. The instrument[14] employs intermediate-image focusing and has the high transmission desirable for coincidence measurements (for example, 6.1% of 4π transmission at a resolution of 2.4%). A source tube was constructed which allows a 2-inch diameter $\frac{1}{4}$-inch thick scintillation crystal to be placed immediately behind the source, subtending a solid angle of $\sim$35% of 4π. A 2-inch diameter 28-inch long light pipe passes out through a vacuum seal and is connected to a triply magnetically shielded RCA 6342 photomultiplier tube. (Standard mu-metal shields are not indicated in the figure.) The entire source-tube assembly can be inserted to the correct position through a vacuum lock. At the spectrometer detector end there is a similar crystal-light-pipe and phototube arrangement with the crystal in the vacuum and covered with 0.00025-inch thick Al foil. Because the diameter of the final image is <2 cm, a 1-inch diameter $\frac{1}{4}$-inch thick crystal detector can be used and advantage can be taken of the somewhat better light collection efficiency achieved by curving the 2-inch diameter light pipe near the crystal end. With 1-Mev electrons focused on a Pilot-B scintillation crystal the half-width of the line in the pulse-height spectrum is $\sim$15%.

Plug-in cathode-follower units (not shown in Fig. 1) are attached to the 6342 phototubes and RG-114/U cables carry the pulses to the coincidence circuits. Each of the 6342 tubes is connected to two 6J4 cathode followers, one for the fast coincidence portion of the circuit and the other for pulse-height selection and slow coincidences. Both the Y^{90} and Ga^{70} problems are similar in that one wishes to detect coincidences between internal conversion electrons focused by the spectrometer and beta rays of end-point energy $\sim$0.5 Mev superimposed on an intense spectrum of beta rays having an end-point energy of $\sim$2 Mev. This requires enough amplification on the beta-ray side so that even very small pulses operate the fast-coincidence circuit, and amplitude limiting so that very large pulses do not overload the amplifier. In the beta-ray side of the circuit the negative pulses from the 6342 anode pass via the 6J4 cathode follower and cable to two Hewlitt-Packard type 460 A amplifiers connected in series. At the end of the first amplifier a 404 A limiter clips the negative pulses and feeds positive pulses of fixed amplitude to the second amplifier. Because of the high counting rates expected in the beta-ray side (up to 10^5/sec), the 6342 anode resistor is made 2000 ohms and the 404 A grid resistor is made 6000 ohms in order to minimize the average pulse current in the respective portions of the circuit.

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[12] M. Deutsch, Nuclear Phys. 3, 83 (1957).

[13] Kloepper, Day, and Lind, Bull. Am. Phys. Soc. Ser. II, 2, 60 (1957).

[14] D. E. Alburger, Rev. Sci. Instr. 27, 991 (1956).

The requirements on the spectrometer detector side are relatively simple since the pulses resulting from focused electrons are of nearly uniform amplitude and the counting rates are usually less than 10^3/sec. In this case positive pulses are taken from the last dynode and fed through two unmodified Hewlitt-Packard 460 A amplifiers to the coincidence circuit. The latter is a standard 6BN6 coincidence circuit using RG-114/U shorted stubs for adjustment of the resolving time. The remainder of the circuitry is of customary design. Pulses from the 6342 tube anodes are fed through separate 6J4 cathode followers to two BEVA nonoverload amplifiers and thence to a gray-wedge unit which serves as a combined pulse-height selector and slow triple coincidence circuit. The fast coincidence 6BN6 output goes to a third nonoverload amplifier and then to the gray wedge. A lower limit coincidence condition is imposed on the fast pulse spectrum so as to reject the singles pulses fed capacitively through the 6BN6 tube. Generally the level of this discriminator is set to accept only those pulses greater than 3–5 times the amplitude of the feed-through pulses.

Tests of the coincidence circuit were made by focusing the 1.06-Mev K-shell internal conversion line[15] of Bi^{207} in the spectrometer and detecting the conversion and Compton electrons of the 0.57-Mev cascade transition in the crystal behind the source. When Pilot-B scintillators were used, with 1800 volts on both photomultipliers, it was found that the coincidence efficiency was close to 100% for all electrons in the beta-ray detector above 100 kev when the resolving time was greater than 3×10^{-9} sec.

