The correction f_{LII} is not significantly different from unity, owing to the large errors involved. This value depends in a sensitive way on the mixing ratio. Moreover, the L_{II} conversion line is weak and poorly resolved.

An estimate of the branching ratios of the transitions has also been made. The ratios we find are: $A^{98}/A^{129}=8.8$ and $A^{98}/A^{31}=3.6$. It would therefore appear that the 31-kev gamma ray cannot follow the 98-kev radiation as suggested by Bernstein and Lewis.[15]

[15] E. Bernstein and H. Lewis, Phys. Rev. **100**, 1345 (1955).

ACKNOWLEDGMENTS

The authors wish to thank Dr. Milo B. Sampson and the cyclotron staff for the Au^{195} bombardments and Mr. George Bulbenko for his aid in the chemical separations. We are grateful to Mr. Norbert Hankin for his help with the computations and scanning of the plates, and to Mr. Helmut Fischbeck for assistance in taking data. Mr. Carl Studer's active cooperation in the construction of equipment and data recording is very much appreciated.

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Radioactive Decay of Se^{83}†

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An experimental investigation, using scintillation techniques, has been made of the gamma radiation emitted by the 69-second isomer of Se^{83}. The Se^{83} was produced by irradiating selenium, enriched in the isotope Se^{82}, in the reactor neutron flux. Gamma rays of energy 2.02±0.05 Mev, 1.01±0.02 Mev, 0.650±0.005 Mev, and 0.350±0.006 Mev were found, each with a (70±1)-second half-life. Of these, only the 0.350-Mev gamma ray was found in the 25-minute isomer. From these measurements, together with beta-gamma and gamma-gamma coincidence measurements and a rough beta-ray end-point determination, a decay scheme is proposed for the 69-second isomer of Se^{83}.

INTRODUCTION

THE radioactive decay of Se^{83} has been investigated by several experimenters.[1–4] Two isomeric states have been found and the respective beta-ray end-point energies determined. Some gamma rays have been found in the 25-minute activity, but none have been reported previously for the 69-second activity.

In 1947 Arnold and Sugarman[1] investigated Se^{83} by means of chemical separation methods, and measured the half-life and beta-ray end-point energy by absorption techniques. They found the half-life to be 67 seconds and the beta-ray energy to be 3.4 Mev. In 1950 Glendenin,[2] using absorption techniques, found a second isomer with a half-life of 25 to 30 minutes. This isomeric state apparently decayed via a beta ray of 1.5 Mev and gamma rays of 170, 370, and 1100 kev. In 1952 the isotope Se^{83} was further investigated by Rutledge, Cork, and Burson[3] using selenium enriched in the isotope Se^{82}. They found a half-life of 25±2.5 minutes for the isomer previously investigated by Glendenin. Their scintillation spectrometer measurements confirmed the existence of a 170- and a 1100-kev gamma ray, but they did not find the 370-kev gamma ray.

All information concerning this isotope prior to the present investigation is conveniently collected in a publication of the U. S. Atomic Energy Commission.[4]

APPARATUS

Samples of Se metal were exposed to the neutron flux in the Pennsylvania State University Research

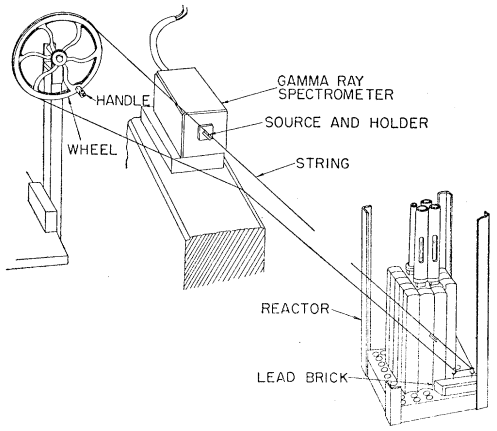

FIG. 1. Exposure apparatus.

† This research was supported in part through a grant from The National Science Foundation.

[1] J. R. Arnold and N. Sugarman, J. Chem. Phys. **15**, 703 (1947).

