Decay Properties of I^{136}

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I^{136}, produced from the slow neutron fission of uranium, has been studied with scintillation techniques. From the single-crystal (NaI) and gamma-gamma coincidence spectra, gamma rays were found at energies of 0.20, 0.27, 0.39, 0.46, 0.53, 0.71, 1.00, 1.321±0.006, 1.55, 1.72, 1.91, 2.25, 2.40, 2.63, 2.84, and 3.2 Mev. Also, from single-crystal (anthracene) and beta-gamma coincidence measurements, four beta-ray groups were observed with energies of 2.73, 4.23, 5.62, and 7.00 Mev, where the latter represents the I^{136}-Xe^{136} mass difference and is present in about 6% of the total beta-ray transitions. A partial decay scheme has been proposed, with energy levels in Xe^{136} at 1.32, 2.64, 2.84, 3.03, 3.23, 3.57, 3.74, and 4.20 Mev. The half-life of I^{136} was measured as 82.8±1.5 seconds. In the course of this investigation a source of 3.8-minute Xe^{137} was prepared, and was found to emit prominent gamma rays of 0.26 and 0.45 Mev.

I. INTRODUCTION

A SHORT-LIVED iodine isotope with a half-life of 1.8±0.4 minutes was discovered in uranium fission by Strassmann and Hahn.[1] Seelmann-Eggebert and Born[2] showed that its daughter was not an active xenon with a half-life between several hours and about one-half minute. Later Stanley and Katcoff[3] assigned a mass number of 136 to this iodine activity and measured its half-life as 86 seconds. More recently McKeown and Katcoff[4] studied I^{136} and reported a decay scheme with a pair of 1.4-Mev gamma rays in cascade, a cross-over transition of 2.8 Mev, and three associated beta rays with energies of 6.4, 5.0, and 3.6 Mev.

For several reasons a further study of this nuclide seemed very interesting. Since it decays to a closed shell of 82 neutrons in Xe^{136}, a characterization of the decay properties of I^{136} would contribute to a better understanding of the energy systematics at this unusually rigid configuration of nucleons. It appeared quite probable that, with the large I^{136}-Xe^{136} energy separation, the decay scheme was more complex than previously reported and that very energetic gamma rays in appreciable intensity might be emitted.

II. SOURCE PREPARATION AND HALF-LIFE DETERMINATION

The I^{136} sources were chemically separated from uranyl nitrate solutions irradiated in the Oak Ridge Grapite Reactor. To the irradiated solutions, containing from 640 to 850 mg of uranium, carrier bromide and iodide were added, followed by selective oxidation of iodide with sodium nitrite and subsequent extraction of the iodine into carbon tetrachloride. After an aqueous wash the iodine was reduced with sodium metabisulfite, backextracted into water and then precipitated as silver iodide. The entire operation from the end of irradiation until the sample was mounted and ready for counting required about four minutes. It was found that thirty-second irradiations gave the most favorable discrimination against other iodine fission products.

Although decay of the iodine sources was followed during most of the experiments as a check on chemical purity, the best value of the I^{136} half-life was determined using an end-window beta proportional counter. Counting began 4–4.5 minutes after irradiation, so any interference from 22-second I^{137} was probably negligible. The contribution from 52-minute I^{134}, 6.7-hour I^{135}, and 21-hour I^{133} amounted to about 20% at the time of the first count. The I^{136} half-life obtained from three careful measurements was 82.8±1.5 seconds, where the quoted error represents our attempt to estimate the combined standard and systematic errors.

III. GAMMA-RAY SPECTROMETRY

All gamma-ray spectra were measured using 3-inch ×3-inch cylindrical sodium iodide crystals mounted on Dumont 6363 photomultiplier tubes in the manner described by Bell.[5] Due to the very energetic beta rays involved in the decay of I^{136}, it was necessary to use thick (3.34 g/cm²) polystyrene absorbers between the crystal and the sample which was axially centered 9.3 cm above the crystal surface. For pulse-height analysis both 20-channel and 256-channel analyzers were used.

A typical single-crystal gamma-ray spectrum of I^{136} is shown in Fig. 1. A spectral analysis of the gamma rays was made by using Gaussian shapes for the full-energy peaks and by matching the distributions of the Compton and pair peaks with standards run under similar experimental conditions. For simplicity, full spectral shapes of only the two most energetic gamma rays are shown. The long-lived iodine background was followed for some time after the 83-second I^{136} had become negligible. This contribution corrected for decay is represented by the broken line in Fig. 1. Almost all

* Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

[1] F. Strassmann and O. Hahn, Naturwissenschaften **28**, 817 (1940).

[2] W. Seelmann-Eggebert and H. J. Born, Naturwissenschaften **31**, 59 (1943).