Sources of Y^{90}, kindly provided by M. Deutsch, were placed in the spectrometer in order to observe the 1.75-Mev internal conversion electron line in coincidence with low-energy beta rays. When a coincidence resolving time of 5×10^{-8} sec was used, the existence of a coincidence peak was established. At the time the only measurement of the half-life of the 1.75-Mev state known to the author was the 6×10^{-9}-sec value determined by Deutsch,[12] and thus it was expected that most of the coincidences would still be detected when the resolving time was reduced to 5×10^{-9} sec. A factor of 10 increase in source strength should then give the same ratio of real-to-random counts as before. However, when these changes were made, a coincidence peak was not readily apparent above the background statistics. Just as it was becoming clear that the half-life must be $\gg 6\times10^{-9}$ sec the results of Kloepper *et al.*[13] appeared and it was felt that another independent measurement of the half-life would be desirable.

For the Y^{90} measurements the resolving time was changed back to 5×10^{-8} sec to enable the use of weaker sources. The pulse-height selector on the beta-ray side was adjusted to accept the lowest third of the spectrum. Figure 2 shows the internal conversion electron line of the 1.75-Mev transition in prompt coincidence with beta rays, where the spectrometer line-width setting is 2.4% and the data are the averages of runs totaling 90 min per point. The intensity of the line is approximately that expected from the decay scheme of Fig. 4 when all of the appropriate factors have been included, although no attempt has been made to determine an independent value of the internal conversion branch. Sources had a strength of $\sim 3\times10^{-4}$ β per sec and consisted of deposits a few mm in diameter on thin cellophane foils. It may be noted that the background coincidence rate under the peak is greater than the calculated random rate and rises with decreasing momentum setting. This effect was traced to the scattering of beta rays of initial energy above 1.75 Mev from the crystal and back into the spectrometer acceptance angle. The data of Fig. 2 were taken with a brass baffle located in the plane of the source and having a 3-mm diameter aperture to admit electrons directly from the source but to reject most of the scattered electrons. It was found that when the baffle was removed and the source was placed very close to the crystal, the scattering effect was so severe as to prevent the coincidence line from being seen above the statistics. The combination of the baffle and a $\frac{1}{4}$-inch separation of the source from the crystal, together with the fact that the mean acceptance angle of the spectrometer is 51° with respect to the axis, makes the baffle geometry effective in reducing the scattering, although the residual effect seen in Fig. 2 remains.

After the internal conversion line was located, the spectrometer was focused at the peak and runs were made on delayed coincidences. Figure 3 shows the delayed coincidence distribution, after subtraction of the calculated random rate, together with part of the prompt distribution obtained with Bi^{207}. Counting rates with the Y^{90} were very low, being 0.9 per min at the first delay setting above a calculated random rate of

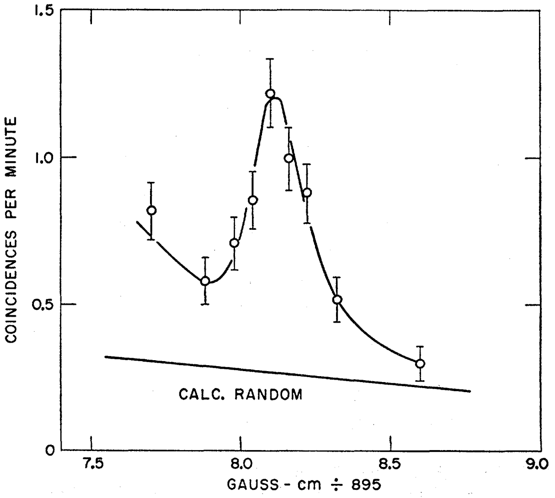

FIG. 2. Internal conversion electrons of the 1.75-Mev Zr^{90} transition in prompt coincidence with Y^{90} beta rays.

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[15] D. E. Alburger and A. W. Sunyar, Phys. Rev. 99, 695 (1955).