[2] L. Glendenin, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1950), Paper No. 61, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.

[3] Rutledge, Cork, and Burson, Phys. Rev. **86**, 775 (1952).

[4] *Nuclear Level Schemes, A=40 to A=92*, compiled by Way, King, McGinnis, and van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

Reactor[5] by means of the exposure system shown in Fig. 1. A large-diameter pulley-wheel was mounted on a table positioned at the edge of the reactor pool. A string encircled the pulley-wheel and extended down to two aluminum eyelets attached to a lead brick placed on the reactor grid plate. This arrangement permitted the samples to be moved rapidly back and forth between the reactor core and the detection equipment at the edge of the reactor pool. The pulley-wheel was rotated manually to expose a sample for a predetermined length of time, usually one minute, and was then rotated rapidly in the opposite direction to withdraw the sample to a position in front of the detection apparatus. Withdrawal times as short as five seconds were easily accomplished. For most of the measurements the reactor was operated at a power level of 100 kw.

Samples used for measuring the Se gamma-ray spectrum were prepared by sealing Se metal pellets or powder in lengths of polyethylene tubing, $\frac{1}{4}$ in. in diameter and 2 in. long. Many samples of normal Se of 99.99% purity were employed, a sample being

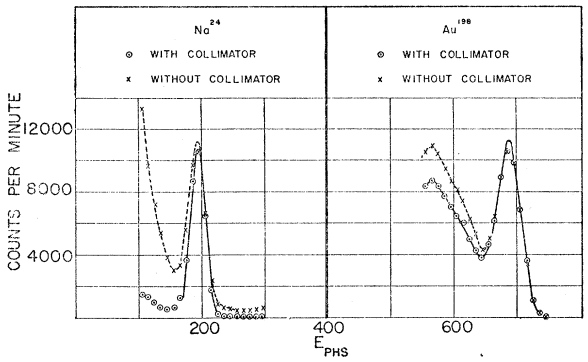

FIG. 2. Collimator tests.

discarded after several exposures to avoid the accumulation of any long-lived activity. One sample[6] of Se enriched to 75.74% Se^{82} was employed to verify the isotopic assignment of the radiation. Samples used for the detection of beta rays were prepared by sealing a thin layer of Se powder between two layers of Scotch cellophane tape, supported by a thin graphite ring.

The gamma-ray spectrometer consisted of a 2-in.×2-in. cylindrical NaI(Tl) crystal attached directly to the end of a DuMont type 6292 photomultiplier tube. Pulses from the photomultiplier tube were fed through a preamplifier and linear amplifier to a 20-channel pulse-height analyzer. Pulses from the preamplifier were simultaneously fed through a second linear amplifier and a single-channel pulse-height analyzer into a linear count-rate meter and strip-chart recorder. Arrangements were made at the input of the pre-

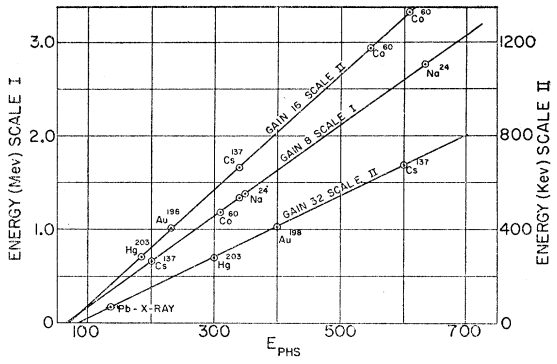

FIG. 3. Gamma-ray spectrometer energy calibration.

amplifier to feed in test pulses, at any time from a precision pulse generator, to test for stability and for gain of the entire system.

It was found to be desirable to enclose the gamma-ray spectrometer in a lead housing, the dimensions of which were 8 in.×8 in.×24 in., giving about three inches of shielding around the crystal. The collimator hole, through the lead shield to the crystal, was $\frac{3}{4}$ in. in diameter and 8 in. long. This housing not only reduced the gamma-ray background to a negligible point, but also enhanced the photopeak relative to the Compton distribution, as shown in Fig. 2. This latter effect is presumably the result of channeling the photons into the center of the crystal and thus reducing the probability for the escape of Compton-scattered photons.