[3] C. W. Stanley and S. Katcoff, J. Chem. Phys. **17**, 653 (1949).

[4] M. McKeown and S. Katcoff, Phys. Rev. **94**, 965 (1954).

[5] P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 5.

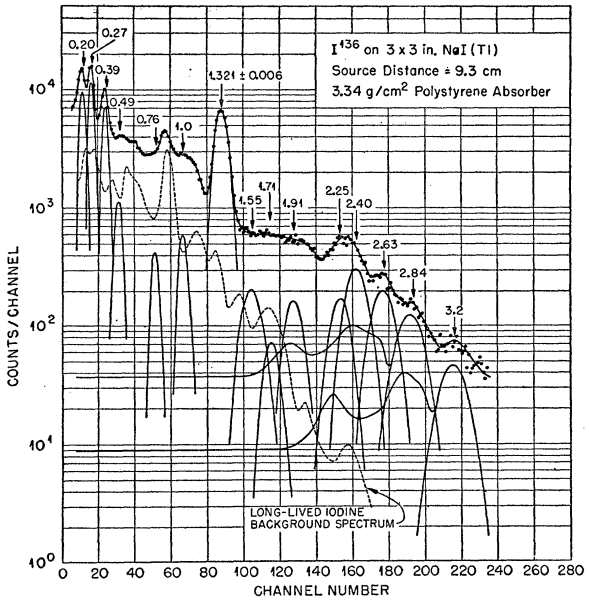

FIG. 1. Analysis of gamma-ray spectrum of I^{136}. For simplicity the complete pulse-height distributions of only the two most energetic gamma rays are shown.

of the background was due to 52-minute I^{134} with a very small contribution from 6.7-hour I^{135}.

At energies greater than 3.2 Mev, there is a poorly defined contribution which may either be due to summing or to other gamma rays. Since its nature was unknown, the general level of this contribution was subtracted from the entire spectrum. Such a procedure may strongly influence the accuracy of the intensity calculated for the 3.2-Mev transition. The 0.49-Mev peak, which is somewhat broader than expected at this energy, was later shown by coincidence experiments to be a composite of two gamma rays at 0.46 and 0.53 Mev.

The standards used for energy calibration were Cr^{51} (0.320 Mev), Y^{88} (0.908 and 1.851 Mev) and ThC″ (2.62 Mev). To avoid energy error as a result of rate-dependent gain shifts by the photomultiplier tube, the most prominent I^{136} peak was measured as 1.321 ± 0.006 Mev when the Y^{88} standard and the sample were counted simultaneously, and this value was used as a means of internal adjustment for the calibration curve.† The first column of Table I lists the best energy values for the gamma rays, and column 2 gives their intensities relative to the 1.32-Mev transitions. We feel that the intensities are accurate to 30% in all cases except for the 3.2-Mev gamma ray, which is probably within 40% of the true value.

From gamma-ray spectra recorded at various times, the heights of most of the peaks were found to decay with periods of approximately 80–90 seconds and to turn into longer-lived components characteristic of other iodine activities. Two notable exceptions were observed. The decay curve for the 0.27-Mev peak was resolved into a long-lived member, and 3.8-minute and 84-second components. Also, in a few cases when spectra were taken early, e.g., about 3 minutes after the irradiation, the 0.39-Mev full-energy peak appeared to consist of about 60-minute, 80-second, and 20-second species. Possible explanations are that there were metastable states involved or that the sample contained 22-second I^{137}, a delayed neutron emitter, and its daughter Xe^{137}. Natural xenon was irradiated in the reactor as a check on the latter hypothesis, and a prominent gamma ray at 0.26 Mev and another of slightly lower intensity at 0.45 Mev were observed to decay with a half-life of about 3.8 minutes. The entire 0.27-Mev peak in Fig. 1 cannot be attributed to Xe^{137} because there was no discernable 3.8-minute contribution at 0.45 Mev. The 22-second contribution to the 0.39-Mev gamma ray could be accounted for by a gamma transition at about that energy in levels of Xe^{137}, or possibly by delayed neutron emission from I^{137} into some of the same Xe^{136} levels populated by the I^{136} decay.

Gamma-gamma coincidence measurements were made using a "fast-slow" coincidence circuit with a resolving time of $2\tau=0.12$ μsec. The source, placed at the center of a collimating anti-Compton shield,[5] was

TABLE I. Summary of I^{136} gamma-ray data.