0.6 per min. The data in Fig. 3, which just by chance fit the exponential curve so well, are the averages of final runs totaling 6 hours per point. Inasmuch as the first delay point is well separated from the prompt curve none of the scattered electrons contribute to the delayed coincidence line. The half-life thus obtained is $(6\pm1.5)\times10^{-8}$ sec, a value in good agreement with the results of Kloepper *et al.* Figure 4 gives the complete decay scheme of Y^{90}.

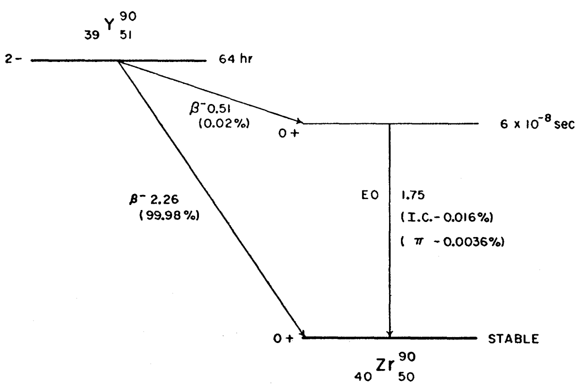

FIG. 4. Decay scheme of Y^{90}.

Ga^{70} BETA-CONVERSION-ELECTRON COINCIDENCE MEASUREMENTS

Experiments on Ga^{70} employing techniques similar to those described above were carried out using sources[16] made by irradiating Ga_2O_3 powder, enriched to 98.4% Ga^{69}, in the Brookhaven reactor. In the first sets of experiments the samples were prepared[17] by trapping a small amount of the Ga_2O_3 powder, estimated to be 15–20 mg/cm² in thickness, between two layers of 0.9-mg/cm² Mylar film supported on Scotch tape. Because of previous experience with the scattering of electrons in the Y^{90} problem, the diameter of the Ga_2O_3 powder spot was made 2 mm so that a small aperture could be used in the antiscattering baffle. Irradiation of identical source mountings without the Ga_2O_3 showed a negligible background from the Scotch tape and Mylar foil.

At the outset it was known that the half-life of the 1.215-Mev 0+ state of Ge^{70} was less than 4×10^{-9} sec and it was decided to look for the internal conversion line in prompt coincidence with beta rays at a resolving time of 5×10^{-9} sec. To test how well the coincidence circuits would operate at high counting rates three sources of Bi^{207} were prepared with an intensity ratio of 1:4:16. The strongest of these resulted in a total counting rate in the beta-ray detector of 60 000 per sec of which the lower half of the spectrum containing pulses due to the 0.570-Mev transition was accepted by the setting of the channel analyzer. The 1.06-Mev K− line was focused by the spectrometer. A comparison of the singles and coincidence rates showed no noticeable loss of coincidences at the highest rate and it was felt that no difficulties would be experienced as long as the total rate in the beta-ray detector was kept below 100 000/sec. Initial rates of this magnitude were achieved with 30-sec irradiations of the gallium samples in the reactor. The procedure was to measure the coincidence and two side-channel counting rates at various settings of the spectrometer magnet current. Values of the resolving time, which could be used together with the channel counting rates to calculate and subtract out the random rate, were obtained from (a) the length of the shorted stubs, (b) the width of the prompt coincidence distribution, and (c) the random counts measured with long delay (Bi^{207} source). All three determinations of τ were in agreement although the value of τ from the last of these methods was the one used for the calculations. The beta-ray channel setting was adjusted so that only those pulses in the lowest third of the spectrum were accepted, excluding tube noise. A residual true coincidence rate after decay of the 21-min activity amounting to ~1 count per min was attributed to 14-hr Ga^{72} and this also had to be subtracted out before correcting for 21-min decay. Because of the Ga^{72} background 12 samples were made up so that a lapse of 2 days would occur before the re-irradiation of any source. Each group of runs, taken at the 6.1% transmission and 2.4% resolution spectrometer setting, showed a continuum of scattering coincidences rising with decreasing momentum setting but there was always evidence of a bump at 1.20 Mev

