the amount necessary to account for the hindrance factor. In fact, Swiatecki has pointed out that the fission threshold energies deduced from spontaneous fission lifetimes are consistent with the systematics established in induced fission.

ACKNOWLEDGMENT

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Decay of I^{134}

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The decay properties of 53-min I^{134} have been investigated with scintillation techniques as part of a program for the systematic study of xenon energy levels. Energies (and intensities) of the gamma rays determined from the single-crystal and coincidence studies are 0.135 (3.2), 0.18, 0.23, 0.27, 0.32, 0.39 (7.2), 0.41 (0.6), 0.43 (2.9), 0.51 (0.9), 0.54 (8.4), 0.61 (19), 0.69 (7.3), 0.75 (1.3), 0.77 (6.0), 0.848 (100), 0.864 (4.6), 0.890 (74), 0.96 (2.0), 1.00 (4.7), 1.07 (18), 1.15 (10), 1.28 (1.4), 1.34 (1.5), 1.46 (3.7), 1.49 (1.0), 1.62 (4.9), and 1.79 (4.9) Mev. There are two gamma rays at each energy of 0.89 and 1.07 Mev. The single-crystal spectra were corrected experimentally for gamma-ray summing. Gamma coincidence spectra were measured by gating at energies of 0.135, 0.41, 0.61, 0.85, 0.89, 1.00, 1.07, 1.15, 1.46, 1.62, and 1.79 Mev in the gamma-ray spectrum. Beta-ray spectra were measured in coincidence with gamma rays at 0.85, 1.00, 1.07, 1.15, 1.46, 1.62, and 1.79 Mev. These measurements and the single-crystal data disclosed beta rays with end-point energies of 2.41, 2.21, 1.68, 1.49, 1.25, and 1.05 Mev. In a three-crystal "beta-gamma-gamma" experiment the 2.41-Mev beta-ray group was shown to populate a level in Xe^{134} at 1.74 Mev; therefore, the energy difference between the ground states of I^{134} and Xe^{134} is 4.15 ± 0.06 Mev.

A decay scheme is proposed with energy levels (and spins) in Xe^{134} at 0.85 (2+), 1.62 (2+), 1.74 (4+), 1.92, 2.34, 2.43, 2.48, 2.64, 2.88, 3.11, 3.30, and 3.41 Mev. A collective nature of the low-lying levels is suggested in that the 1.62- and 1.74-Mev states appear to be members of a "vibrational" doublet at about twice the energy of the first excited state.

The half-life of I^{134} was redetermined as 52.8 ± 0.3 min.

I. INTRODUCTION

IN recent years there have been a number of attempts to systematize and explain the low-lying levels of even-even nuclei in the medium-weight ($A=40$–140) region. Although a large quantity of experimental information has been accumulated, in only a few cases have the levels of more than two or three nuclides of the same Z been thoroughly investigated. The even xenon isotopes show promise for a systematic study of thos sort, since their excited states are abundantly populated by beta-decay from iodine nuclides of convenient half-life. In addition to the earlier work[1] on xenon nuclides with $A=126$, 128, 130, and 132, recent research at this laboratory[2–4] has been performed on the decay of I^{130}, I^{132}, and I^{136}. With this report of the results of experiments on levels in Xe^{134} from the decay of I^{134}, the even xenon isotopes form one of the largest sets of well-characterized energy levels of a given family. The nuclide Xe^{134} is of great interest since its heavier near-neighbor Xe^{136} is a closed-shell nuclide, but one which exhibits a surprising "vibrational" behavior. The low-lying levels of its lighter, near-neighbor Xe^{132} also appear to have a collective nature. As will be seen, Xe^{134} seems to possess a similar level structure with a doublet of 2+ and 4+ character at an energy of approximately twice that of the first 2+ state.

Abelson[5] found a new 54-min iodine activity among the products of uranium fission, and demonstrated that it was the daughter of a tellurium isotope with a 43-min half-life. Katcoff, Miskel, and Stanley[6] assigned the 54-min period to I^{134} by fission-fragment range measurements.

The first detailed investigation of the radiations from I^{134} was reported by McKeown and Katcoff.[7] The gamma-ray spectrum obtained by these investigators showed an intense gamma ray at 0.86 Mev, which was interpreted as the de-excitation of the first excited state of Xe^{134}. Additional gamma rays were found at 0.120, 0.200, 1.10, and 1.78 Mev. The most energetic beta component was found to have an energy of 2.5 ± 0.2 Mev, and to be in coincidence with the intense 0.86-

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‡ Operated by Union Carbide Nuclear Company for the U. S. Atomic Energy Commission.

[1] Nuclear Data Sheets, National Academy of Sciences—National Research Council, Washington, D. C.
[2] I^{130}: W. G. Smith, P. H. Stelson, and F. K. McGowan, Phys. Rev. **114**, 1345 (1959).
[3] I^{132}: R. L. Robinson, E. Eichler, and N. R. Johnson (to be published).
[4] I^{136}: N. R. Johnson and G. D. O'Kelley, Phys. Rev. **114**, 279 (1959).
[5] Philip Abelson, Phys. Rev. **56**, 1 (1939).
[6] S. Katcoff, J. A. Miskel, and C. W. Stanley, Phys. Rev. **74**, 631 (1948).
[7] M. McKeown and S. Katcoff, Phys. Rev. **94**, 965 (1954).

Mev gamma ray. Another beta ray of energy 1.5 Mev was in coincidence with gamma rays above 0.9 Mev.

While the work by the present authors was in progress, an extension of the available information on I^{134} was reported by Holm and Ryde,[8] who found gamma rays at 1.80, 1.62, 1.45, 1.3, 1.14, 1.07 0.86, 0.63, 0.42, 0.21, and 0.138 Mev. The peak at 0.86-Mev was observed to be wider than a peak due to a single gamma ray, and 0.86−0.86-Mev coincidences were observed. The beta-ray spectrum was complex, with a maximum energy of 2.35±0.15 Mev, and "inner" groups of 1.57 and 1.3 Mev. Coincidence experiments indicated that either or both 0.86-Mev gamma rays were in coincidence with the 2.35-Mev beta ray. From beta-decay systematics, Holm and Ryde correctly surmised that the 2.35-Mev beta group decayed to the level in Xe^{134} at about 1.7 Mev.

II. SOURCE PREPARATION AND HALF-LIFE DETERMINATION

A principal difficulty in producing I^{134} sources is the elimination of other iodine activities. Because of the distribution of tellurium half-lives, it is possible to separate I^{134} from its fission-product tellurium parent with only a few percent of 21-hr I^{133} as the principal contaminant, provided the length of irradiation and the time of the tellurium isolation are chosen appropriately. This method excludes 6.7-hr I^{135}, which is the major interference when an iodine fraction is separated directly from fission.

The I^{134} sources for this study were prepared by irradiating a uranyl nitrate solution containing 2.6 g of natural uranium for one minute in the Oak Ridge graphite reactor. After irradiation, the pneumatic transfer "rabbit" containing the liquid sample was ejected from the reactor, and dropped into a shield for two minutes to enhance the yield of Te^{134} by decay of 0.6-min Sb^{134}. A needle punctured the sample capsule and the liquid was transferred pneumatically to a separatory funnel, in which the fission products were contacted with freshly preciptated tellurium together with iodide and bromide "holdback" carriers.

After separation from the fission products, the tellurium was dissolved in nitric acid. Carrier iodide was added and oxidized to periodate in basic sodium hypochlorite solution (necessary for complete iodine exchange); then the periodate was reduced to iodide with sodium metabisulfite. Sodium nitrite produced free iodine which was extracted into carbon tetrachloride. This iodine fraction, which contained the unwanted I^{135}, was discarded, and after a suitable growth period (about 50 min), the separation was performed again. The activity finally was reduced and precipitated as silver iodide. At the time of the first count the sample usually consisted of about 95% I^{134} and 5% I^{133}.

[8] G. Holm and H. Ryde, Arkiv Fysik **15**, 387 (1959).

The I^{134} half-life measured with an end-window beta proportional counter was 52.8±0.3 min.

III. GAMMA-RAY SPECTROMETRY

Gamma-ray spectra were measured with 3-in.×3-in. cylindrical NaI crystals mounted on Dumont 6363 photomultiplier tubes. Polystyrene absorbers (1.33 g/cm²) were used to stop the beta rays and a 256-channel analyzer was used for pulse-height analysis.

Single-Crystal Spectra

The single-crystal gamma-ray spectrum (high-energy portion) taken at a source-to-detector distance of 9.3 cm is shown in Fig. 1. Decomposition of the spectrum was made by using Gaussian shapes for the full-energy peaks and by matching the distribution of the Compton and pair peaks with standards run under similar experimental conditions. For simplicity, full spectral shapes of only a few of the gamma rays are shown. The dashed curve represents the long-lived background which is almost totally 21-hr I^{133}, and the broken line is the contribution from the coincident or "real" summing of cascade events coupled with the random summing of noncorrelated radiations. The method for determining this sum spectrum is discussed below.