Gamma-ray energy, Mev	Single-crystal intensity relative to 1.32-Mev gamma rays	Gamma ray appeared in coincidence with: 1.32 Mev[a]	0.39 Mev[b]	0.20 Mev[b]
0.20 ±0.01	0.13	0.08	VS	?
0.27 ±0.01	0.19	?	?	?
0.39 ±0.01	0.20	0.11	W	VS
0.46 ±0.02	0.04	0.03	S (0.51 Mev)	?
0.53 ±0.02		0.03		
0.71 ±0.03	0.03	0.02	W	?
1.00 ±0.04	0.06	0.07	W	?
1.321±0.006	1.00[c]	0.44	VS	VS
1.55 ±0.04	0.04	0.06	?	?
1.72 ±0.05	0.02	0.04	?	No
1.91 ±0.05	0.05		?	No
2.25 ±0.07	0.07	0.12 (2.0 Mev)	?	No
2.40 ±0.07	0.13		?	No
2.63 ±0.05	0.11	No	?	No
2.84 ±0.08	0.08	No	?	No
3.2 ±0.1	0.05	No	?	No

[a] The values in this column give the ratio (intensity of the coincident γ)/(intensity of the 1.32-Mev γ in window).

[b] Since these data are considered primarily of qualitative value, only the general coincidence intensity is noted. The intensity symbols are VS = very strong, S = strong, W = weak, ? = data insufficient to determine if true coincidences are present, and No = no indications for coincidences.

[c] This intensity results from a cascade of two 1.32-Mev gamma rays to the ground state of Xe^{136}. The upper transition has 0.26 unit and the lower one 0.74 unit of the intensity (see Discussion).

† *Note added in proof.*—The error quoted for this measurement represents only the precision with which the I^{136} and Y^{88} gamma rays were compared. We have redetermined the energy of the low-energy gamma ray of Y^{88} as 0.899 ± 0.004 Mev by counting simultaneously with a source of Bi^{207} (0.5697 and 1.064 Mev) and with a source containing Cs^{137} (0.6616 Mev) and Co^{60} (1.1728 and 1.3325 Mev). The higher-energy gamma ray of Y^{88} was found to be 1.832 ± 0.006 using Na^{24} (1.368 and 2.754 Mev) as a standard. These results are in good agreement with unpublished measurements by R. L. Heath of 0.900 and 1.830 Mev. Using our new values for the energies of the Y^{88} gamma rays we obtain 1.307 ± 0.006 Mev for the energy of the prominent I^{136} peak, and the other gamma-ray energies of Table I should be adjusted accordingly.

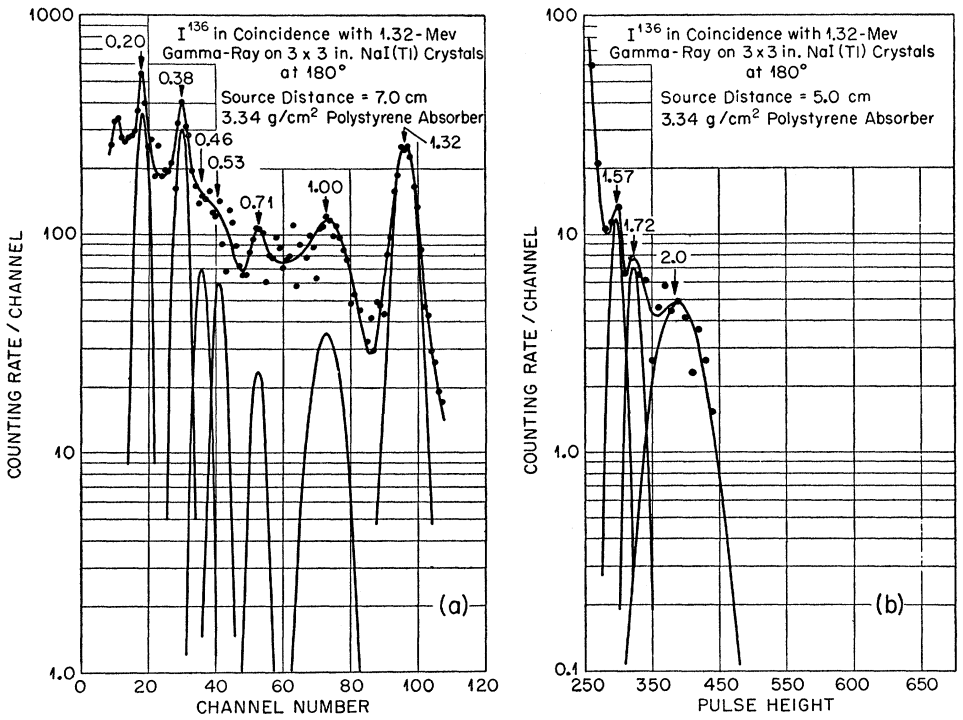

FIG. 2. I^{146} gamma-ray spectrum in coincidence with 1.32-Mev gamma rays. (a) Low-energy portion. (b) High-energy region.

viewed by two 3-inch×3-inch NaI crystals at 180° to each other.