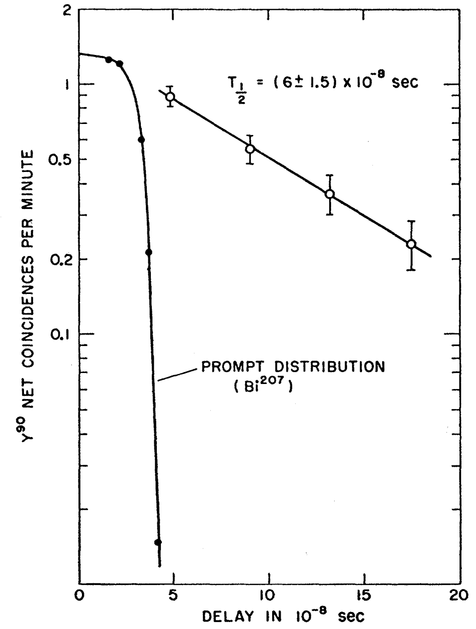

FIG. 3. Delayed coincidence distribution between Y^{90} beta rays and the K–1.75-Mev line together with a portion of the prompt coincidence distribution obtained with a Bi^{207} source.

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[16] The source material, originally prepared at Oak Ridge, was kindly placed at the author's disposal by M. Deutsch.

[17] The author is indebted to Dr. B. Pate for assistance in preparing the samples.

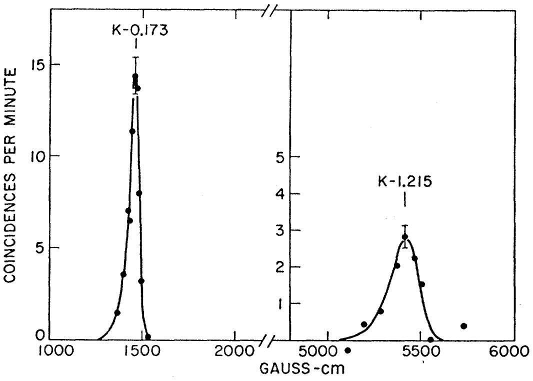

FIG. 5. Internal conversion electron spectrum in delayed coincidence with Ga^{70} beta rays, normalized to a rate of 100 000 total counts per sec in the beta-ray detector behind the source. The delay setting used was the same as for the first delay point in Fig. 6.

which was 2–3 times larger than the statistical errors of the points. Normalized to a counting rate of 100 000/sec in the beta-ray detector, the bump was ~5 counts per min while the underlying continuum of true coincidences was ~8 counts per min at that point and rose to 20 per min at the lowest momentum setting (1.1 Mev). The ratio of total real counts to calculated random counts at the beginning of a run was about 1 at the 1.2-Mev setting. In spite of the evidence from many such sets of runs it was not felt that the existence of the electric monopole transition had been established firmly.

When it was learned that Kendall had obtained a half-life value of 2.8×10^{-9} sec, calculations were made to see if one could make use of the lifetime to get away from the prompt coincidences resulting from both scattered electrons and from Ga^{72}. Upon folding an exponential corresponding to this half-life into the prompt coincidence distribution ($\tau=5\times10^{-9}$ sec) by numerical integration, it was found that 50% of the events would be detected at a delay setting which discriminated against prompt coincidences by a factor of 100. In spite of the poor statistics on each run, the evidence for the monopole conversion line then became much more clear than in the prompt coincidence work. The right-hand portion of Fig. 5 shows the average data of 20 runs over the spectrum, each one consisting of a series of 5-min counts on all of the points. The point below zero is due to statistics in subtracting out the calculated random rate. When one includes all of the appropriate factors such as the spectrometer transmission, the normalized source strength, an estimate that 80% of the 0.44-Mev beta rays are effective in producing coincidences, and the factor of 50% due to the time delay setting, the intensity of the line (assuming 100% internal conversion) corresponds to a transition intensity of 0.0025% per beta ray with an error of ~40%. The energy of the transition is 1.215±0.010 Mev, where an estimated source thickness correction of 0.010 Mev has been made. It may be noted that the peak counting rate of 2.8 counts per min is just about half the amplitude of the somewhat indistinct bump found in the prompt coincidence runs, as one would expect from the calculations mentioned above.