The analyzed peaks at 1.46, 1.62, and 1.79 Mev are broader than those expected at these energies. Also, the valleys between these peaks and the region above 2 Mev show appreciable residuals. If the summing has been properly accounted for, then it would appear that there are additional gamma rays in the spectrum and/or an appreciable level of bremsstrahlung to be accounted for.

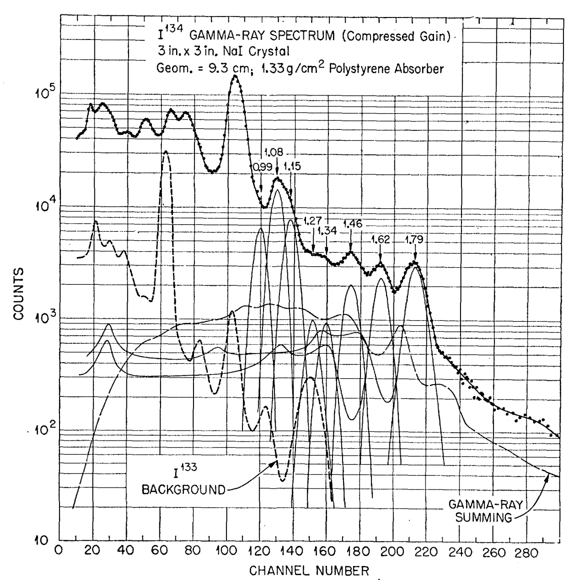

FIG. 1. Gamma-ray spectrum of I^{134}. Low amplifier gain was used to emphasize the high-energy portion. The contribution from coincident gamma-ray summing was measured as discussed in the text. For simplicity the complete pulse-height distributions of only the two most energetic gamma rays are shown.

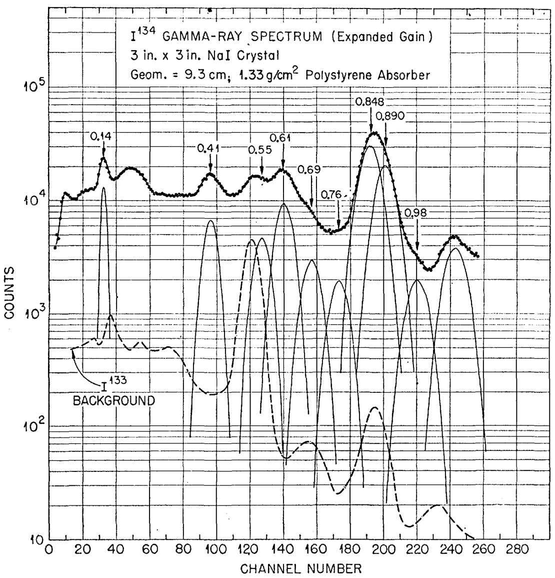

FIG. 2. Gamma-ray spectrum of I^{134}. Amplifier gain was increased to show details of the low-energy part of the spectrum. Contributions due to gamma-ray summing and Compton spectra of higher-energy gamma rays are not shown in the figure, but were used in the analysis.

The low-energy portion of the spectrum taken at increased gain is shown in Fig. 2. The widths of the 0.41-, 0.55-, and 0.61-Mev peaks indicate that there may be more than one gamma ray at about these energies. Also, there is some evidence for another gamma ray in the vicinity of the backscatter peak. To check this latter point a lead collimator was placed between the source and detector, and the resulting spectrum showed an additional gamma ray at about 0.22 Mev. Using a $\frac{1}{8}$-in. thick NaI detector to reduce the contributions from high-energy gamma rays, it was possible to define more clearly the lowest-energy peak in Fig. 2 and to establish its energy as 0.135 Mev.

To avoid energy error as a result of counting rate-dependent gain shifts, the I^{134} source was counted simultaneously with standard sources of Na^{22} and Cs^{137}. In this manner three of the peak positions in the I^{134} gross spectrum were found to be at 0.862 ± 0.007, 1.075 ± 0.010, and 1.789 ± 0.015 Mev. These values were then used as a means of internal adjustment for the calibration curve. In the first column of Table I we list the best energy values for the resolved gamma rays and in Col. 2 their single-crystal intensities relative to the 0.85-Mev transitions.

Sum Spectra

As seen in Fig. 1, the summing contribution produces considerable distortion and complication of the desired gamma-ray spectrum. Experimentally this distribution has been accounted for by utilizing a modification of the sum-coincidence circuit of Hoogenboom[9] as shown in Fig. 3. The gains of the two NaI-crystal-photomultiplier assemblies were matched and their outputs summed in the linear adder. The amplified sum pulses were then fed to a 256-channel pulse-height analyzer and the photomultiplier outputs were also fed to a coincidence mixer which gated the analyzer each time a sum event occurred in the two crystals.

Tests were performed with standard sources such as Cr^{51} and Co^{60}. Their single-crystal spectra were first measured so that the energy region above the photopeaks might be compared with the experimental sum spectrum obtained with the apparatus described in the preceding paragraph. In the case of Co^{60} it was found that the sum spectrum, which is almost completely due to "real" summing of cascade gamma rays, could be duplicated rather precisely with the apparatus of Fig. 3. With a Cr^{51} source, where the sum spectrum is comprised of randomly summed events, it was found necessary to adjust the resolving time to about 1 μsec so that the height of the experimental sum peak matched that observed in a single-crystal spectrum. However, the region between the sum peak and the photopeak was lower than that of the single-crystal spectrum; but when the decay scheme involves many cascade events, as is the case with I^{134}, this small discrepancy becomes negligible. The counting time required in a summing experiment of this type is one-half that for a single-crystal case due to the doubled detector geometry. The prominent sum peaks observed for I^{134} by this method are in qualitative agreement with those obtained with a 3-in.×3-in. NaI well crystal.

Gamma-Gamma Coincidence Spectra

For the gamma-gamma coincidence measurements, the source was placed at the center of a collimating anti-Compton shield and was viewed by two 3-in.×3-in. NaI crystals at 180° to each other. A "fast-slow" coincidence circuit having a resolving time, 2τ, of 0.19 μsec was used to gate the 256-channel analyzer. Spectral analysis was performed in the same manner as described for the single-crystal data.

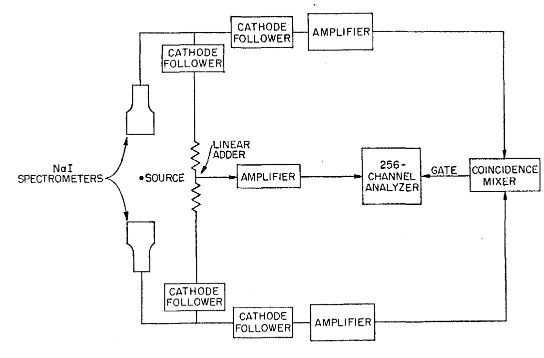

FIG. 3. Block diagram of the apparatus used to measure gamma-ray sum spectra.

[9] A. M. Hoogenboom, Nuclear Instr. 3, 57 (1958).

TABLE I. Summary of I^{134} gamma-ray data.

E_γ (Mev)	Singles intensity[b]	"Coincidence quotient"[a] with gamma rays of energy (Mev): 0.135	0.41[c,d]	0.61	0.85[c]	0.89[c]	1.00[c]	1.07[c]	1.15	1.46[c]	1.62[c]	1.79	0.86 − 0.86 Mev Sum pulses
0.135 ±0.005	3.2 ±0.8		Strong	0.12	0.038	0.038	0.012	0.026	0.01	0.049			0.040
0.18 ±0.01													0.029
0.23 ±0.01					0.019	0.013		0.034					0.058
0.27 ±0.01													0.044
0.32 ±0.02							0.021	0.021					
0.39 ±0.01	}			0.17	}	}			0.01[h]				
0.41 ±0.01	} 8.2 ±3.7	0.71	Weak		} 0.10	} 0.096	0.10		0.025	0.11			0.078
0.43 ±0.01	}				}	}		0.16					
0.51 ±0.02	} 8.4 ±2.8								0.036				
0.54 ±0.02	}			0.31	0.12	0.11			0.049[i]	0.23			0.044
0.61 ±0.02	20 ±4	0.64	Strong		0.19	0.20	0.12	0.077	0.049				0.19
0.69 ±0.03	7.3 ±3.0	0.043			0.048	0.053							0.076
0.75 ±0.02	} 5.5 ±2.6				} 0.056						0.12		
0.77 ±0.02	}				}		0.33	0.083					
0.848 ±0.009	100	1.06	} Very strong[e]	1.16	0.29	1.02	0.93	1.03	0.79	1.01		0.6	
0.864 ±0.014			}								0.42		
0.890 ±0.009[c]	74 ±8	0.88	}	0.69	0.69	0.074[f]			0.76				0.31[f]
0.96 ±0.03							0.14[g]	0.12					
1.00 ±0.02	7.0 ±3				0.046	0.033				0.087	0.46		
1.07 ±0.02[c]	18 ±3	0.20	Weak	0.13	0.18	0.046	0.23		0.04	0.23			
1.15 ±0.02	10 ±2				0.10	0.13					0.040		0.17
1.28 ±0.05	1.4 ±0.7	0.065			0.035								
1.34 ±0.05	1.5 ±0.8				0.022								
1.46 ±0.03	} 3.6 ±1.4			0.062	0.046			0.064					
1.49 ±0.03	}										0.093		
1.62 ±0.03	4.9 ±1.5				0.022		0.31			0.13			
1.79 ±0.02	6.6 ±2.0				0.049								