Energy calibration of the gamma-ray spectrometer was achieved by the use of sources of Au^{198}, Cs^{137}, Co^{60}, and Na^{24}, all of which emit gamma rays of known energy. Typical calibration curves are shown in Fig. 3. An intensity calibration was obtained using sources of Co^{60}, Au^{198}, and Na^{24}. The disintegration rate of the Co^{60} source had been obtained by the U. S. Bureau of Standards. That of the Au^{198} source was measured by coincidence counting.[7] The disintegration rate of the Na^{24} source was not known, but the relative intensities

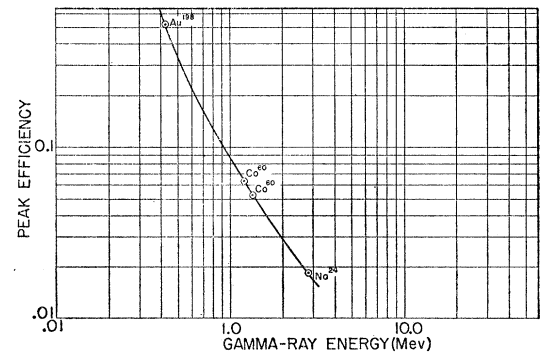

FIG. 4. Peak efficiency *vs* energy.

[5] W. M. Breazeale *et al.* U. S. Atomic Energy Commission Report NYO-7895, 1956 (unpublished).

[6] Obtained on loan from the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[7] A. C. G. Mitchell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 201 ff.

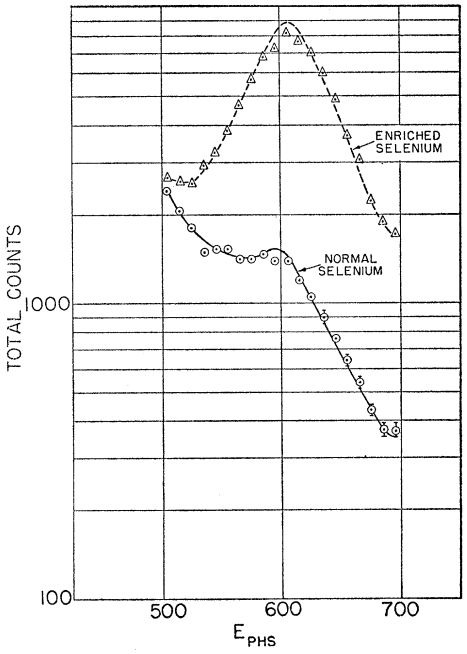

FIG. 5. 350-kev gamma ray from 70-second isomer of Se^{83}.

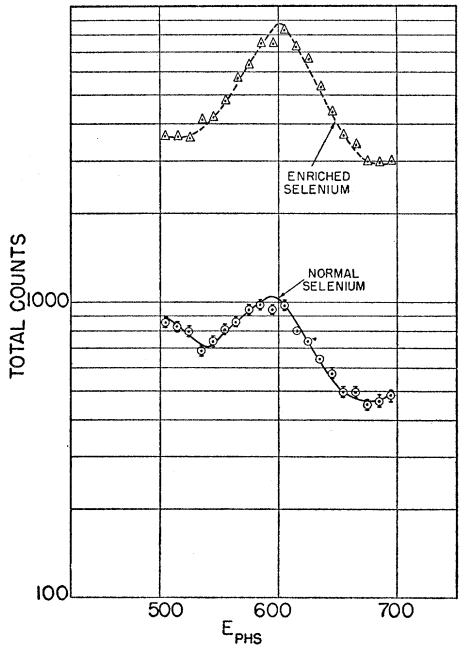

FIG. 6. 650-kev gamma ray from 70-second isomer of Se^{83}.

of the 1.37-Mev and 2.75-Mev gamma rays are known to be 1:1.[8] Energy spectra were measured for these sources, and the area under each photopeak determined after subtracting the extrapolated continuum under each peak. In this way the peak efficiencies of the detector for the Au^{198} and Co^{60} gamma rays were determined. By normalizing the intensity of the 1.37-Mev gamma ray of Na^{24} to that of the 1.33-Mev gamma ray of Co^{60}, the peak efficiency for the 2.75-Mev gamma ray of Na^{24} was obtained. The resulting intensity calibration curve for the gamma-ray spectrometer is shown in Fig. 4.