In order to measure the 0.173-Mev K-line in coincidence with beta rays, a new set of thinner samples was made as follows: Scotch tape was scraped down on the nonsticky side to about one-half the initial thickness (i.e., from 8 to 4 mg/cm^2) and then stuck to a brass mask having a hole 4 mm in diameter. Finely ground Ga_2O_3 powder (enriched material) was placed into the aperture. By rubbing the powder into the sticky surface and removing the excess, there remained a translucent layer of gallium oxide estimated to be 1 mg/cm^2 in thickness. A second piece of Scotch tape with a 5-mm diameter hole was stuck over the first so as to leave the powder deposit exposed but to eliminate other sticky surfaces enabling the samples to be placed easily into a source holder. A larger diameter than before was used for these sources, since it was known that measurements could be taken in delay and one need not be concerned about the effects of electron scattering with a larger baffle aperture. The Ga_2O_3 deposits were four times the area but contained only $\frac{1}{6}$ the amount of powder as the earlier ones. Three-minute irradiations of the samples were made in the reactor and they were placed in the instrument with the powder side facing the spectrometer.

Prior to each set of runs, the prompt coincidence distribution was checked by using a source of Na^{24} beta rays. This source consisted of Na_2CO_3 powder stuck between two pieces of Scotch tape, irradiated in the reactor, and then placed on a holder having a large aperture in the antiscattering baffle. By intentionally allowing a large number of electrons scattered from the crystal to enter the spectrometer acceptance angle, this source was very convenient for obtaining a prompt distribution and for checking the coincidence efficiency under very nearly the same conditions as for the 0.173-Mev K-line measurements. A prompt Na^{24} curve is included in Fig. 6. The line shown in the left-hand part of Fig. 5 is the delayed coincidence peak of a 0.173±0.002-Mev transition after subtraction of a random coincidence rate, amounting to 20–30% of the total counts, and correction for decay. It is the average of 4 runs. Upon applying all of the factors as in the case of the 1.215-Mev line, and including the theoretical K-conversion coefficient for a 0.173-Mev $E2$ transition, the 0.173-Mev transition intensity was found to be 0.21% per beta ray. Several runs made on the 0.173-Mev K-line in *prompt* coincidence with beta rays at a resolving time of 7×10^{-9} sec displayed a peak of ~30 counts per min above a background of 100 scattering coincidences per min. The net peak intensity was, as expected, about twice as intense as the delayed peak shown in Fig. 5 although the background was so high that the intensity determination was less accurate than for the delayed coincidence conditions.

After the above runs were completed, the K-1.215-Mev internal conversion line in delayed coincidence with beta rays was checked by using the thin sources. Data were taken at three points, one at the peak of the line and background points above and below the line. From the average data of 16 runs of 5 min per point, the intensity of the monopole transition was found to be essentially the same as measured previously.

HALF-LIFE OF THE 1.215-Mev STATE IN Ge^{70}

The technique for measuring the half-life of the 1.215-Mev state in Ge^{70} was similar to that used in the case of Zr^{90}. It consisted of focusing the spectrometer at the peak of the 0.173-Mev K-line and observing the decrease in the net beta-conversion-electron coincidence counting rate with delay setting. Figure 6 shows the delayed coincidence distribution obtained by averaging 11 final runs, each run consisting of a series of 5 points of 5 minutes each. At the first delay setting, the real-to-random ratio was 3 when this point was taken at the beginning of a run and 5 when the point was taken at the end of a run. As in the Zr^{90} work, the delay was varied by changing the length of the RG-114/U cable between the beta-ray detector cathode follower and the corresponding Hewlett-Packard amplifier and using a propagation time of 4.0×10^{-9} sec per meter for length-to-time conversion. The curve fitting the points best gives a half-life value of $(3.0\pm0.5)\times10^{-9}$ sec in good agreement with the measurement by Kendall. In Fig. 6 the dashed portion of the delayed coincidence distribution was obtained by numerically folding the 3.0×10^{-9} sec half-life into the Na^{24} prompt curve. The vertical position of the Na^{24} curve has been normalized to the delayed curve.