[a] If there is no number shown for the "coincidence quotient," it can mean either that there was no evidence for a coincident peak or that there was possibly a small indication for it, but the nature of the data made its inclusion in the table questionable.
[b] Relative to the 0.848-Mev gamma ray as 100 units. The intensities shown here are those obtained from the single-crystal experiments, whereas the intensities shown in the decay scheme are the best values determined from both the single-crystal and coincidence data.
[c] There is evidence for multiple gamma rays with about this energy.
[d] Since the data from this experiment are considered primarily of qualitative value, only a relative indication of the "coincidence quotients" is shown.
[e] This peak was very broad and appeared to include both the 0.85- and 0.89-Mev gamma rays. It is not possible to tell, but it could also include the 0.86-Mev gamma ray.
[f] The $q_{0.89,0.89}$ value of 0.074 yields 3.7 units of intensity for the upper member of a 0.89–0.89-Mev gamma-ray cascade (see Fig. 15). An intensity of 8.5 units is obtained for this same gamma-ray transition from the "three-crystal" (gamma-gamma-gamma) experiment where the observed "coincidence quotient" is 0.31. The average value of ~6 is shown in the decay scheme.
[g] The energy observed for this peak was 0.93 Mev.
[h] The energy observed for this peak was 0.36 Mev.
[i] The energy observed for this peak was 0.51 Mev.

Often a gamma peak may appear prominent in a coincident spectrum and yet in the summary of gamma-gamma coincidence information in Table I it may be shown strikingly reduced and occasionally not be listed at all. This is a result of removing the coincidence contribution from higher-energy gamma rays which give Compton events falling in the single-channel window. The analytical method involved is discussed below.

Coincidence data are conveniently discussed in terms of "coincidence quotients", q, the ratio of the number of coincident gamma rays of interest to the number of "gating" gamma rays in the single-channel window. The expression used to obtain these values is given in Eq. (1) in a slightly modified form of that used previously.[10]

$$q_{1,2}=\left[\frac{P_1e^{\mu d}}{C_w\epsilon_1\Omega}-\sum_i q_{1,i}D_i\bar{W}_{1,i}(\theta)\right]\frac{1}{D_2\bar{W}_{1,2}(\theta)},\qquad(1)$$

where $q_{1,2}$ is the number of events of γ_1, the gamma ray of interest, in coincidence with γ_2, divided by the number of counts due to γ_2 (the "gating" event of interest) in the single-channel window; P_1 is the coincident peak area of γ_1; $e^{\mu d}$ corrects for the fraction of γ_1 absorbed by any material in its path; ϵ_1 and Ω are the peak efficiency and solid angle for the detection of γ_1; and C_w is the number of counts in the window of the single-channel analyzer. D_2 is the fraction of counts in the window due to γ_2, and knowing the window width, one can obtain this fraction from the single-crystal spectrum.

The term $\sum_i q_{1,i}D_i\bar{W}_{1,i}(\theta)$ corrects for coincidences arising from "gating" events in the window from any gamma ray (γ_i) other than γ_2. Here D_i is the fraction of counts in the window due to γ_i, and $q_{1,i}$ is the relative number of γ_1 coincident with γ_i as determined from other coincidence experiments or as deduced from the decay scheme. (In this present study all $q_{1,i}$ values were determined experimentally). The $\bar{W}(\theta)$ terms are the angular distribution functions for the indicated pairs of coincident gamma rays integrated over the face of the crystal.[11] Since no $\bar{W}(\theta)$ determinations were made for I^{134} gamma rays, the values in all cases were assumed to be unity.

We show in Table I the "coincidence quotients" calculated by the above method for each of the gamma-gamma coincidence experiments. These q values are used in conjunction with the single-crystal intensities and the decay scheme of Fig. 15 to calculate the intensity of each gamma-ray transition. This procedure usually involves a series of successive approximations until internal consistency is achieved.

Corrections for coincidence counts due to sum pulses and bremsstrahlung in the window are not as straight-

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

[11] M. E. Rose, Phys. Rev. **91**, 610 (1953).

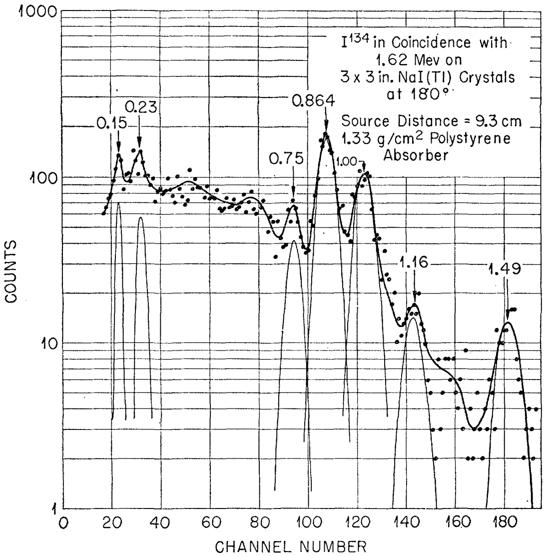

FIG. 4. I^{134} gamma-ray spectrum in coincidence with a 134-kev window set at 1.62 Mev.

forward as is the correction for Compton events. The contributions due to sum pulses could be measured by using the sum-coincidence circuit described above, in conjunction with a third NaI detector. A coincidence would be demanded between the third detector and a single-channel window set on the desired sum energy. Correcting for bremsstrahlung in the window is even more difficult in that one must deduce the effect by a comparison with appropriate standards. Since these corrections were not applied in this work some of the smaller "coincidence quotients" of Table I may contain sizeable errors.

In some of the coincidence spectra the random coincidence contribution is drawn as a dashed line, while in others there is no indication of such an effect. In these latter spectra the random counts were subtracted from the gross spectrum and the difference plotted, so that the analyzed peaks are equivalent for the two methods.

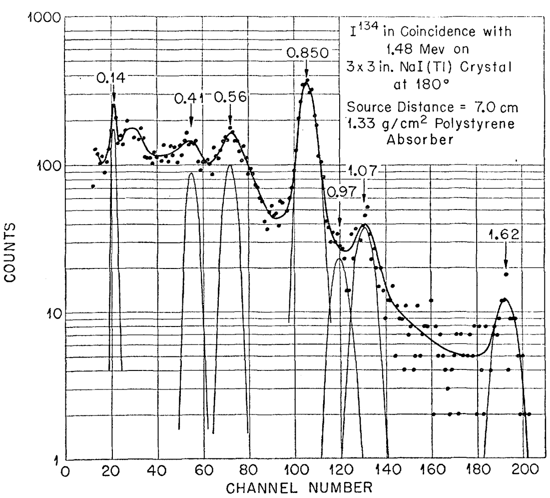

FIG. 5. Gamma rays from I^{134} in coincidence with 1.48 Mev. The single-channel window was 82 kev wide.

With a single-channel window 97-kev wide centered at 1.79 Mev, the only prominent feature of the coincident spectrum was a peak at 0.853 Mev. There were some indications for other weak gamma rays, but probably these are due to sum pulses and bremsstrahlung counts in the window.

Figure 4 shows the spectrum in coincidence with a 134-kev window centered at 1.62 Mev. One of the more interesting features of this spectrum is the energy of the most pronounced peak. This experiment was performed four times and the energy of the prominent peak was consistently in the range 0.86−0.87 Mev, the best value being 0.864 ± 0.014 Mev. In both the single-crystal spectra and other coincidence measurements, gamma rays have been found at 0.85 and 0.89 Mev, but none at the energy observed here. Since this peak is best fitted by a single Gaussian distribution at 0.864 Mev it is thought to be an additional gamma ray as shown in the decay scheme, which conclusion is compatible with the "gamma-beta" coincidence results discussed below. If it can be assumed that the sum spectrum in a single-channel window set at 1.62 Mev is primarily due to 0.85−0.89-Mev gamma-ray events, then in Fig. 4 most of the coincidence spectrum below about 0.7 Mev would be accounted for, as would an appreciable portion of that between the 0.995- and 1.49-Mev peaks.

In Fig. 5 we show the spectrum in coincidence with an 82-kev single-channel window centered on 1.48 Mev which includes counts from both the 1.46- and 1.49-Mev gamma rays. Small residues at about 0.76 and 1.3 Mev and the excessive widths of the peaks at 0.41 and 0.56 Mev may indicate weak gamma rays at each of these energies.