The low-energy region of the spectrum coincident with 1.32 Mev was run at expanded amplifier gain and is shown in Fig. 2(a). Spectral analysis was accomplished in the manner described for the single-crystal data, although here the analysis was somewhat complicated by the poorer counting statistics. However, by assuming that the solid line drawn through the points is a reasonable representation of the gross shape, the analysis gave rather clearly resolved peaks with one exception, the region of 0.25–0.30 Mev which showed a broad distribution with a counting rate about 40% of the gross level. The most noteworthy feature of this spectrum is the strong 1.32-1.32-Mev coincidence intensity. Figure 2(b) shows the high-energy coincidence spectrum. The diffuse distribution at about 2 Mev could be explained by the three gamma rays at 1.91, 2.25, and 2.40 Mev. Both of these spectra have been corrected for random coincidences and any long-lived activity. Intensities of coincident gamma rays relative to the 1.32-Mev peak in the single-channel window were calculated in a manner similar to that described previously.[6] The calculation was somewhat simplified since the 1.32-Mev gamma ray comprised about 97% of the total I^{136} counts through the single-channel analyzer, making corrections for the small remaining contribution unnecessary. Column 3 of Table I lists the number of coincident gamma rays per count in the window due to the 1.32-Mev gamma ray.

[6] N. R. Johnson and G. D. O'Kelley, Phys. Rev. **108**, 85 (1957).

Figure 3 shows the gamma-ray spectrum in coincidence with the single-channel window set at 0.39 Mev. The broken curve is the contribution of long-lived iodine activities present in the sample. There is some evidence for coincidences at about 1.6 Mev and possibly at even higher energies, but poor statistics limited the analysis to gamma rays through 1.32 Mev. The Compton background contribution in the window from other I^{136} gamma rays is quite appreciable, and as there are some uncertainties in the detailed features of the decay scheme, it is not possible to compute reliable values for the number of coincidences per 0.39-Mev gamma ray. The utility of the 0.39-Mev gamma-gamma coincidence data is, therefore, mainly qualitative. It should be mentioned, however, that the 0.39- and 0.75-Mev peaks which are seen in Fig. 3 can be accounted for by Compton pulses in the window using the proposed decay scheme of Fig. 6. A summary of the gamma rays coincident with the 0.39-Mev peak is listed in column 4 of Table I. With the single-channel window covering the 0.27-Mev region, the observed coincidence spectrum could be explained by Compton pulses from higher-energy gamma rays. In a final gamma-gamma coincidence experiment the window as set on the 0.20-Mev peak, and two prominent gamma rays were observed at 0.39 and 1.32 Mev, with essentially no coincidence contribution beyond about 1.4 Mev. Once again complete spectral analysis was impractical as a result of unfavorable counting statistics. The relative numbers of 1.32- and 0.39-Mev gamma rays per 0.39-Mev event in the window were

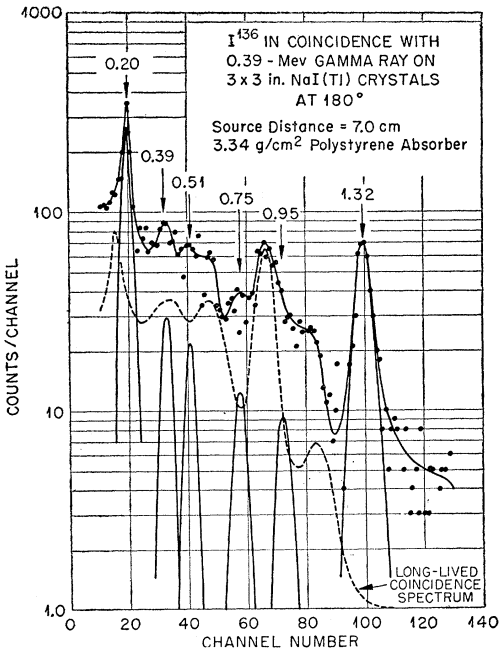

FIG. 3. I^{136} gamma rays coincident with 0.39-Mev gamma ray.

about 1 and 0.5, respectively. These coincidence data are summarized in Table I, column 5.

It should be mentioned that in all coincidence experiments, both beta-gamma and gamma-gamma, the spectrum discussed was the result of summing the data for several consecutive bombardments in which the contributions from both long-lived coincidence backgrounds and random rates have been removed.

IV. BETA-RAY SPECTROMETRY

Beta-ray spectra also were determined by the scintillation method in which a cylindrical anthracene crystal $1\frac{1}{4}$ inch in diameter and 1 inch long was attached to a Dumont 6292 photomultiplier tube surrounded by specular reflector. A cylindrical beta spectrometer crystal was adequate for this investigation, because the fraction of electrons scattered from the surface is small for these high energies.

