(b) The decay to the isomeric level follows the formation of the Pb^{208} compound nucleus.

The states of the compound nucleus differ, however, in the two cases, in the value of their angular momentum, the compound system formation being different. In the case of the photonuclear process, $J=1$; while in the case of inelastic neutron scattering (3-Mev neutrons), J is of the order of 3.

A definite answer to these questions cannot be given without a detailed calculation of the excitation efficiency based on the two assumptions we have suggested above.

ACKNOWLEDGMENTS

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Positron Spectra of Eu^{152} and Eu^{152m}†

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An intermediate-image beta-ray spectrometer equipped with spiral baffles has been used to investigate positrons in the decays of Eu^{152} and Eu^{152m}. Thirteen-year Eu^{152} emits a positron group to the 0.122-Mev 2+ first excited state of Sm^{152} with an end-point energy of 0.715 ± 0.010 Mev and an intensity of 1.6×10^{-4} per disintegration (log $ft=11.9$) and a positron group to the 0.366-Mev 4+ second excited state with an end point of 0.47 ± 0.03 Mev and an intensity of 0.8×10^{-4} per disintegration (log $ft=11.5$). 9.3-hr Eu^{152m} emits a positron group to the ground state of Sm^{152} with an end-point energy of 0.895 ± 0.005 Mev and an intensity of 7×10^{-5} per disintegration (log $ft=8.65$) and a positron group to the 0.122-Mev state with an intensity of 4×10^{-5} per disintegration (log $ft=8.6$). The shape of the latter group has not been established. However, its end point, when the alpha shape factor is applied, gives better agreement with the 0.122-Mev energy separation from the ground-state beta ray than the end point of the uncorrected spectrum. The result is consistent with, but not positive proof of, the assumed spin of 0− for Eu^{152m}. The β^- end-point energies of Eu^{152} and Eu^{152m} are 1.470 ± 0.010 Mev and 1.855 ± 0.010 Mev respectively. An energy separation of 0.050 ± 0.015 Mev between Eu^{152m} and Eu^{152} is derived from the various β^+ and β^- end-point measurements. No L-conversion electrons could be found in Eu^{152m} decay corresponding to a 0.05-Mev isomeric transition. An upper limit of 3×10^{-5} per disintegration was obtained for the fractional decay of Eu^{154} by positron emission.

INTRODUCTION

The helicity of the neutrino has been determined recently by Goldhaber, Grodzins, and Sunyar[1] in an experiment using 9.3-hr Eu^{152m}. A combined measurement of circular polarization and resonant scattering of gamma rays following orbital electron capture showed that the neutrino is left-handed. In the analysis, one assumption, based largely on plausibility arguments with respect to existing experimental information, was that the spin of Eu^{152m} is 0−. Aside from a direct measurement of the spin of Eu^{152m}, which has not been carried out thus far, there are several other ways in which the spin assignment can be made. Studies could be made of the beta-ray branching to the 0.344-Mev 2+ first excited state of Gd^{152} or of the positron branch emitted to the 0.122-Mev 2+ first excited state of Sm^{152} (see Fig. 5). In either case a unique first-forbidden or so-called "alpha" shape should occur in the distribution if the spin-parity of Eu^{152m} were actually 0−.

An experiment on Eu^{152m} was carried out early in the present work with the intermediate-image spectrometer in which beta rays focused by the spectrometer were measured in coincidence with 0.344-Mev gamma rays detected by means of a 2×2 inch NaI scintillation crystal behind the source. Owing to the weakness of the branch to the first excited state of Gd^{152} (~2%), the coincidence yield with a reasonable real-to-chance rate was found to be too small to permit a spectrum shape determination.