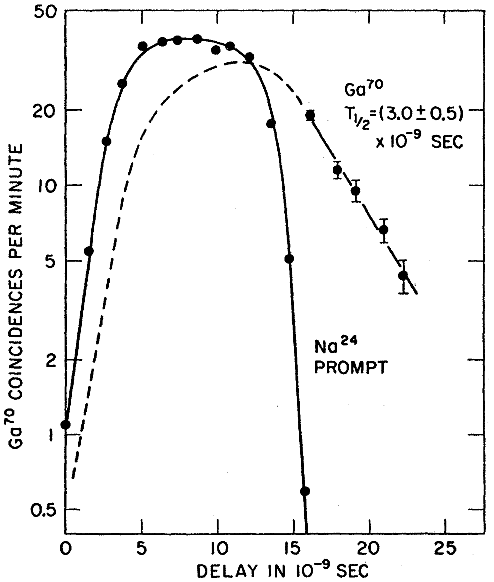

FIG. 6. Delayed coincidence distribution between Ga^{70} beta rays and the K–0.173-Mev line together with the prompt coincidence distribution obtained with a Na^{24} source.

Ga^{70} GAMMA-RAY AND BRANCHING RATIO MEASUREMENTS

The beta-ray branch of 0.21% to the 1.215-Mev state derived from the 0.173-Mev K-line intensity as described above is clearly inconsistent with the 0.5% branch obtained by Bunker *et al.*[6] Since this indicated that either the assumption of $E2$ for the 0.173-Mev transition was incorrect or that the gamma-ray or conversion line intensity measurements were in error, it was felt that a recheck of the branching should be carried out. This was done by determining the absolute intensity of the 1.042-Mev gamma ray using a 3×3 inch NaI crystal detector and the absolute beta-ray strength of the same source in the intermediate-image spectrometer. The gamma-ray strength was found by placing the source on the axis of the NaI crystal and recording the total number of counts under the full-energy-loss peak using an Atomics 20-channel pulse-height analyzer. A peak-to-total ratio[18] of 0.40 was used to derive the total counting rate and the tables[19] of calculated efficiencies of NaI crystals prepared by Wolicki, Jastrow, and Brooks were used to find the absolute intensity. After the gamma-ray measurement the source was placed in the spectrometer and the counting rate at one point near the maximum of the spectrum was taken. Corrections for decay were made.

Prior to these runs, sources were studied in the spectrometer in order to show that the entire beta-ray spectrum decayed with the 21-minute half-life of Ga^{70} and that it had the 1.65-Mev end point reported previously. No deviations from expectations were found over two half-lives of the Ga^{70} activity. The ratio of the counting rate at the point selected in the above experiments to the total spectrum was calculated by finding with a planimeter the areas under the total spectrum and under a spectrometer window curve at the setting mentioned above. The total beta-ray disintegration rate was then obtained by dividing the integrated spectrum by the solid angle of the instrument. These gamma- and beta-ray measurements were carried out on six different sources and their average corresponds to a 1.042-Mev gamma-ray intensity of 0.48% per beta ray.

The energy of this gamma ray was measured by comparing the position of the full-energy-loss peak in the pulse-height spectrum with that of the 1.0639-Mev gamma ray of Bi^{207}. A 2×2 inch NaI crystal mounted on a nonshifting DuMont 6292 photomultiplier tube was used. In varying the counting rate due to Bi^{207} by a factor of 10, the shift of the full-energy-loss peak for

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[18] P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, 1955), p. 139.

[19] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report NRL-4833, 1956 (unpublished).

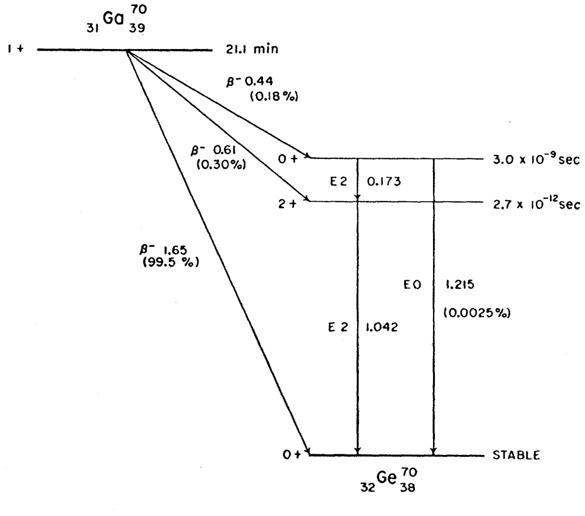

FIG. 7. Decay scheme of Ga^{70}.

this special tube was observed to be less than 1 part in 500 of the pulse amplitude. The Ga^{70} gamma-ray energy based on three runs interlaced with runs on Bi^{207} was thus determined as 1.042±0.005 Mev, the small error being possible because of the proximity of the line to that of the Bi^{207} standard.