The beta-ray counter consisted of a plastic scintillator[9] $\frac{1}{8}$ in. thick and 2 in. in diameter, attached to a DuMont 6292 photomultiplier tube and protected from light by a 0.75-mil aluminum foil. The electronics system was identical with that of the gamma-ray spectrometer.

EXPERIMENTAL RESULTS

A. Gamma Rays from 69-Second Isomer

Samples of normal Se were exposed to the reactor neutron flux for one minute, withdrawn to a position in front of the gamma-ray spectrometer; and after an appropriate delay time the spectrometer was turned on for a one-minute count. This procedure was repeated five times at five-minute intervals to obtain a satisfactory number of total counts on the 20-channel analyzer. For each portion of the spectrum a new sample was employed. The delay time was necessary in the case of the two lower energy gamma rays because of competing 10-second and 18-second activities from other isotopes.

In this way gamma rays of 350±6 kev, 650±5 kev, 1.01±0.02 Mev, and 2.02±0.05 Mev were found. Gamma-gamma coincidence counting subsequently

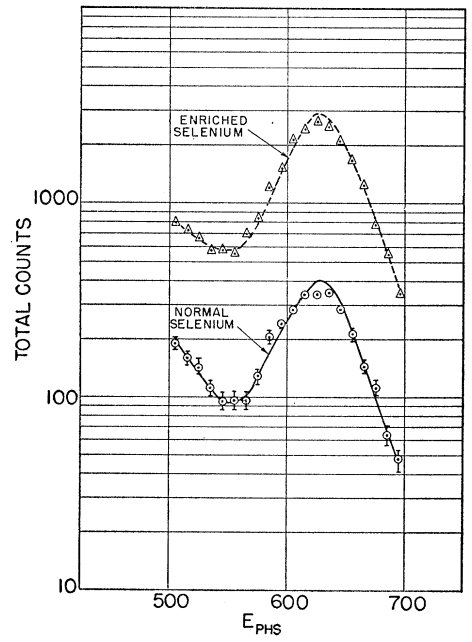

FIG. 7. 1.01-Mev gamma ray from 70-second isomer of Se^{83}.

[8] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[9] Plastic Phosphor NE 102, obtained from Nuclear Enterprises Ltd., Winnipeg, Canada.

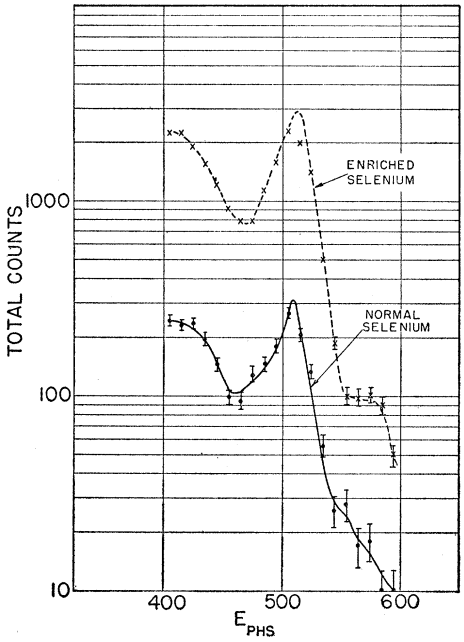

FIG. 8. 2.02-Mev gamma ray from 70-second isomer of Se^{83}.

indicated that there are two unresolved 1-Mev gamma rays. To ascertain whether these gamma rays were in the short-lived isomer, the half-life of each was measured. This was done by setting the single-channel analyzer to accept only the gamma ray of interest and recording the decay on the strip-chart recorder. The recorder chart data were then analyzed carefully by the method of least squares. In each case the half-life was found to be 70±1 sec.