Positrons are known[2] to occur in the decay of Eu^{152m} with an end-point energy of 0.83 ± 0.05 Mev and an intensity of ~0.02% per disintegration, as established by means of a three-crystal pair spectrometer. It was presumed that the end point corresponded to the decay to the ground state of Sm^{152}. The approach followed in the present work was to make a magnetic analysis of the Eu^{152m} positron spectrum with the hope of detecting a branch to the 2+ first excited state of Sm^{152}, and of determining its shape if possible. Another aim of the experiments was to make a more accurate measurement

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[1] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

[2] L. Grodzins and H. Kendall, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).

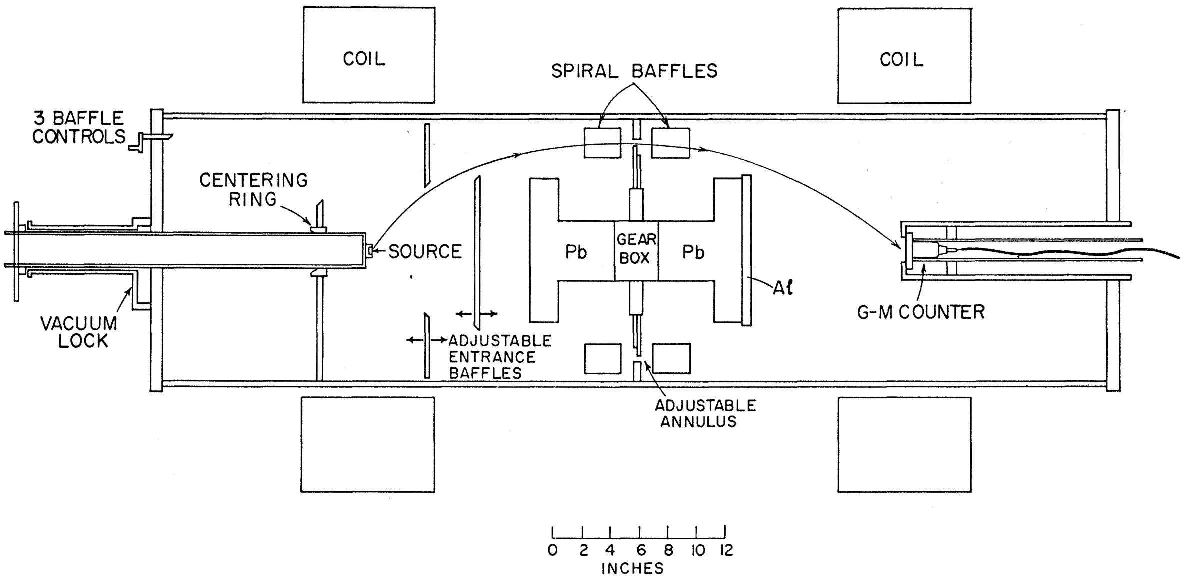

FIG. 1. Intermediate-image beta-ray spectrometer showing the locations of the two spiral baffles. Initial tests described in the text were made with the right-hand spiral baffle only.

of the positron end point, which determines the total decay energy and hence the neutrino recoil energy in the helicity experiment. Further, if positrons could also be detected in the decay of 13-yr Eu^{152} and their end-point energy measured, one would have a value for the energy separation between Eu^{152m} and Eu^{152} independent of that based on measurements of the spectrum of negative beta-rays.

THE SPECTROMETER SPIRAL BAFFLE SYSTEM

For a recent series of experiments[3] on positrons in the decays of several iridium isotopes, a spiral baffle was designed for the intermediate-image beta-ray spectrometer.[4] This consists of a double-ring mounting holding 48 flat blades spaced 7.5° apart, each blade being a $\frac{1}{16}$-inch thick brass plate $2\frac{1}{2}$ in. long (axial dimension) and 2 in. wide (radial dimension). By turning the mounting rings with respect to each other, the pitch angle of all blades can be varied simultaneously and locked into position at a given angle. Figure 1 shows the location for which the baffle was designed, i.e., as close to the annulus as possible and on the detector side of the annulus for easy installation. The electron paths traced in the work of Slätis and Siegbahn[5] were taken as an indication of the approximate pitch angle to be expected and suggested that the trajectories near the annulus are straight enough to allow the use of short flat blades. At the annulus radius the blades are 0.95 inch apart so one would expect to lose 6.6% of the transmission because of the cross section of the blades.