The chemical procedure used for the rapid separation of iodine radioactivity from fission products led to rather thick sources for beta-ray spectrometry. Sources of about 2 mg/cm^2 of silver iodide precipitate were both supported and covered by layers of polyester film[7] with 6.5 mg/cm^2 surface density. In addition, the sources were sometimes supported on about 9 mg/cm^2 filter paper.

Energy calibration of a beta scintillation spectrometer to several Mev is very difficult, since there are no convenient monoenergetic internal conversion lines above about 1 Mev. The energy scale for the I^{136} beta-ray measurements was established in the following way: a series of internal conversion electron sources, usually Hg^{203} (0.193, 0.264 Mev), Ba^{137m}(0.624 Mev), and Bi^{207} (0.482, 0.976 Mev), were employed to calibrate the multichannel analyzer using an amplifier gain such that one Mev was almost full scale on the analyzer. An equation expressing the linear relationship between beta energy in Mev and analyzer pulse height units was derived from these measurements. Using a precision pulse generator, the gain of the amplifier was reduced by a measured factor (usually 10), whence it was only necessary to increase the slope of the Mev-pulse height equation by the appropriate amount to obtain the new calibration. This technique has been checked by measuring the 4.71-Mev beta-ray group of Br^{84} and the Compton distribution from the gamma rays of N^{16} at 6.13 Mev and Br^{84} at 3.93 Mev. All measurements agreed with these reported values to about 1%.

Fermi analysis of the beta spectrum shown in Fig. 4 yielded components of 7.00±0.10, 5.62±0.15, and 4.30±0.15 Mev. The analysis was not extended to lower energies because of spectral distortions caused by the thick sources and uncertainties in correcting for the large gamma-ray background. As the entire spectrum was not analyzed, only the relative intensities of the resolved groups could be obtained, as follows: $I(7.0\text{-Mev}\beta):I(5.62\text{-Mev}\beta):I(4.3\text{-Mev}\beta)=0.1:1.0:3.6$.

Beta-gamma coincidence spectrometry serves not only to elucidate the positions of gamma rays in a decay scheme, but also to determine the "inner" beta groups more accurately than is possible by analysis of the single-crystal spectrum. If an intense and energetic gamma-ray distribution is also present, the beta-gamma coincidence technique generally yields an interpretable spectrum undistorted by summing effects.

The same electronic system as mentioned above for gamma-gamma measurements was used for the beta-

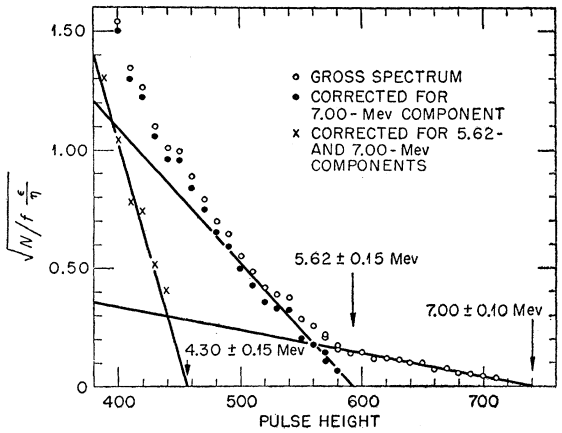

FIG. 4. Fermi analysis of the high-energy region of the I^{136} beta-ray spectrum.

[7] Polyester Tape Number 850, available from Minnesota Mining and Manufacturing Company, 800 Bush Avenue, St. Paul, Minnesota.

gamma experiments, except that the $1\frac{1}{4}$-inch×1-inch anthracene crystal spectrometer was connected to one channel and a 3-inch×3-inch NaI spectrometer to the other. The "fast-slow" coincidence circuit could be arranged to display on a multichannel analyzer the pulse-height distribution of either channel gated by the other.

Placement of the 7.00- and 5.62-Mev beta-ray groups was first investigated by recording gamma-ray spectra coincident with them. With the single-channel analyzer set to accept electrons greater than 5.8 Mev, no coincident gamma rays were observed above the random background. This demonstrates that the 7.00-Mev beta transition decays to the ground state of Xe^{136}. When the single-channel analyzer was set to record beta rays above 4.5 Mev, a few coincident gamma rays were seen at 1.32 Mev, suggesting that the 5.62-Mev beta component decays to the first excited state of Xe^{136} at 1.32 Mev.