The spectra in coincidence with 1.16 and 1.07 Mev are shown in Figs. 6 and 7, respectively. Window widths of 42 kev were used in both cases. The most notable difference in the two spectra is that the 1.15-Mev gamma ray is coincident with both the 0.85- and 0.89-Mev peaks, whereas the 1.07-Mev gamma ray appears to be in coincidence with only the 0.85-Mev transition.

Figure 8 shows the coincidence results with a 47-kev single-channel window set at 0.99 Mev. A significant feature is that only in this spectrum is a gamma ray at 0.93 Mev observed, and since it appears merely as an inflection on the side of the 0.848-Mev peak, there is some question about the energy assigned. If the gamma-ray energy is 0.93 Mev as shown, there appears no reasonable way to incorporate it into the decay scheme of Fig. 15 without assigning additional levels. Very weak gamma rays are probably present at about 1.14, 1.28, and 1.42 Mev although the poor counting statistics in this region make it very difficult to decompose the spectrum with much reliability.

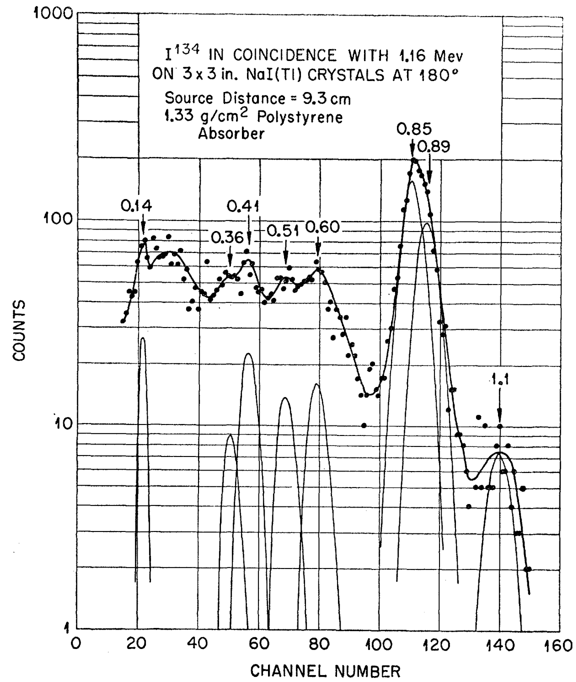

FIG. 6. Gamma-ray spectrum from I^{134} coincident with the events in a 42-kev window set at 1.16 Mev.

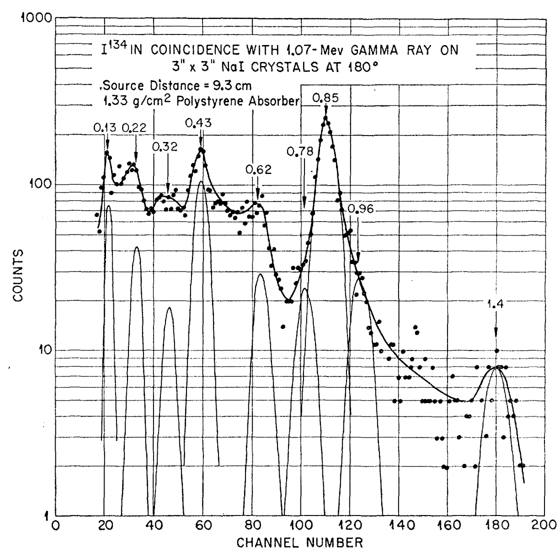

FIG. 7. I^{134} gamma-ray spectrum in coincidence with 1.07-Mev gamma rays. The width of the single-channel window was 42 kev.

In an effort to point out the differences between the spectra coincident with the 0.848- and 0.890-Mev gamma rays, we gated with relatively narrow windows (31 and 35 kev, respectively) centered at 0.83 and 0.91 Mev. The results are shown in Figs. 9 and 10. One of the most notable differences between the single-crystal measurement and the spectrum coincident with 0.83 Mev is a 50–60% reduction in the height of the 1.62-

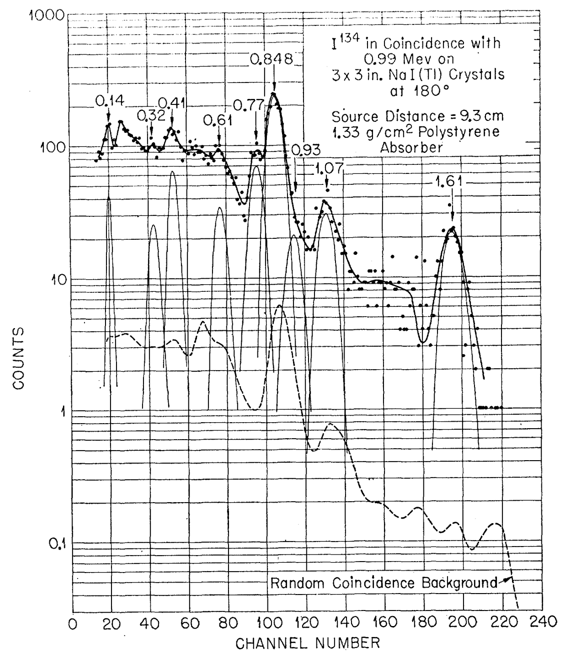

FIG. 8. Gamma-ray spectrum of I^{134} coincident with the counts in a 47-kev window centered at 0.99 Mev in the gamma-ray spectrum.

Mev peak. This result, which is consistent with the recent observations of Holm and Ryde,[8] indicates a weak ground state transition at 1.62 Mev.

In the spectrum coincident with 0.91 Mev most of the region above 1.15 Mev is due to 0.85-Mev gamma-ray counts in the window. However, all of the 1.07- and 0.89-Mev peaks cannot be accounted for similarly, which in the light of the other data necessitates postulating multiple transitions with about these energies in the scheme. The well-defined peak at 0.848 ± 0.009 Mev provides a good energy determination for this gamma ray.

Gamma-gamma coincidence experiments also have been performed for single-channel window settings of 0.61, 0.41, and 0.135 Mev. Both the single-crystal and coincidence data lead to uncertainties concerning the number of gamma rays with about these energies as well as to their locations in the decay scheme. Therefore, especially for the 0.41- and 0.135-Mev settings, it seemed advisable to attempt an experimental determination of the spectrum coincident with Compton pulses, rather than to account for these in the analytical fashion usually employed. We have done this for each of these three cases by first determining the gross coincidence spectrum with the window set at the peak of interest, and then shifting the window to a pulse height at which the region covered is most like the desired Compton distribution. After appropriate normalization, the difference between the two spectra was plotted and analyzed. This method, too, is subject to error, but it

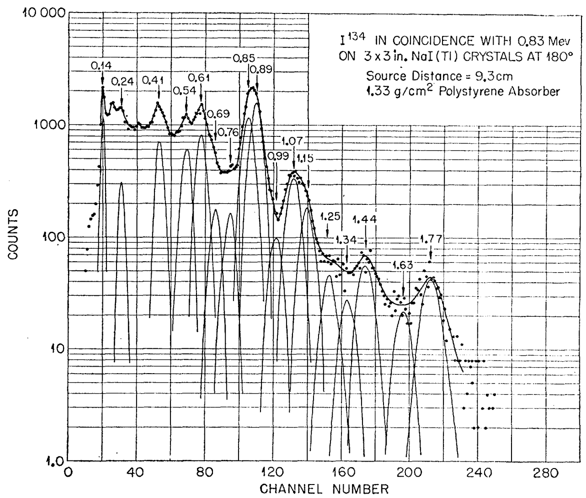

FIG. 9. I^{134} gamma-ray coincidence spectrum observed when a narrow window (31 kev) was set at 0.83 Mev so that most of the events in the window were due to the 0.848-Mev gamma ray.

is felt that for such cases as these it is probably more reliable than an analytical approach.

The results of the method for a 34-kev window setting at 0.61 Mev are shown in Fig. 11(a). The Compton-gamma coincidence contribution was measured with the window at 0.86 Mev. The region above the 1.43-Mev peak is not shown, but there was some suggestion of a low-intensity transition at about 1.8 Mev as there was also in the vicinity of 1.3 Mev.

Figure 11(b) shows the spectrum coincident with the events in a 32-kev single-channel window centered at

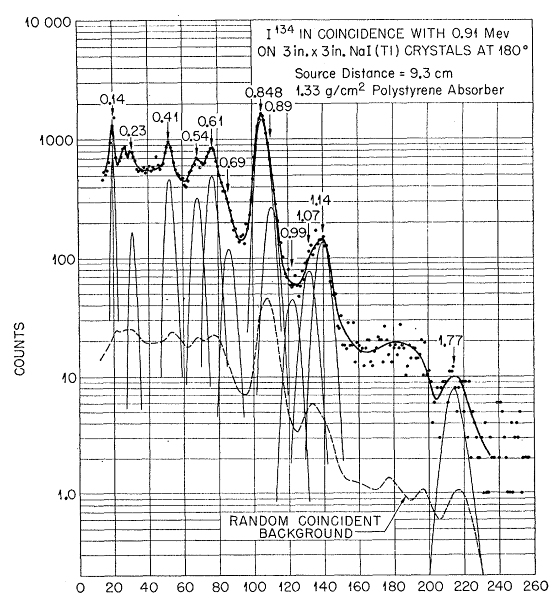

FIG. 10. Gamma rays from I^{134} coincident with the events in a 35-kev single-channel window centered at 0.91 Mev. This stresses the effect of the 0.89-Mev gamma ray and diminishes the contribution to the counts in the window from the 0.848-Mev gamma ray.