Transmission tests were made by measuring the yield of the K conversion line of the 1.06-Mev transition of Bi^{207} without the baffle and then with the baffle in place. A plot of the yield as a function of pitch angle showed a maximum at an angle of 18° where the transmission is 85% of that without the baffle. The loss of 8.4% transmission over and above that due to the blade cross section is probably accounted for by the curvature of the electron paths and by the lack of rigidity of the blade system.

With the spiral baffle in place, it was possible to observe the positron spectrum of internal pairs from the 1.77-Mev transition of Bi^{207} (8% branch) using a 15-microcurie source. Measurements were then made on the rejection ratio, which may be defined as the ratio of the yield of electrons which reach the detector when the current direction is set so as to allow electrons through the spiral baffle to the yield when the current through the coils is reversed but has the same value. The latter yield arises from scattering. Two sources of widely different intensities were used, i.e., a weak one when electrons were passed through the spiral baffle and a strong one which gave an observable scattering yield when the field current was reversed. A rejection ratio of $\sim 10^5$ was thus measured when the K conversion line of the 1.06-Mev transition of Bi^{207} was focused on the annulus.

In the decay of 9.3-hr Eu^{152m} it was known that the total yield of positrons[2] is only $\sim 10^{-4}$ per disintegration and that most of the decays proceed by negative beta-ray emission with an end-point energy of $\sim$1.8 Mev. Initial tests made on Eu^{152m} sources with the spectrometer set to pass positrons displayed a positron spectrum ending at about 0.9 Mev accompanied by a high-energy

[3] Scharff-Goldhaber, Alburger, McKeown, and Hudis (to be published).

[4] D. E. Alburger, Rev. Sci. Instr. **27**, 991 (1956); Phys. Rev. **109**, 1222 (1958).

[5] H. Slätis and K. Siegbahn, Arkiv Fysik **1**, 339 (1949).

tail due to the scattering of negative beta rays. The tail had about the intensity expected from the previously measured rejection ratio, i.e., the β^- scattered yield just above the β^+ end point was 10% of the peak positron yield. Because of the uncertainty in the extrapolation of the scattering tail back below the positron end point, it was felt that a higher rejection ratio would be necessary. (A method of actually measuring the scattering contribution under the β^+ spectrum is described in the section on Eu^{152m}.) In order to obtain a higher rejection ratio, a second spiral baffle was constructed which is similar to the first except that it has a fixed pitch angle of 18°. It was placed in a symmetrical position on the source side of the annulus. Figure 1 shows a schematic diagram of the complete baffle system. With the orientation of the second baffle adjusted visually so that the blades of the two baffles were in line, the transmission was measured and it was found that the second baffle resulted in a further 12% reduction in yield, making the transmission with both baffles in place 75% of that obtained with no spiral baffles at all. The rejection ratio at 1 Mev under these conditions was later found from strong Eu^{152m} sources to be $\sim 5\times 10^5$, or a factor of 5 higher than with one spiral baffle alone.

MEASUREMENTS ON Eu^{152} (13-yr)