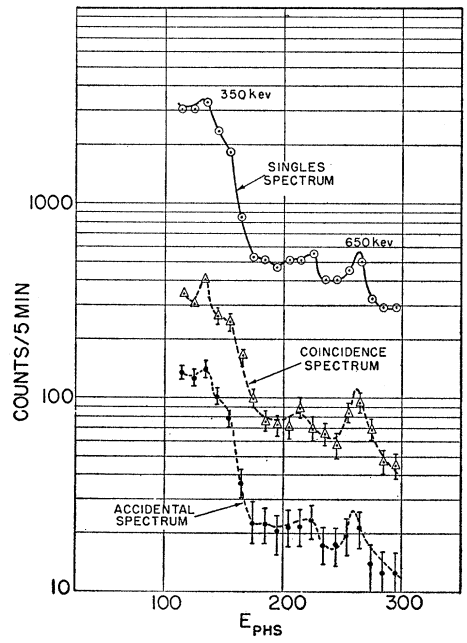

FIG. 9. Beta-gamma coincidences with 350-kev and 650-kev gamma rays of Se^{83}.

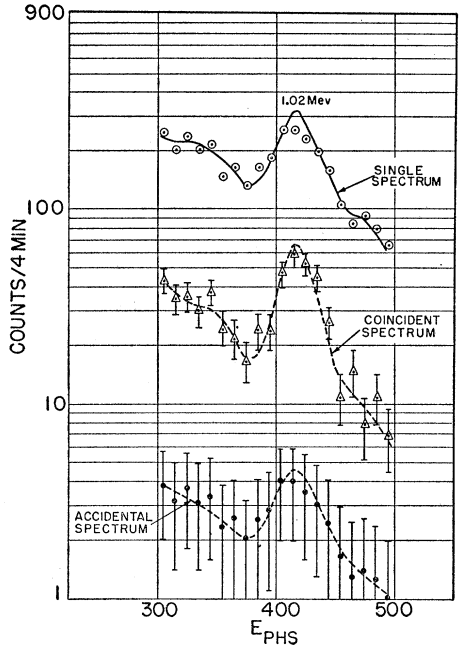

FIG. 10. Beta-gamma coincidences of 1.01-Mev gamma ray in Se^{83}.

To further justify the assignment of these gamma rays to an isomer of Se^{83}, the enriched sample of Se^{82} was exposed in a like manner. All of the above-mentioned gamma rays were found, with their intensities increased in approximately the same ratio as the isotopic enrichment. The gamma-ray spectra are shown in Figs. 5–8. The relative intensities of the gamma rays are given in Table I.

B. Beta-Gamma Coincidence Measurements

In order to determine which of the observed gamma rays are in coincidence with beta rays, the beta-ray detector was placed near the gamma-ray spectrometer so that the sample could be positioned between them. The 20-channel analyzer was gated with the output pulses from the beta-ray counter so that only those gamma-ray pulses in coincidence with the beta rays would be observed. Figures 9–11 show the gamma-ray spectrum both with and without the use of the coincidence circuit, as well as the calculated accidental coincidence spectrum. From these data it is concluded

TABLE I. Relative gamma-ray intensities.

Gamma-ray energy (Mev)	Relative intensity
2.02 ±0.05	3.5
1.01 ±0.02	8.8
0.650±0.005	1.8
0.350±0.006	1.1

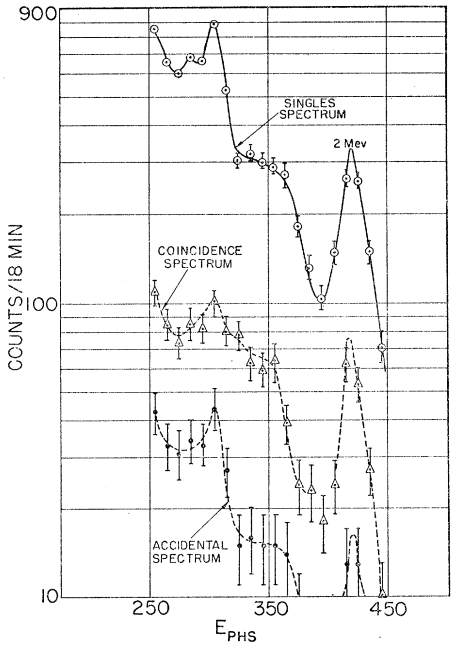

FIG. 11. Beta-gamma coincidences of 2.02-Mev gamma ray in Se^{83}.

that all of the gamma rays are in coincidence with beta rays.