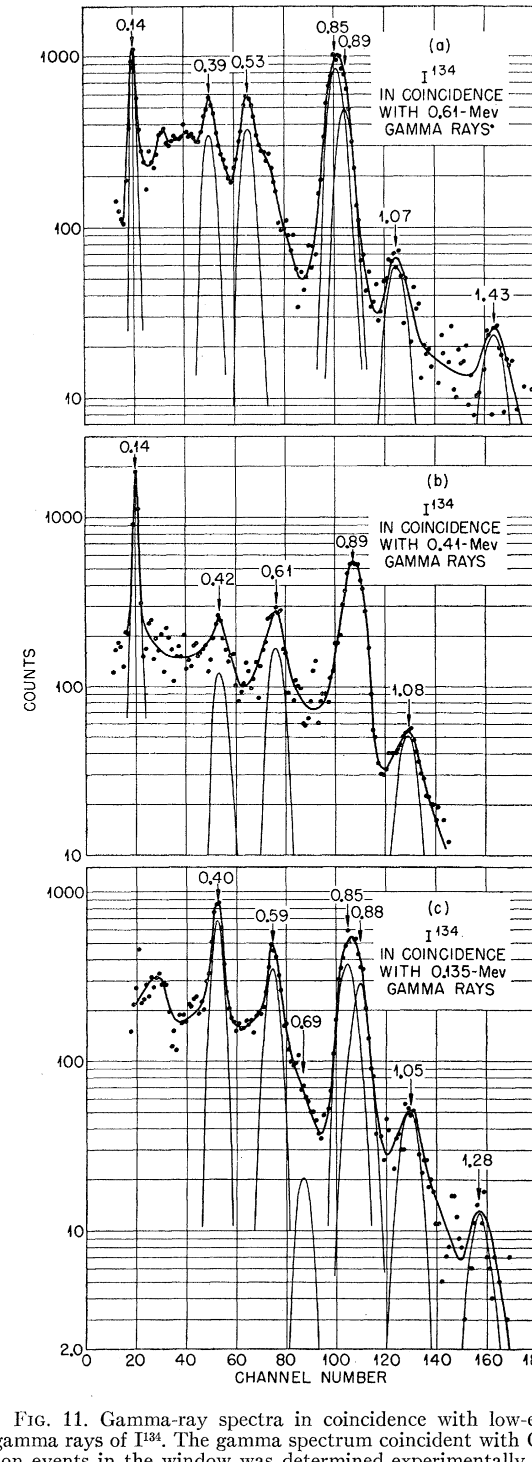

FIG. 11. Gamma-ray spectra in coincidence with low-energy gamma rays of I^{134}. The gamma spectrum coincident with Compton events in the window was determined experimentally as described in the text. (a) Coincidence spectrum obtained for a window width of 34 kev centered at 0.61 Mev. (b) Spectrum in coincidence with gamma rays in a 32-kev window set at 0.41 Mev. (c) Coincidence spectrum observed with a 3-in.×3-in. NaI crystal gated by the 0.135-Mev pulses from a $\frac{1}{8}$-in. thick, 3-in. diameter NaI detector.

0.41 Mev. The Compton-gamma coincidence correction was obtained with the window at 0.32 Mev, and thus may have led to small errors as there is some evidence for a weak 0.32-Mev gamma ray. Spectral decomposition was not performed on the large peak at about 0.89 Mev since slight gain shifts between the two runs may have caused considerable error. Its width, however, does imply that several gamma rays are present at about this energy. The peak at 0.42 Mev confirms that likewise there are multiple transitions here. In Table I we give simply a relative indication of the coincidence intensities for this experiment, as it is felt to be of qualitative value only.

The spectrum in coincidence with the 0.135-Mev gamma ray is displayed in Fig. 11(c). While a 3-in.×3-in. NaI crystal was used in the single-channel side for all the previously discussed experiments, a $\frac{1}{8}$-in.×3-in. NaI crystal was employed in this case in order to reduce the Compton level from higher-energy gamma rays. To determine the spectrum coincident with Compton events, the window was set at 190 kev. As seen in Fig. 11(c), it appears that there is a very weak coincidence peak at 0.69 Mev. If the locations of the 0.69- and 0.14-Mev gamma rays are correct as shown in the decay scheme of Fig. 15, then it would appear that a small error has been introduced in the attempted correction for Compton pulses in the window.

The spectrum of gamma rays decaying to the 1.74-Mev level of Xe^{134} has been measured in a triple coincidence experiment using three NaI crystals. Outputs from two detectors were in "fast-slow" coincidence, while the signal from the third crystal fed the multichannel analyzer and also served as a second "slow" coincidence gate. The resolving time, 2τ, was 2.5 μsec. Both single-channel windows were set to accept pulses in the energy range 0.80−0.92 Mev and the spectrum obtained is shown in Fig. 12. The random coincidence background, which is indicated by a dashed line, is a very large fraction of the main peak, and consequently, the energy of this peak when analyzed is subject to considerable error. As will be noted from Fig. 12, this experiment has provided the best definition of some of the low-energy transitions.

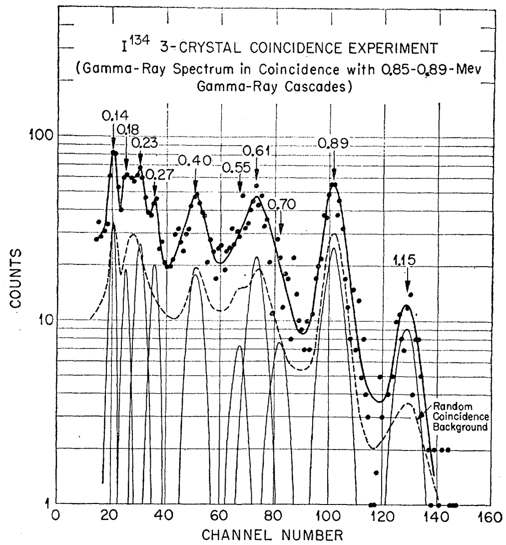

FIG. 12. Results of a 3-crystal gamma-ray coincidence experiment designed to measure the spectrum coincident with 0.85–0.89-Mev cascades. The multichannel analyzer recorded the gamma spectrum from one 3-in.×3-in. NaI crystal when two other 3-in.×3-in. NaI detectors simultaneously registered an event in the energy range 0.80–0.92 Mev.

IV. BETA-RAY SPECTROMETRY

All beta-ray spectra were determined by the scintillation method. Cylindrical anthracene crystals, $1\frac{1}{4}$ inches in diameter and either $\frac{1}{2}$ or 1 in. long, were attached to Dumont 6292 photomultiplier tubes. The side of each crystal was wrapped with aluminum foil reflector, and the end was covered with an aluminized Mylar foil of 1 mg/cm^2 surface density, which served both as an optical reflector and a window. In the early experiments of this study the $1\frac{1}{4}$-in.×1-in. crystal was used, but later it was feared that the large crystal with its higher gamma sensitivity was contributing beta-gamma sum events to the beta spectra; however, no significant differences were noted in the spectra obtained with these two crystals. Gamma-ray contributions to the spectra were determined by absorbing the beta particles in about 1.5 g/cm^2 of copper. The distance between the source and the anthracene detector varied from 2 to 4 cm.

Silver iodide sources of about 1 mg/cm^2 were slurried onto a backing of 6.5-mg/cm^2 Mylar tape, and were covered with rubber hydrochloride film of 0.4 mg/cm.^{2}

Single-Crystal Spectrum

Fermi analysis of a single-crystal beta spectrum is shown in Fig. 13(a). Data near the end point were corrected for resolution distortion using the method of Owen and Primakoff.[12] The energy of 2.43±0.05 Mev obtained for the most energetic beta group is in good agreement with the value 2.35±0.15 Mev obtained by Holm and Ryde[8] using a magnetic spectrometer. An analysis of the single-crystal spectrum showed, in addition to inner groups at about 2.2, 1.7, and 1.5 Mev, a component at 1.2 Mev. This lowest-energy group is doubtful because the low-energy part of the spectrum was somewhat distorted by scattering from the anthracene crystal and from the thick source and backing. Although it was difficult to resolve these inner groups from the singles spectrum with confidence, the coincidence experiments described below verified their existence.

[12] G. E. Owen and H. Primakoff, Phys. Rev. 74, 1406 (1948); Rev. Sci. Instr. 21, 447 (1950).