An aged sample of ~0.2 mC of Eu^{152}, obtained from an irradiation of Eu_2O_3 (enriched in Eu^{151}) for several weeks in the reactor, was deposited on a 1-mil thick Al backing and examined in the spectrometer at a resolution setting of 4%. The spectrometer transmission at this resolution is 6% of a sphere (with the spiral baffles in place). Positrons, having a peak net yield of 360 per minute above a background of 36 per minute, were observed consisting of two distinct components. Their end-point energies, determined from the Kurie plot analysis shown in Fig. 2, are 0.715 ± 0.010 Mev and 0.47 ± 0.03 Mev. This source, which we shall designate as sample A, was then used to measure the end point of the β^- spectrum at 2.4% resolution. It was found that in addition to beta rays ending at 1.470 ± 0.010 Mev there was a weak tail above 1.47-Mev ending, according to a Kurie plot analysis, at 1.83 Mev. Because of the small intensity of the tail it was thought that scattering effects might be responsible for its occurrence. However a strong source of 9.3-hr Eu^{152m} showed no such tail when the β^- end-point region above 1.8 Mev was examined. It was tentatively concluded that a small amount of 16-yr Eu^{154} was present in sample A. Estimates, based on the relative amounts of Eu^{151} and Eu^{153} present and the relative neutron cross sections, agreed with the ratio of the 1.47- and 1.83-Mev beta-ray yields observed. In order to check the Eu^{154} end point, a source (sample B) containing Eu^{154} and Eu^{152} in the ratio of 2:1 was examined, and its end point was in agreement both with the tail observed in sample A and with the Eu^{154} beta-ray end points reported in the literature.

Sample B was examined for positron emission, and the result obtained was a very low intensity positron distribution having approximately the same shape and end point as the curve from sample A. The positron yield from sample B was that expected from the relative amount of Eu^{152} present and it was concluded that there were no additional positrons which could be ascribed to Eu^{154}. The upper limit on the fractional decay of Eu^{154} by positron emission is estimated to be 3×10^{-5}.

After an extrapolation of the Eu^{152} β^- Kurie plot of sample A, the momentum distribution was constructed and the relative areas under the β^- and β^+ momentum distributions were deduced. The intensity of the 0.715-Mev positron component (see Fig. 2) is 1.6×10^{-4} per disintegration, while the "inner group" has an intensity of 1.3×10^{-4} per disintegration. However, as pointed out by Leisi and Scherrer (private communication), the 1.405-Mev gamma-ray transition, an $E1$ transition which occurs in Eu^{152} decay with a strength of 25% per disintegration, will produce positron-electron internal pairs. By taking the $E1$ internal pair conversion coefficient as 2.0×10^{-4}, the integrated number of positrons resulting from this transition should be 0.5×10^{-4} per disintegration, or about 40% of the intensity of the "inner group." The presence of internal pairs is suggested by the shape of the "inner group" which is peaked at an energy considerably higher than expected for a simple beta-ray spectrum. A simple calculation shows that for a sample of only a few mg/cm² thickness, the estimated thickness of our source, the external pair production is at least two orders of magnitude less intense than internal pair production at this transition energy. We, therefore, subtract the internal pair contribution from the "inner group" to obtain the intensity of the 0.47-Mev positrons. The intensities of the 0.715 and 0.47-Mev positron components are then 1.6×10^{-4}

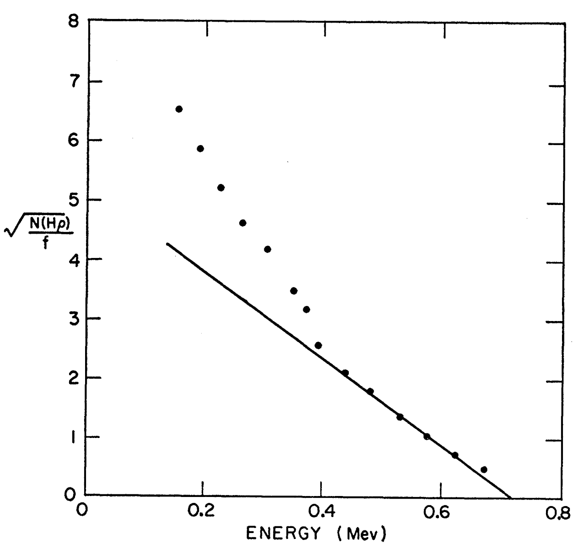

FIG. 2. Kurie plot analysis of the positron spectrum of 13-yr Eu^{152}.

and 0.8×10^{-4} per disintegration, respectively, and the corresponding log *ft* values are 11.9 and 11.5, respectively.