C. Gamma-Gamma Coincidence Measurements

To determine the coincidence relationship of the gamma rays, the beta-ray counter was replaced by a second gamma-ray spectrometer, which was connected through the single-channel analyzer to operate the gate in the 20-channel analyzer. Each spectrometer was housed in a collimator of $2\frac{3}{4}$ in. length for this measurement. Each pulse-height analyzer was adjusted to respond to only one gamma-ray photopeak, and the coincidence rate determined for several combinations of the four gamma rays. The results of these measurements, corrected for accidental coincidence counting rates, are shown in Table II.

TABLE II. Gamma-gamma coincidences.

γ/γ (Mev)	Coincidence rate (counts/sec)
1.0/2.0	0.018±0.018
1.0/1.0	0.042±0.014
0.650/1.0	0.098±0.064
0.350/1.0	0.129±0.031
0.350/0.650	0.200±0.032

From Table II at appears that the last four pairs of gamma rays are in coincidence with each other; there is no evidence for coincidences in the case of the first pair.

D. Beta-Ray End-Point Measurements

The end-point energy of the Se^{83} beta rays was investigated by using the beta-ray detector, although the $\frac{1}{8}$-in. thick phosphor, equivalent to 1-Mev electron range, was not well suited to this purpose. The beta-ray detector was connected to the 20-channel analyzer, which was gated by the output from the single-channel analyzer. The single-channel analyzer was fed by the gamma-ray spectrometer, and was adjusted to accept only the 1-Mev photopeak. Thus only those beta rays which were in coincidence with 1-Mev gamma rays were detected. In Fig. 12 the pulse-height distribution of the beta rays from Se is compared with those from Au^{198}, Si^{31}, K^{42}, and Al^{27}. An attempt to determine the end point of the Se spectrum is made by drawing tangents through corresponding parts of each pulse-height distribution and determining the intersection of the tangent with the abcissa. These intersections are plotted *vs* end-point energy in Fig. 13. The results imply an end-point energy of about 1.5 Mev for the Se beta rays. The counting rate was too low for reliable half-life measurements, although a value of the order of one minute is indicated. Attempts to measure the Se^{83} beta rays without requiring gamma-ray coincidences were not successful, owing to competing activities in other isotopes and in the source mounting. The results of the beta-ray measurements, although suggestive, are not considered to be definitive.

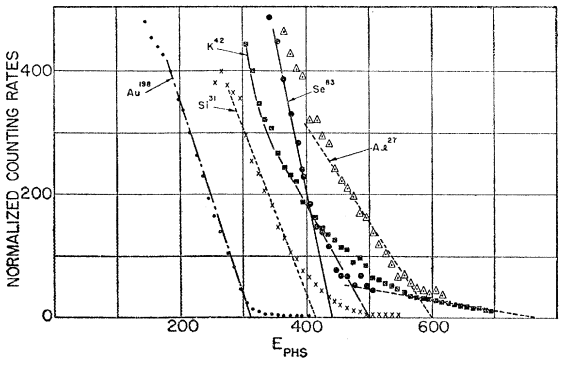

FIG. 12. Beta-ray spectra of Se^{83} compared with known beta-ray spectra.