Beta-ray spectra in coincidence with the prominent gamma rays were measured also. The beta-ray spectrum obtained in coincidence with the intense 1.32-Mev gamma rays was analyzed into components of 5.60±0.15, 4.23±0.20, and 2.73±0.20 Mev, as shown in Fig. 5. Agreement between the single-crystal beta energies and those of the first two coincident beta components is quite good. An attempt was made to observe the beta rays coincident with the 0.39-Mev gamma ray. Although a component of 3.5–4.0 Mev appeared in coincidence, its analysis was made difficult by the beta coincidences with the many Compton electrons in the window from the 1.32-Mev gamma rays.

V. DISCUSSION

A decay scheme incorporating most of the above experimental observations is shown in Fig. 6. Since no gamma rays were in coincidence with beta rays greater than 5.8 Mev, the 7.00-Mev beta transition is assumed

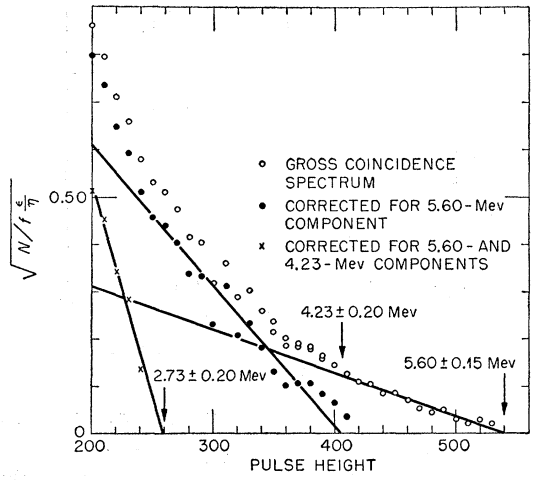

FIG. 5. Fermi analysis of I^{136} beta-ray spectrum coincident with 1.32-Mev gamma rays.

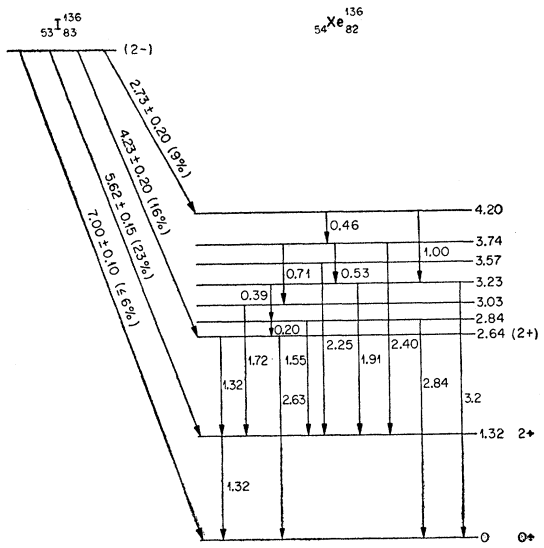

FIG. 6. Decay scheme proposed for I^{136}. Energy values are in Mev. The percentage branching for the beta rays was determined from gamma-ray intensities. Only intensities of the observed beta rays are shown.

to proceed to the ground state of Xe^{136} and to represent the I^{136}-Xe^{136} mass difference. The appearance of a 5.62-Mev beta group in coincidence with a 1.32-Mev gamma ray, as well as the observation of a 1.32-Mev gamma peak in coincidence with beta particles greater than 4.5 Mev, establishes the first excited level at 1.32 Mev. Placement of the second excited level at 2.64 Mev is based both on the 1.32-1.32 Mev gamma-gamma and the 1.32-4.23 Mev gamma-beta coincidences. The experiment showing a 2.73-Mev beta ray in coincidence with 1.32-Mev gamma rays implies a level at about 4.2–4.3 Mev. Absence of coincidences between 1.32-Mev and the gamma rays at 2.84- and 3.2-Mev suggests levels at these energies. The 0.27-Mev gamma ray was not included because it did not appear prominently in the coincidence experiments, and hence may have arisen from a metastable state or from Xe^{137}. The remaining gamma transitions have been arranged in the level scheme which may contain ambiguities because of the qualitative nature of some of the data.

Relative beta intensities from the Fermi analysis of the single-crystal data, together with relative gamma intensities and the decay scheme, may be used to compute the relative intensities of the two 1.32-Mev gamma rays. Using 1.00 unit for the total 1.32-Mev intensity (see Table I), 0.30 unit may be assigned to the upper cascade gamma ray by this method. The 1.32-1.32 Mev gamma-gamma coincidence data indicate that the intensity of the upper transition is 0.22 units. Since both intensities are thought to be accurate to 20%, they are in agreement, and their mean value, *viz.* 0.26, was used in the calculation of absolute beta intensities shown below. A measurement of the number of 1.32-