The negative-electron spectrum from a source of 13-yr Eu^{152} was measured in the region above 0.85 Mev at a resolution setting of 2.4%. Internal conversion lines corresponding to the known gamma-ray transitions of 0.866, 0.963, 1.085, 1.110, and 1.405 Mev were found superposed on the beta-ray continuum. A Kurie plot was made using points in those regions free of conversion lines and above the lower energy beta-ray groups, i.e. from 1.12 to 1.32 Mev and from 1.41 Mev to the end point. The points of this Kurie plot fell on a straight line. Thus we do not confirm the results of Bhattacherjee *et al.*[6] that the highest energy group has the unique first-forbidden or alpha shape and that Eu^{152} must have a spin of 4^-. A further study of this shape should probably be made with a high-resolution spectrometer.

MEASUREMENTS ON Eu^{152m} (9.3-hr)

Owing to the large neutron cross section for the formation of Eu^{152m} (1400 barns) very high specific activities were obtained by irradiating $EuCl_3$ in the reactor for 1–2 hours at a flux of 2×10^{13} neutrons/cm^2 sec. A small amount of the active powder was dissolved in water and a drop of the solution was evaporated onto a $\frac{1}{4}$-mil thick Al backing over an area ~1 cm in diameter. In the final runs the sources read (300–500) r of beta rays on contact and they were estimated to contain more than 20 millicuries of Eu^{152m} and to be a few mg/cm^2 in thickness. The procedure for taking the positron spectrum was to run a complete set of 2-min points spaced $\frac{1}{2}$ min apart and then to reverse the order of taking points on the next run such that the sum of the two sets canceled the effect of the 9.3-hr decay.

Figure 3 shows one of the distributions obtained at a spectrometer resolution setting of 2.4% (transmission 4.5% of a sphere with the spiral baffles in place) when focusing positrons. Each point is the average of four 2-min runs taken as described above over a period of 5 hours. Only the upper half of the spectrum was taken in detail since this is the main region of interest. At an energy just above the positron end point about half the yield is field independent and it is ascribed to scattered gamma rays plus natural counter background. The field-dependent portion of the background just above the positron end point is ~2% as great as the peak positron counting rate and it is attributed to the scattering of beta rays through the spiral baffle system. In order to prove that the background is the result of scattering and at the same time to measure the field-dependent background under the positron spectrum, a technique suggested by A. Schwarzschild was used. Since the intermediate-image spectrometer has a final focus as well as an annular intermediate focus, one may move the detector axially far enough to avoid the detection of properly focused particles without greatly altering the scattering yield. As determined by focusing through the annulus the *K*-1.06-Mev electrons from a source of Bi^{207} (with the field direction set to allow negative electrons through the spiral baffles), the detector (exit aperture 1.5 cm diameter) had to be moved axially only 20 mm away from the focus in order to reduce the number of electrons detected by a factor of 1000. With the detector in that position, no greater yield could be observed at any other magnetic field setting. Runs on the Eu^{152m} tail (spectrometer field set to pass positrons) when the detector was in the away-from-focus position then gave a yield above 4500 gauss-cm (see Fig. 3) which matched closely to the curve when the detector was at the focus. A change in the detector position, 10 mm further away from the focus, also gave the same results. These tests show that the number of scattered electrons crossing the axis in the general vicinity of the final focus is approximately uniform and thus one would expect that a run over the whole spectrum, taken with the detector in the away-from-focus position, should display the true distribution of scattered electrons which lies under the positron spectrum at the focus. A background curve, corrected for decay only, is included in Fig. 3. Open-circle background points are not plotted above 4500 gauss-cm since they nearly coincide with the solid points of the main spectrum. It may be noted that if the scattering background depended only on the intensity of the negative electrons incident on the baffles, the background should follow the shape of the beta-ray spectrum and thus decrease below 4000 gauss-cm rather than increase. One may conclude that the scattering through the spiral baffles increases with decreasing energy.