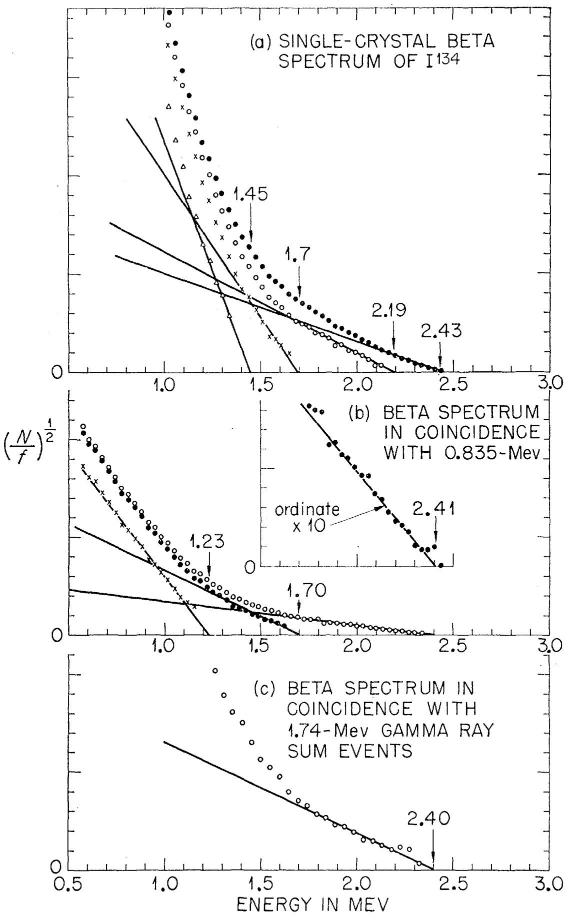

FIG. 13. Fermi analysis of a single-crystal measurement of the I^{134} beta spectrum, together with results of beta-gamma experiments pertaining to the place of the 2.41-Mev beta group in the decay scheme. All spectra were determined by use of an anthracene scintillation spectrometer. (a) The single-crystal spectrum. (b) Beta-ray spectrum in coincidence with a 29-kev window set at 0.835 Mev in the gamma-ray spectrum. Most of the beta events arise from coincidences with the 0.848-Mev gamma ray. (c) Analysis of the beta spectrum recorded in coincidence with 1.74-Mev gamma coincidence sum pulses (see text).

"Gamma-Beta" Coincidence Experiments

Two "gamma-beta" experiments were performed to determine the gamma-ray spectrum in coincidence with beta rays of a selected energy. The gamma-ray detector was a 3-in.×3-in. NaI crystal shadowed by a 1.33-g/cm^2 polystyrene beta-ray absorber. The $1\frac{1}{4}$-in.×1-in. anthracene crystal was used for beta detection. When the gamma spectrometer was gated by beta particles of energy greater than 2.1 Mev, a few coincident gamma events were recorded which indicated a gamma energy of 0.85–0.90 Mev. The statistical accuracy was very poor because of the small number of gate pulses available from the upper 0.3-Mev portion of the 2.4-Mev beta group; however, this experiment did indicate that the 2.4-Mev beta component decays to either the 0.848- or 1.74-Mev excited states of Xe^{134}. A second experiment was performed in which beta particles above 1.6 Mev gated the gamma spectrometer. Most of the gate pulses were due to either the 2.2- or 2.4-Mev beta components, with only a few events from the 1.7-Mev group. This time, a favorable coincidence rate was obtained. The most prominent feature of the coincident gamma-ray spectrum was an intense, broad peak at 0.87 Mev, which was analyzed into two peaks with indicated energies of about 0.86 and 0.90 Mev. Less intense, but well resolved, was a peak at about 1.09 Mev. There were indications of peaks at about 0.5 and 0.6 Mev, in low intensity.

Beta-Gamma Coincidence Spectra

The beta-gamma experiments were performed by recording beta-ray spectra in coincidence with selected gamma-ray peaks, using equipment similar to that already described for the gamma-beta determinations. In Fig. 13(b) is shown the beta-ray spectrum in coincidence with a gamma-ray energy interval 29 kev wide, centered on 0.835 Mev; under these conditions most of the events falling within the energy interval are due to the 0.848-Mev gamma ray. Although the Fermi analysis shows the most energetic component at 2.41 ± 0.07 Mev, with inner groups at 1.70 ± 0.08 and 1.23 ± 0.07 Mev, it is possible that beta rays were present at 2.2, 1.5, or perhaps 1.8 Mev (see decay scheme) but were obscured by the more intense components.

The gamma-beta and beta-gamma experiments just described, together with gamma-ray intensities and positions of the energy levels in Xe^{134} determined from gamma spectrometry, suggested that the 2.4-Mev beta group of I^{134} proceeded to the 1.74-Mev level in Xe^{134}. As a test of this hypothesis, a determination was made of the beta spectrum in coincidence with 1.74-Mev gamma-ray sum pulses. Except for the addition of an anthracene beta detector, the experimental arrangement was similar to the gamma-ray sum coincidence circuit described above and sketched in Fig. 3. The gains and geometries of the two NaI gamma detectors were matched, and their outputs were summed. A single-channel analyzer with a window 99-kev wide was centered on the 1.74-Mev peak of the gamma-ray sum spectrum, and supplied a gate pulse to a "slow" channel of the "fast-slow" coincidence mixer. The 256-channel analyzer recorded only those beta-ray pulses from the anthracene spectrometer for which there was both a fast coincidence ($2\tau\simeq0.19$ μsec) between the beta pulse and a gamma sum event, and a slow coincidence with 1.74-Mev sum pulses. The important feature of the coincident beta spectrum displayed in Fig. 13(c) is the very intense group at 2.40 ± 0.05 Mev. This evidence, in conjunction with the beta-gamma results, demonstrates that the 2.4-Mev beta group decays to the 1.74-Mev level of Xe^{134}.

An attempt was made to determine the beta-ray component in coincidence with the gamma rays in a

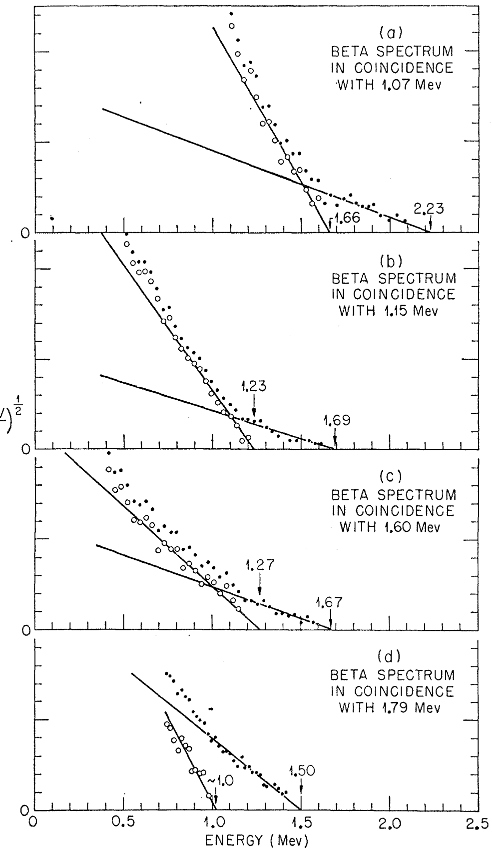

FIG. 14. Analyses of coincident beta-ray spectra observed when a single-channel window was set to the following energies in the gamma-ray spectrum (and window widths): (a) 1.07 Mev (60 kev), (b) 1.15 Mev (52 kev), (c) 1.60 Mev (70 kev), (d) 1.79 Mev (90 kev).

single-channel window set at 0.99 Mev. From the gamma-ray spectrum of Fig. 1 it will be noted that this transition is very weak. In a window 40-kev wide only half of the counts are due to the 1.00-Mev gamma ray; 10% of the other counts arise from the sum spectrum, and the remainder from Compton events of higher-energy gamma rays. The coincident beta spectrum under these conditions showed components of 2.20 ± 0.16, 1.49 ± 0.08, and 1.08 ± 0.10 Mev. Gating events from the 1.07-Mev gamma ray probably account for the beta component at 2.20 Mev, and the 1.49-Mev beta group can be ascribed to the gamma ray of interest at 1.00 Mev. The origin of the 1.08-Mev beta group is obscure.

The results of a measurement of the beta spectrum coincident with the 1.07-Mev gamma peak are shown in Fig. 14(a). More than 90% of the counts within the 60-kev window centered at 1.07 Mev are due to a gamma ray of that energy; the remainder originate mainly from Compton events from the 1.79-, 1.62-, 1.46-, and 1.15-Mev gamma rays. Hence, the beta group at 2.23 ± 0.06 Mev is thought to originate from coincidences with the 1.07-Mev gamma ray and the 1.66 ± 0.05 Mev beta group can probably be ascribed to coincidences with the 1.07- and 1.62-Mev gamma rays.