Mev gamma rays per disintegration was made using a gamma scintillation spectrometer simultaneously with a 4π beta proportional counter. After correcting for long-lived activities which were also detected in the 4π counter, the number of 1.32-Mev gamma rays per disintegration was determined as 0.95 ± 0.10. It then was possible to compute absolute beta intensities using only the decay scheme and the gamma-ray intensities. This procedure is expected to give more precise results than those computed from the Fermi analysis of the beta spectrum, as the latter is subject to errors from the thick sources and instrumental effects such as summing. Beta intensities and the corresponding comparative half-lives for the three most energetic beta groups were 7.00 Mev (6%), $\log ft=8.1$; 5.62 Mev (16%), $\log ft=7.2$; 4.2 Mev (23%), $\log ft=6.5$. The intensity of the 7.00-Mev beta group is very sensitive to the precision of the gamma-ray intensity determinations, and we feel that the quoted beta intensity is probably an upper limit.

It is interesting to attempt an identification of the ground state spin of I^{136} which contains 53 protons and 83 neutrons. A reasonable assumption is that there will be little interaction between the odd neutron and the rigid 82 neutron core and, therefore, that it probably has $f_{7/2}$ character. Its even-odd isotonic neighbors whose spins have been measured (Ba^{139}, Ce^{141}, and Nd^{143}) follow such an assignment. The spin contribution from the three protons beyond the closed shell is not so simply defined because three of the lighter isotopes (I^{123}, I^{125}, and I^{127}) have measured spins of $\frac{5}{2}+$, whereas the measured value of I^{129} and I^{131} is $\frac{7}{2}+$. However, one can hope to gain some information from a review of the ideas pertinent to these assignments. De-Shalit and Goldhaber[8] have pointed out that, as neutrons of the iodine isotopes fill the $h_{11/2}$ orbitals, the additional neutron pairs produce a stabilizing effect on the $g_{7/2}$ proton state (this effect is most pronounced when $l_n \approx l_p$). Although recent measurements of the quadrupole and magnetic moments of I^{125} indicate a predominantly $d_{\frac{5}{2}}$ configuration for its ground state,[9] the stabilizing effect of an additional $h_{11/2}$ neutron pair can be seen in I^{127}. Here the large deviation of the I^{127} magnetic moment from the Schmidt value for a $d_{\frac{5}{2}}$ proton indicates some contribution from a proton configuration of $(g_{7/2})_{\frac{5}{2}}^3$. By the time the 76th and 78th neutrons have filled in I^{129} and I^{131}, respectively, the $g_{7/2}$ proton state almost certainly predominates. Accordingly, it would not seem unreasonable to extrapolate to the case of I^{136} and assume that the proton contribution is mainly $g_{7/2}$ in character. Then when it is coupled with an $f_{7/2}$ neutron a 0− ground state should result for I^{136}. However, this assignment seems improbable since it would indicate that the beta transition to the 2+ first excited level in Xe^{136} would be more forbidden than that to the 0+ ground state, contrary to the experimental observation. If, on the other hand, an $f_{7/2}$ neutron couples with given configurations of $(g_{7/2})^3$ protons, states of 1− or 2− could result. The $\log ft$ of 8.1 for the beta group to the 0+ ground state of Xe^{136} is consistent with a 2− assignment.

Since Xe^{136} is an even-even nuclide, spin assignments of 0+ and 2+ can be made for the ground and first excited states respectively. Comparative half-lives for the beta transitions to the 1.32- and 2.64-Mev levels are compatible with spin 2 and even parity for each state.

The behavior of low-lying levels in even-even nuclei has been interpreted in terms of two types of collective motion, a "free vibration" model by Scharff-Goldhaber and Weneser[10] and a "shape unstable" model by Wilets and Jean.[11] The latter authors used the equations of Bohr and Mottelson[12] to calculate a value of 0.78 for $E_1/\hbar\omega$ for Xe^{136}, where E_1 is the energy of the first excited state (they used $E_1=1.4$ Mev) and ω is the characteristic phonon frequency of a statistically undeformed nucleus. When corrected to our observation of $E_1=1.32$ Mev the ratio $E_1/\hbar\omega$ becomes 0.74. This large value considered with the ratio $E_2/E_1=2$, probably indicates very nearly pure harmonic quadrupole vibration of the core, with a very small coupling contribution from the four protons beyond the closed shell. As has been stressed by Scharff-Goldhaber and Weneser,[10] for such cases the cascade process between the second and first excited levels proceeds by $E2$ radiation with only a very small $M1$ admixture.