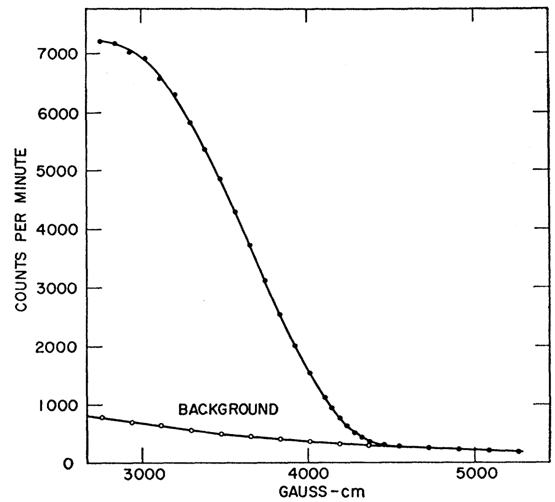

FIG. 3. Positron spectrum of 9.3-hr Eu^{152m} above 0.4 Mev. The magnetic-field-dependent background is due to the scattering of beta rays through the spiral baffle system and was measured as described in the text.

[6] Bhattacherjee, Nainan, Raman, and Sahai, Nuovo cimento **7**, 501 (1958).

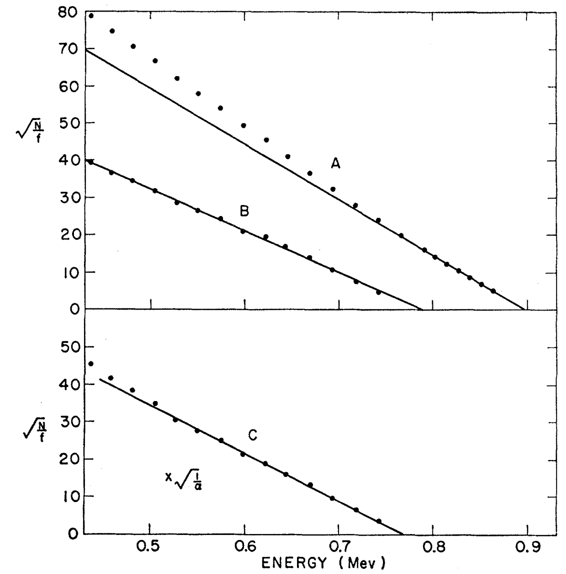

FIG. 4. Kurie plot analysis of the Eu^{152m} positron spectrum. Curve *A*—total spectrum; curve *B*—normal Kurie plot after subtraction of the high-energy distribution; curve *C*—alpha shape factor applied to the inner group.

A Kurie plot of the net positron spectrum after correction for counter dead time and subtraction of the background is shown in curve *A* of Fig. 4. The presence of two components is clearly indicated, the higher one having an end-point energy of 0.895 ± 0.005 Mev. By making use of standard procedures the higher energy group was subtracted and a Kurie plot made of the remainder as shown in curve *B*. The best straight line through the points of curve *B* extrapolates to an energy of 0.788 Mev which is 0.107 Mev below the end point of the high-energy group. On the other hand, when the alpha shape correction factor is applied to the inner group, as shown in curve *C*, the best straight line fit extrapolates to an energy of 0.768 Mev which is 0.127 Mev below the end point of the upper group. This same general behavior of the end points of the inner group occurred in the analysis of several different runs. The end-point energies of the two groups must differ by 0.122 Mev in order to agree with the known gamma-ray energy.