With the window of the single-channel analyzer 52-kev wide and centered on the peak at 1.15 Mev, the spectrum of Fig. 14(b) was obtained. Here, only about 65% of the counts falling within the energy interval are due to the 1.15-Mev gamma ray. The gamma sum spectrum amounts to 12% of the counts, with appreciable intensity from the spectra of the 1.07-, 1.46-, 1.62-, and 1.79-Mev gamma rays. These interferences account for the beta component of 1.69 Mev; however, the component of 1.23 ± 0.06 Mev appears to result from a coincident with the 1.15-Mev gamma ray.

Because there are gamma rays at both 1.46 and 1.49 Mev (see Table I), two beta-gamma coincidence experiments were performed with the single-channel window set at 1.46 and 1.48 Mev in the gamma-ray spectrum. In both cases beta groups were found at about 1.05 and 1.5 Mev, with indications for higher-energy events. Although it is difficult to interpret these results, as there was a large contribution to the counts in the window from the gamma-ray sum spectrum and from Compton events from the 1.79-Mev gamma ray, these results are not inconsistent with a coincidence between the 1.05-Mev beta group and the 1.49-Mev gamma ray.

Figure 14(c) displays the beta spectrum in coincidence with events in a 70-kev window set at 1.60 Mev in the gamma-ray spectrum. The only important interference is offered by the gamma-ray sum spectrum, which amounts to about 18% of the counts in the window. Coincident beta groups are shown analyzed at 1.67 ± 0.05 and 1.27 ± 0.04 Mev.

The results with a 90-kev window set on the peak at 1.79 Mev are shown in Fig. 14(d). A prominent beta group is seen at 1.50 ± 0.05 Mev, and a second group is resolved with an end point of 1.0 ± 0.1 Mev.

Energies of the I^{134} beta-ray transitions from the various beta-gamma coincidence experiments are summarized in Table II. The results of the single-crystal beta-ray measurements and preferred energy values of the beta-ray transitions as determined from all experiments are presented in Table III. The beta intensities in Table III were calculated from gamma intensities and the decay scheme, and the comparative half-lives were computed using the Moszkowski nomographs.[13]

V. DISCUSSION

The decay scheme shown in Fig. 15 agrees with most of the experimental observations. The left-hand side of the scheme gives the features most strongly substantiated by experiment, while the right-hand side shows the gamma-ray transitions and additional levels which agree with, but are less definitely indicated by the experimental data. Twenty-one of the twenty-seven gamma rays listed in Table I have been incorporated

[13] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

TABLE II. Energies of I^{134} beta-ray transitions, as determined from beta-gamma coincidence experiments.

Beta component[a]	Beta-ray energies in coincidence with gamma rays of energy (Mev)							
	0.848[b]	1.00[c]	1.07	1.15	1.46[d]	1.62[e]	1.79	(Sum) 1.74
$\beta_{1.74}$	2.41±0.07							2.40±0.05
$\beta_{1.92}$	?	2.20±0.16[f]	2.23±0.06		2.19±0.09[f]			
$\beta_{2.48}$	1.70±0.08		1.66±0.05	1.69±0.07[f]		1.67±0.05		?
$\beta_{2.64}$	?	1.49±0.08			1.50±0.06[f]		1.50±0.05	
$\beta_{2.88}$	1.23±0.07			1.23±0.06		1.27±0.04		
$\beta_{3.11}$		1.08±0.10[f]			1.06±0.05		1.0±0.1	

[a] Beta subscripts denote energies of final states in Xe^{134}.
[b] The single-channel window was set at 0.835 Mev to discriminate against counts due to the 0.89-Mev gamma ray.
[c] The single-channel analyzer was set to 0.99 Mev.
[d] The single-channel analyzer was centered on 1.48 Mev. Results were the same as obtained at 1.46 Mev, except that better statistical accuracy was achieved.
[e] Actual setting of the single-channel analyzer was 1.60 Mev.
[f] This group is believed to originate from coincidences with other gamma-ray spectra in the single-channel window, but is included here as a measurement of the particular beta energy.

into this scheme. To account for the coincidence results, it was necessary to assume that there were two gamma rays, each with energies of 0.89 and 1.07 Mev.

Both the gamma-gamma coincidence data and the single-crystal intensities indicate that the 0.848-Mev transition, and not the 0.890-Mev transition, decays to the ground state of Xe^{134} from its first excited level. Similarly, the 0.890-Mev gamma ray is shown in a cascade from the level at 1.74 Mev. It was shown that this latter level is fed by a 2.41-Mev beta-ray group; hence, an energy separation of 4.15±0.06 Mev is indicated between the ground states of I^{134} and Xe^{134}.

Since the 1.62-Mev level is a point of considerable interest and is discussed at some length below, a detailed justification for its existence follows. (1) The intensity of the 1.62-Mev gamma ray coincident with the counts in a window at 0.83 Mev was less than half that observed in the single-crystal experiment, and as the data show that no other ground-state transition is present, the 1.62-Mev group must represent a transition to the Xe^{134} ground state. (2) The measurement of the gamma-ray spectrum coincident with 1.62 Mev was repeated several times and the energy of the most pronounced peak was consistently greater than 0.848 Mev, the best value being 0.864±0.014 Mev. (3) Finally, as shown in Table I, the small "coincidence quotients" for the gamma rays coincident with the 1.62-Mev peak are ≤ 0.46 and these are consistent only with a 1.62-Mev ground-state transition.

TABLE III. Summary of the energies, intensities, and comparative half-lives of I^{134} beta-ray transitions.

Beta component[a]	Singles energy, Mev	Preferred energy,[b] Mev	Intensity[c] %	log *ft*
$\beta_{1.74}$	2.43±0.05	2.41±0.06	25±8	7.0±0.1
$\beta_{1.92}$	2.19±0.07	2.21±0.08	12_{-4}^{+3}	$7.2_{-0.1}^{+0.2}$
$\beta_{2.34}$		(1.81[d])	$9.4_{-4.7}^{+4.8}$	$7.0_{-0.2}^{+0.3}$
$\beta_{2.48}$	1.70±0.05	1.68±0.06	$0.5_{-0.0}^{+4.0}$	$8.2_{-0.9}^{+0}$
$\beta_{2.64}$	1.45±0.07	1.49±0.06	15±3	6.5±0.1
$\beta_{2.88}$	1.20±0.08	1.25±0.06	23±8	$6.0_{-0.1}^{+0.2}$
$\beta_{3.11}$		1.05±0.07	1.0±0.2	7.1±0.1

[a] Beta subscripts denote energies of final states in Xe^{134}.
[b] From a weighted average of the single-crystal measurements and the coincidence results of Table II.
[c] Beta intensities and their errors were calculated using the decay scheme and the gamma-ray intensity data.
[d] Energy calculated from the decay scheme, but not observed directly.

Levels at 1.92, 2.48 2.64, 2.88, and 3.11 Mev are based on both single-crystal information and gamma-gamma and beta-gamma coincidence data. Although assigned with less certainty, the levels at 2.43, 3.30, and 3.41 Mev are necessary to explain the gamma-gamma coincidence results. The level at 2.34 Mev seems well established since all the intensity of the 0.61-Mev gamma ray appears to cascade through the 0.89- and 0.85-Mev transitions, while no other gamma rays are strongly in coincidence with 0.61 Mev. However, this level presents a conflict in that no beta-ray transition was observed to it, yet the gamma-ray intensities call for a branch even more intense than the 1.69-Mev beta-ray group which was observed feeding the 2.48-Mev level. Possible sources of difficulty are that we have not accounted for internal conversion of the 135-kev transition; there may be another 0.6-Mev gamma ray elsewhere in the scheme; there could be undetected gamma rays of very low energy cascading into the 2.34-Mev level; or perhaps the inconsistency is due to the interpretation given the Fermi plots.

A reasonable assumption for the ground state neutron configuration of I^{134} is that it can be described as a $d_{3/2}$ neutron hole. The odd proton is probably a $g_{7/2}$ particle which is in line with the recent observations of Fletcher and Amble.[14] They pointed out that as a closed neutron shell is approached in the iodine isotopes, the $g_{7/2}$ proton level becomes more stable than the $d_{5/2}$ level. DeShalit and Goldhaber[15] have explained such behavior in terms of added stabilization of the $g_{7/2}$ proton state resulting from the addition of $h_{11/2}$ neutron pairs (this stabilizing effect of a particle of one kind by a pair of the other kind is strongest when $l_n \approx l_p$). Therefore, in line with the rules for jj coupling recently stated by Brennan and

[14] P. C. Fletcher and E. Amble, Phys. Rev. **110**, 536 (1958).
[15] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).