Runs were then made on the complete gamma-ray spectrum in order to obtain the ratio of the 0.173- and 1.042-Mev gamma-ray intensities. Two sets of data on a number of sources were taken, first using an RIDL 100-channel pulse-height analyzer to record the complete spectrum at one time and then on the Atomics 20-channel pulse-height analyzer. In the latter case the full-energy-loss peaks of the two gamma rays were run successively after adjusting the amplifier gain so that the peaks occurred at the same pulse height. Areas under the full-energy-loss peaks corrected for decay were compared and the calculated crystal efficiencies and peak-to-total ratios appropriate to a 3×3 inch crystal were used to derive the ratio of gamma-ray intensities. Upon correcting for the 8% total internal conversion coefficient of the 0.173-Mev transition, the ratio of the 0.173-Mev transition intensity to that of 1.042 Mev was found to be 0.32. By combining this ratio with the absolute intensity of the 1.042-Mev gamma ray, a beta-ray branch of 0.15% to the 1.215-Mev level is derived.

DISCUSSION

All of the data on the decay of Ga^{70} are summarized in Fig. 7. When one considers the internal conversion results leading to the beta-ray branching ratio of 0.21% to the 1.215-Mev state together with the value 0.15% obtained from the absolute beta- and gamma-ray measurements, the intensity of the 0.173-Mev K-line may be taken as a check on the $E2$ character of this transition. On the other hand, if the $E2$ assignment is accepted as correct, then the 0.18% average of these two independent measurements may be taken to be the most probable branching ratio to the 1.215-Mev state. Subtracting this figure from the total intensity of the 1.042-Mev gamma ray gives a branching ratio of 0.30% to the 1.042-Mev state. The estimated errors in the intensities of both of the weak beta-ray branches are 30%. Logft values are 5.10 for the ground-state beta ray, 5.9±0.1 for the beta ray to the 1.042-Mev level, and 5.6±0.1 for the beta ray to the 1.215-Mev level. The first two of these are the same as obtained by Bunker *et al.* while the last compares with their logft value of 5.15. Energies of the beta-ray end points given in Fig. 7 were taken from the paper of Bunker *et al.*

As mentioned previously, the half-life value of 3.0×10^{-9} sec for the 1.215-Mev state agrees well with the results of Kendall and shows that the 0.173-Mev $E2$ transition is exceedingly fast, being 100 times the single-particle transition rate. Included in the figure is the half-life of 2.7×10^{-12} sec for the 1.042-Mev state as derived from Coulomb excitation by Temmer and Heydenburg.[7] This transition is 10 times as fast as the theoretical single-particle rate.

The existence of the electric monopole crossover transition in Ge^{70} is now believed to have been established by the observation of an internal conversion electron line in delayed coincidence with Ga^{70} beta rays. The exact agreement of the transition energy with the sum of the 0.173- and 1.042-Mev gamma-ray energies is fortuitous. One may say that the 0+ nature of the second excited state has been proved beyond any doubt on the basis of intensity considerations. In view of the upper limit of 0.5% on the intensity of a 1.215-Mev gamma ray relative to the 1.042-Mev gamma ray found by Bunker *et al.*, the intensity of the internal conversion line of, for example, a 1.215-Mev $E2$ transition would be weaker than the line observed by at least a factor of 4000. Even for an $M5$ transition, the line observed is 400 times too intense to be consistent with the gamma-ray data. Thus the only assignment possible is $E0$.