An assumption made in the above analysis is that the higher energy component has a linear Kurie plot. In order to support this assumption a run was made on the negative beta-ray distribution using a source of similar dimensions but having a suitable strength for counting negative electrons. The beta rays go mainly to the ground state of Gd^{152} and thus the shape of this distribution should be the same as that of the positrons to the ground state of Sm^{152} since both final states are $0+$. The Kurie plot of the beta-ray distribution was found to be accurately linear from 0.9 Mev to the extrapolated end point of 1.855 ± 0.010 Mev. The small admixture of beta rays to the 0.344-Mev state of Gd^{152} was negligible. We therefore feel that the assumption of a linear Kurie plot for the ground-state positron group is probably justified over the upper half of the spectrum.

The Eu^{152m} end-point energy of 1.855 Mev was also obtained with the 20-mC sources by making a Kurie plot analysis of points very close to the end of the spectrum. From an area comparison of the momentum distributions of the positrons and of the beta rays, after extrapolating the Kurie plot to lower energies, the relative positron branchings were derived. The 0.895-Mev and 0.77-Mev components occur in 7×10^{-5} and 4×10^{-5} of the disintegrations respectively and the corresponding log *ft* values are 8.65 and 8.6 respectively.

Search for an Isomeric Transition in Eu^{152m}

According to the analysis given in the next section the energy separation between Eu^{152m} and Eu^{152} is 0.050 ± 0.015 Mev. If an isomeric transition exists it should convert in the *L*, *M*, and *N* shells and thus yield internal conversion electrons in the region of ~0.04 Mev. Unfortunately the *K* Auger electrons following electron capture and internal conversion are also present in this vicinity. Nevertheless it was felt that a search should be made for lines of an isomeric transition even though the intermediate-image spectrometer is not a high-resolution instrument.

A Geiger counter with a 50-μg/cm^2 thick grid-supported window was installed on the spectrometer and thin sources of Eu^{152m} were made by evaporating $EuCl_3$ onto $\frac{1}{4}$-mil thick Al foil and irradiating them in the reactor. Runs on the low-energy spectrum were made at 1.0% resolution using sources 30–300 μg/cm^2 in thickness. The normal *K*-Auger electron spectrum consisting of the *K*-2*L*, *K*-*L*-*M* and *K*-2*M* groups, was observed but there was no evidence for additional lines. An upper limit of 5% may be placed on the intensity of the *L* line of an isomeric transition relative to the *K*-2*L* Auger line unless the lines of the isomeric transition lie under the Auger lines. In the latter instance, conversion lines of as much as 15% of the intensity of the *K*-2*L* line might go undetected if they lie under the *K*-2*L* or *K*-*L*-*M* groups.

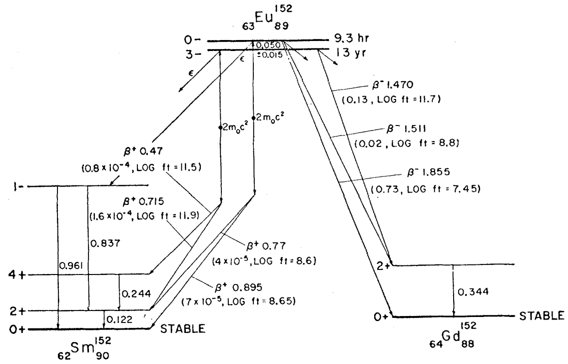

FIG. 5. Partial decay scheme of Eu^{152} and Eu^{152m}.

DISCUSSION

Those portions of the Eu^{152} and Eu^{152m} decay schemes affected by the present work are shown in Fig. 5. In view of the known spin of 3− for Eu^{152}, of the spins of 0+, 2+, and 4+ for the ground and first two excited states of Sm^{152}, and of the energy separation between the two observed positron end points, it may be assumed that the Eu^{152} positrons represent decays to the 2+ and 4+ states with no branch to the ground state occurring. The total energy in the decay of Eu^{152} to Sm^{152} is then 1.859 ± 0.010 Mev based on the end point of the 0.715-Mev positron going to the 0.122-Mev state.