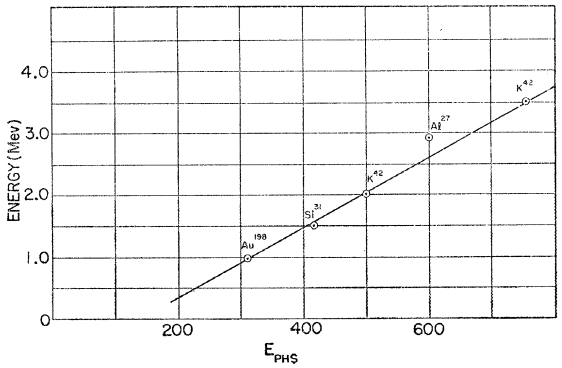

FIG. 13. Beta-ray energy calibration curve.

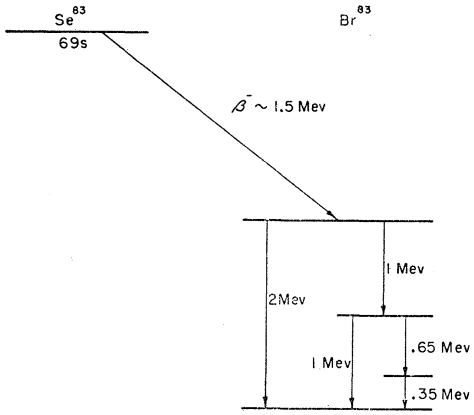

FIG. 14. Proposed decay scheme of Se^{83} (69-second isomer).

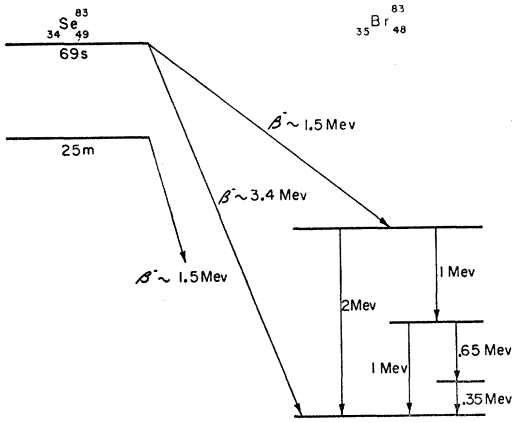

Fig. 15. Proposed decay scheme of Se^{83}.

E. Gamma Rays from 25 Minute Isomer

An investigation, as yet incomplete, of the gamma-ray spectrum associated with the 25-minute isomer indicates a strong 0.350-Mev component, but gives no evidence of any of the other gamma rays found in the 69-second isomer.

CONCLUSIONS

The above results indicate that the radioactive decay of Se^{83} is accompanied by gamma rays of energy 2.02 ± 0.05 Mev, 1.01 ± 0.02 Mev, 0.650 ± 0.005 Mev, and 0.350 ± 0.006 Mev. Half-life measurements and measurements with the isotopically enriched Se sample indicate that these gamma rays must be attributed to the 69-second isomer of Se^{83}. The beta-gamma coincidence measurements indicate that all of the gamma rays are in coincidence with beta rays, and consequently represent transitions in Br^{83}. The gamma-gamma coincidence measurements, together with the relative intensity measurements, indicate that the 0.350-Mev and 0.650-Mev gamma rays follow one another in cascade, while the 1-Mev gamma rays are partly in cascade with these and partly represent a crossover transition. The absence of all but the 0.350-Mev gamma ray in the 25-minute isomer indicates that this gamma ray is not followed by any of the others. The decay scheme of Fig. 14 is consequently proposed.

The nuclear shell model[10] implies a spin of 9/2+ for the ground state of Se^{83}, $\frac{1}{2}-$ for an excited state in Se^{83} and $\frac{3}{2}-$ for the ground state of Br^{83}.[4] The beta decay from the excited state of Se^{83} to the ground state of Br^{83} is therefore expected to be allowed. The maximum beta-ray energy of the 69-second state is 3.4 Mev, and that of the 25-minute state is 1.5 Mev. This implies that the 69-second state is the excited state of Se^{83}. This, together with the evidence for a beta ray of 1.5 Mev from the excited state of Se^{83}, suggests the tentative decay scheme shown in Fig. 15.

[10] J. H. D. Jensen, in reference 7, p. 414 ff.