One may derive the partial half-life for internal conversion in the K shell of the 1.215-Mev $E0$ transition in a straightforward manner. It follows from the 3×10^{-9}-sec total half-life and the intensity of the 1.215-Mev transition, which is 1.4% as strong as the 0.173-Mev $E2$ transition, that the $E0$ partial half-life is 2.2×10^{-7} sec. Since the K and L lines are unresolved, a correction must be made for the L-line contribution assuming a $K/(L+M)$ ratio[1] of ~10. The end result is a value $T_{\frac{1}{2}K}=(2.4\pm1.2)\times10^{-7}$ sec for the 1.215-Mev electric monopole transition, where the error is mostly due to the errors of 30% in the beta-ray branch and 40% in the number of $E0$ internal conversion electrons per beta ray. No correction is necessary for nuclear pair emission inasmuch as the magnitude of the effect for Ge^{70} is expected to be weaker than internal conversion by a factor of 100.

The partial half-life for nuclear pair emission, thus estimated as $\sim 2.4\times 10^{-5}$ sec, would correspond to a fractional decay of the 1.215-Mev state via nuclear pair emission of $\sim 1\times 10^{-4}$. Bunker *et al.* obtained an upper limit of 2×10^{-4} which is not much above the yield expected. With improved techniques it might be possible to establish this mode of de-excitation of the 0+ state.

In the notation of Church and Weneser,[1] the electric monopole strength parameter ρ appears in the equation $W=\Omega\rho^2$ relating the absolute transition probability W to the reduced monopole conversion probability Ω. The value of ρ for Ge^{70} is 0.09 with an error of 25% from the present measurements. For the monopole transition in Ge^{72}, $\rho=0.11$ based on the observed half-life of 3×10^{-7} sec for the 0.69-Mev transition. Thus it would appear from these results that the Ge^{70} and Ge^{72} monopole matrix elements are not appreciably different.

A strength parameter of $\rho=0.06$ for the monopole transition in Zr^{90} is calculated on the basis of the measured half-life.

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Semiphenomenological Two-Nucleon Potential*

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It is found that a good fit of the unpolarized and polarized two-nucleon scattering data up to 150 Mev can be obtained by adding a phenomenological short-range attractive spin-orbit potential to the meson-theoretic Gartenhaus potential (which contains both central and tensor terms). It is shown that the deep attractive wells which result for certain states can be modified so as to eliminate all undesirable bound states without hurting the fit with the scattering data (at least up to 150 Mev). The predictions of the combined Gartenhaus—spin-orbit potential are examined at 210 and 300 Mev. While the addition of a spin-orbit potential helps materially at these higher energies, it is likely that a precision fit of the 300-Mev scattering will require additional terms in the two-nucleon interaction (containing higher powers of the nucleon momentum than the first).

1. INTRODUCTION

In a previous communication,[1] we gave a preliminary account of the improved agreement with the high-energy nucleon-nucleon scattering data obtained by adding a spin-orbit potential to the meson-theoretic potential deduced by Gartenhaus.[2] In this paper we give a more detailed report of our work and compare it with the recent work of Gammel and Thaler.[3]

In the past few years, Chew and Low[4,5] have developed a static nucleon p-wave pion interaction model which has enjoyed a certain amount of success. Their model may be viewed as a static extended source $PS(PV)$ model where, of course, only p-wave pions can be emitted; or as a $PS(PS)$ model where the s-wave virtual pions are somehow suppressed. Klein[6] has suggested that the experimentally observed suppression of real s-wave pions indicates that the virtual s-wave pions should also be suppressed.

The successes of the Chew-Low model for pion-nucleon scattering and photopion production up to moderate energies led Gartenhaus[2] to derive the corresponding static two-nucleon potential. More precisely, Gartenhaus used the nonrelativistic, p-wave, extended source (cutoff) Hamiltonian. He calculated in second and fourth order using nonrelativistic perturbation theory but omitted the so-called ladder correction terms (i.e., he employed the "Brueckner-Watson" method). The resulting potentials are shown in Figs. 1–6.

Gartenhaus' meson-theoretic potential gives a good fit to all of the low-energy data. This is encouraging since there are (in essence) no free parameters in his potential: the renormalized coupling constant $f_0^2=0.089$ and the cutoff energy $\omega_m=6\mu$ are taken from Chew and Low's work on photopion production and pion-nucleon scattering. Unfortunately, when Gammel and Thaler[7] fed the Gartenhaus potential into their computer program and calculated the scattering predictions

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