In Fig. 7 we have shown a comparison of the I-Xe mass differences in the manner used by Way and Wood.[13] Here the mass difference of the isobaric pairs

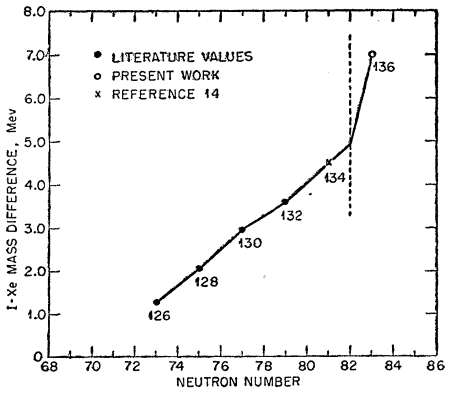

FIG. 7. I-Xe mass differences as a function of the iodine neutron number.

[8] A. De-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).
[9] P. C. Fletcher and E. Amble, Phys. Rev. **110**, 536 (1958).
[10] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[11] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).
[12] A. Bohr and B. Mottelson, Kgl. Danske Videnskab. Selskab., Mat.-fys. Medd. **27**, No. 16 (1953).
[13] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

has been plotted as a function of the neutron number of the iodine member. For masses 126–132 the Q_{β^-} values listed in the table of Strominger, Hollander, and Seaborg[14] have been used. The value for mass 134 is taken from Cameron's table of mass excesses and decay energies,[15] and that for 136 is from the present work. These data emphasize the discontinuity in decay energy associated with the closing of the 82-neutron shell.

[14] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585–904 (1958).
[15] A. G. W. Cameron, Atomic Energy of Canada Limited, Report CRP-690, 1957 (unpublished).

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Cloud-Chamber Measurement of the Half-Life of the Neutron*

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The half-life of the free neutron has been measured by a cloud-chamber method. It turned out to be 12.7 min with an error of ~15%, ~10% being due to the poor statistics. This determination has about the same accuracy as the best previous measurement and confirms it by an independent method.

I. INTRODUCTION

THE beta decay of the neutron, which was first predicted by Chadwick and Goldhaber,[1] was observed by Snell and Miller[2] in a neutron beam from the Oak Ridge pile. Snell, Pleasanton, and McCord[3] detected coincidences between electrons and low-energy positive particles of approximately the mass of the proton. By a spectrometer method, Robson[4–6] showed the positive particles to be protons and was able to get the energy distribution of the electrons. He found the half-life for neutron decay to be 12.8 minutes, with an error of ±2.5 minutes. The problem was also taken up by Spivak *et al.*[7] Their first measurements gave the half-life in the range 8–15 minutes. The accuracy was then increased and a half-life of 12±1.5 minutes was obtained. In all the above measurements, the products of the decay were detected by means of counters. Protons were accelerated by electrostatic fields and the errors were due mainly to the uncertainty in the value of the collection factor.

It seemed then of some interest to repeat the measurement of the neutron half-life by using a completely different method and trying to eliminate the uncertainty introduced by the collection factor. The idea of the experiment described in this paper is the following. (See Fig. 1.) A neutron beam from the Argonne CP-5 reactor is freed from gamma rays and is sent through the sensitive region of a diffusion chamber where the events occurring are photographed at a rate of, say, two frames per second. The number of recorded electrons which can be attributed to neutron decays should give the half-life when the neutron density in the chamber is known from activation measurements.

No problems should arise in finding the collection factor of the decay products. On the other hand, background problems more serious than those faced by other authors have to be overcome. All the possible sources of background electrons have to be reduced to an acceptable level. They are expected to come mainly from (1) gamma rays from the room background, (2) gamma rays in the neutron beam, and (3) gamma rays produced by neutron captures in the walls of the cloud chamber or in the surrounding materials.

A heavy lead housing shields the cloud chamber and a neutron mirror reduces the gamma rays in the beam to a tolerable level. Materials with low absorption cross section for thermal neutrons are used in the construction of the cloud chamber. Very thin Mylar windows at the entrance and exit of the neutron beam from the chamber also reduce the electron background caused by (3).

In the following sections we shall describe (a) the diffusion chamber, (b) the method of obtaining a suitable beam, (c) the shielding of the chamber, (d) the operation of the chamber, (e) the experimental results, and (f) the conclusions.

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[1] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. (London) **A151**, 479 (1935).
[2] A. H. Snell and L. C. Miller, Phys. Rev. **74**, 1217 (A) (1948).
[3] Snell, Pleasanton, and McCord, Phys. Rev. **78**, 310 (1950).
[4] J. M. Robson, Phys. Rev. **77**, 747 (1950).
[5] J. M. Robson, Phys. Rev. **78**, 311 (1950).
[6] J. M. Robson, Phys. Rev. **83**, 349 (1951).
[7] Spivak, Sosnovsky, Prokofiev, and Sokolov, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva*, 1955 (United Nations, New York, 1956), Paper No. 650.