Eu^{152m} has a total energy for decay to Sm^{152} of 1.917 ± 0.005 Mev based on the 0.895-Mev positron to the ground state. By subtracting 0.961 Mev one obtains 0.956 ± 0.010 Mev as the energy available for the electron capture decay of Eu^{152m} to the 0.961-Mev 1− state of Sm^{152}. This result is 0.066 Mev higher than the decay energy derived previously[2] from positron measurements and 0.031 Mev higher than the capture energy of 0.925 ± 0.010 Mev derived recently from resonant scattering experiments by Moon *et al.*[7]

The decay energies obtained from the positron measurements lead to an energy separation of 0.054 ± 0.011 Mev between Eu^{152m} and Eu^{152}. On the negative-beta-ray side the difference between the total decay energies is 0.041 ± 0.014 Mev. A weighted average of 0.050 ±0.015 Mev is taken as the most probable energy of the isomer above the ground state. This is to be compared with earlier measurements leading to an energy separation of 0.080 ± 0.025 Mev[8] and 0.030 ± 0.040 Mev,[9] respectively.

It is interesting to note that the log ft values of the two first-forbidden positron groups and of the beta ray to the 0.344-Mev state from Eu^{152} are all approximately the same (11.3 to 11.9) and that the log ft values of the two positron groups and of the beta ray to the 0.344-Mev state in Eu^{152m} decay are also close to each other (8.5 to 8.9). The total disintegration energies of both Eu^{152} and Eu^{152m} to the two sides differ by only 0.062 Mev, there being a slightly larger decay energy to Sm^{152}.

The question of the spin of Eu^{152m} has not been settled definitely by the present work. In all of the positron spectrum analyses the Kurie plot points of the inner spectrum fit a straight line equally well with or without the alpha shape correction factor. However, there was each time a tendency for the end point of the uncorrected Kurie plot to be too high, by about 0.015 Mev, to agree with the 0.122-Mev first-excited state, whereas the end point of the alpha-corrected plot was close to the correct energy. The end point of the inner group is quite sensitive to the choice of straight line through the higher group points above 0.8 Mev. In view of the magnitude of the background which was subtracted and of the errors which might arise from the extrapolation of the Kurie plot of the higher energy group, we feel that we have not proved beyond doubt that the inner group has an alpha shape on the basis of energy arguments. However, the results agree more favorably with the alpha shape correction and thus support the assumed spin of 0− for Eu^{152m}.

From the upper limit on the intensity of lines corresponding to an isomeric transition of $\sim$0.05 Mev, the lower limit on the transition probabilities for various multipole orders may be derived. Factors used in the estimates include (a) the number of K-shell vacancies per disintegration ($\sim$0.3) resulting from electron capture and from internal conversion, (b) the K-Auger conversion probability of 0.10, (c) the upper limit on the intensity of isomeric conversion lines relative to the Auger lines, as discussed in the preceding section, and (d) the theoretical internal conversion coefficients for a transition of 0.05 Mev. Lower limits on the partial half-lives for the emission of 0.05-Mev gamma radiation were derived and compared with theoretical single-particle half-lives for $M3$ and $E2$ multipoles. These are the two most likely radiations inasmuch as the spin of Eu^{152m} is most probably 0− but could also be 1−. The retardation factor, which is the ratio of the theoretical to the observed transition probability, is $>5\times10^6$ if the transition is $M3$ and $>3\times10^{12}$ if it is an $E2$ radiation.

We are indebted to Dr. Lee Grodzins for the preparation of some of the sources and to Dr. A. Schwarzschild for helpful suggestions.

[7] Moon, Shute, and Sood, Phys. Rev. Letters **1**, 21 (1958).
[8] See L. Grodzins, Phys. Rev. **109**, 1014 (1958).
[9] O. Nathan and M. A. Waggoner, Nuclear Phys. **2**, 548 (1957).