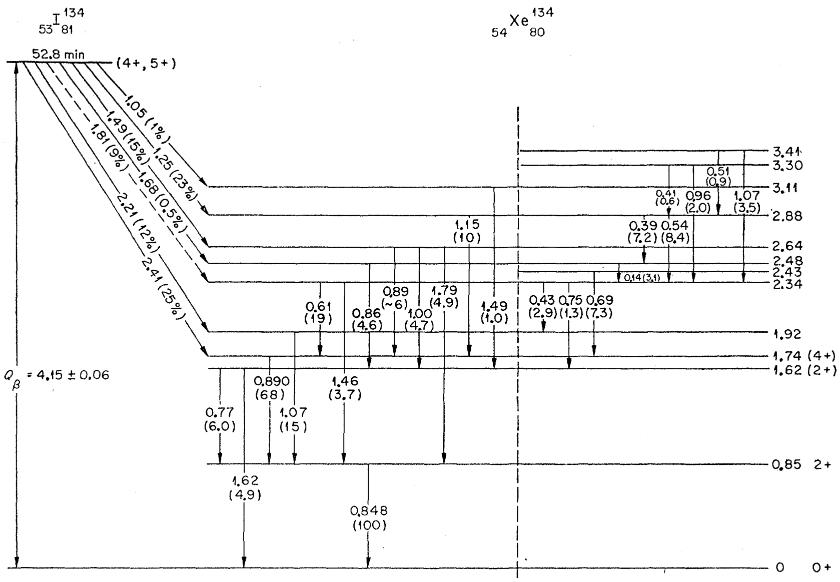

FIG. 15. Decay scheme proposed for I^{134}. All energies are in Mev. Relative intensities deduced from the single-crystal and coincidence data are given in parentheses beneath the gamma-ray energies. Intensities of the beta groups were calculated from the relative gamma-ray intensities and the decay scheme. The 1.81-Mev beta group is the only one shown which was not observed directly (see Discussion and Table III).

Bernstein,[16] the most likely spin possibilities for I^{134} are 2+, 4+, and 5+. We can rule out 2+ since no beta decay was observed to the 2+ first excited state of Xe^{134}. Either a 4+ or 5+ assignment would be consistent with the experimental observations.

As Xe^{134} is an even-even nuclide, its ground and first excited states are expected to have spin assignments of 0+ and 2+, respectively. The 1.74-Mev level is most likely 4+ since it is fed by a strong beta-ray group and there is no detectable beta decay to the first 2+ level. Further, there is a strong cascade transition to the 2+ first excited state, but no observable crossover transition to the ground state. The levels at 1.92, 2.48, 2.64, 2.88, and 3.11 Mev are fed by beta decay, and therefore, probably have high spins.

The level at 1.62 Mev decays to both the first 2+ and to the 0+ ground state. Also, this level is not populated by beta decay, yet is fed by gamma decay of levels which probably have spins of 3 to 5. Thus, it would seem that the 1.62-Mev level has a spin of 2+ and may be a member of a multiplet predicted[17–19] at about twice the energy of the first 2+ state for medium-weight,

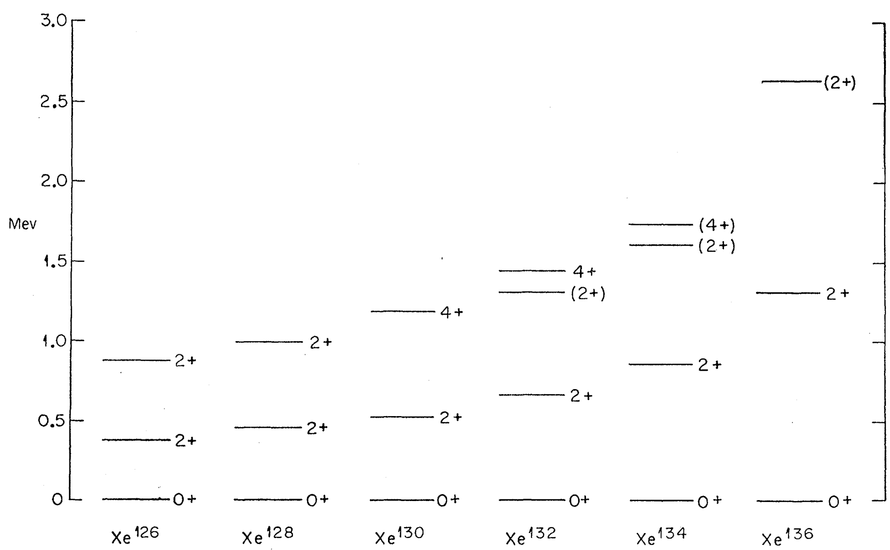

FIG. 16. Low-lying energy levels of even xenon isotopes.

[16] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).
[17] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[18] L. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).
[19] B. J. Raz, Phys. Rev. **114**, 1116 (1959).

even-even nuclei. Then although Xe^{134} is only two neutrons removed from a closed shell, its low-lying levels, like the surprising case of Xe^{136}, appear to possess collective properties. The asymmetric rotor model of Davydov and Filippov[20] has had moderate success in predicting some of the low-lying energy states, and gamma-ray transition probabilities between them, for this class of nuclei. It gives the energy states of an asymmetric top as a function of γ, where γ determines the deviation of the nuclear shape from axial symmetry. The ratio of the energy of the second 2+ state (1.62 Mev) to that of the first 2+ state (0.85 Mev) observed in the present case corresponds closely to $\gamma=30°$. The Davydov-Filippov model predicts the first 3+ level in Xe^{134} to be at 2.54 Mev, the sum of the first and second 2+ levels. As shown in Fig. 15, there is a level close to this energy at 2.48 Mev which is indeed compatible with a 3+ assignment; in further agreement with the predictions of the model for $\gamma=30°$, gamma emission occurs from this level to the second 2+ and not to the first 2+ state. In the case considered, the ratio $B(E2, 2'\rightarrow 2)/B(E2, 2'\rightarrow 0)$ is expected to approach infinity, whereas we observe a much smaller value of 50 corresponding to $\gamma\approx 27°$. The model appears unsuccessful in predicting energies for any of the higher spin states of Xe^{134}.

[20] A. S. Davydov and G. F. Filippov, Nuclear Phys. **8**, 237 (1958).

The first few levels of the even xenon nuclides are shown schematically in Fig. 16. The continuous increase in first excited state energies as N approaches 82 is, of course, to be expected. However, it is surprising that the collective behavior as evidenced by the ratio of second to first excited state energies of ~ 2 does persist up to the closed shell. The graph suggests that second excited state doublets should exist in Xe^{126}, Xe^{128}, and Xe^{130}.

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Neutron-Deficient Nuclides of Hafnium and Lutetium*

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New neutron-deficient nuclides of lutetium and hafnium were produced by bombarding lutetium oxide with 300- to 400-Mev protons. The genetic relationships and mass assignments were established by means of high-purity chemical separations and a series of chemical isolation experiments in which the daughter activity was determined as a function of time.

The positron spectra of the different nuclides were measured with an anthracene crystal detector and a 256-channel pulse height analyzer. Gamma radiation was also observed for Lu^{168}, Lu^{169}, Lu^{170}, Hf^{168}, and Hf^{169} by means of a NaI crystal detector and the pulse height analyzer. The half-lives and maximum positron energies observed are: Lu^{168}, $T_{\frac{1}{2}}=7.0$ min, $E_{\beta^+}=(1.20\pm0.05)$ Mev; Lu^{169}, $T_{\frac{1}{2}}=1.5$ days; Lu^{170}, $T_{\frac{1}{2}}=1.9$ days, $E_{\beta^+}=(1.8\pm0.1)$ Mev; Hf^{168}, $T_{\frac{1}{2}}=22$ min, $E_{\beta^+}=(1.7\pm0.1)$ Mev; Hf^{169}, $T_{\frac{1}{2}}=1.5$ hr; Hf^{170}, $T_{\frac{1}{2}}=9$ hr.

INTRODUCTION

In the course of a study of the spallation reactions of tantalum and tungsten with 300–400-Mev protons using the Carnegie Institute of Technology synchrocyclotron, several new neutron-deficient nuclides of hafnium and lutetium were observed. After performing a few preliminary experiments, a detailed study was undertaken to establish the half-lives, genetic relations, and radiation characteristics of these new nuclides. The investigation included the hafnium nuclides of Hf^{168}, Hf^{169}, and Hf^{170} and those of lutetium of the same mass numbers.

In these more detailed studies Lu_2O_3 was bombarded with 300–400 Mev protons producing only the neutron-deficient nuclides of hafnium and lutetium by (p,xn) and (p,pxn) reactions, and eliminating interfering neutron excess nuclides of these elements. In order to avoid separating the lutetium activities from the many other rare-earth activities produced in the bombardment, the lutetium decay products were chemically separated from the purified hafnium fraction. All lutetium nuclides produced, heavier than Lu^{168}, decay to stable ytterbium nuclides with the exception of Lu^{169}, which decays to 32-day Yb^{169}. The well-known spectrum of Yb^{169} was used as evidence for the mass assignment of Hf^{169} and Lu^{169}. The half-lives observed for these nuclides are listed in Table I. All the nuclides decay either completely or in part by electron-capture. Positron emission was observed in Hf^{168}, Hf^{169}, Lu^{168}, and Lu^{170}. In addition to these six nuclides, some evidence was found for Hf^{167} and Lu^{167} with half-lives

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