Beta-Gamma Directional Correlations in the Decay $Sb^{124} \rightarrow Te^{124}$†

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We have measured the β-γ directional correlations involving the 1.6-Mev β group of Sb^{124} and the second excited 2^+ state (at 1325 kev) of Te^{124}. Both of the γ rays (0.72 and 1.32 Mev) de-exciting this state were used. For the 0.72-Mev γ ray, the results for the coefficient ϵ in $W(\theta)=1+\epsilon P_2(\cos\theta)$ are: $\epsilon=0.20\pm0.02$, 0.18 ± 0.02, 0.19 ± 0.03, and 0.22 ± 0.06 for β energies of 1.02, 1.16, 1.30, and 1.44 ± 0.07 Mev, respectively. For the 1.32-Mev γ ray, we find $\epsilon=-0.28\pm0.08$ for a β-energy range of 1.0–1.6 Mev. From these results, the mixing ratio for the 0.72-Mev γ ray is $\delta=+0.8_{-0.2}^{+0.7}$. It is shown that the 1.6-Mev β transition must be due, at least partly, to the B_{ij} matrix element. By assuming $u=x=0$ (in Kotani's notation), our data can be fitted by either $Y/z=0.04$ (i.e., an essentially unique transition), or $Y/z=1.2$. Evidence for the existence of a 1.25-Mev level in Te^{124} is also given.

1. INTRODUCTION

THE measurement of β-γ directional[1] and circular polarization[2] correlations has recently made possible the determination of all matrix elements for the highest energy β group of Sb^{124}, which is a first-forbidden nonunique transition. Since this is a transition between 3^- and 2^+ states, one would normally expect vector-type matrix elements to predominate which correspond to one unit of angular momentum carried away by the lepton field ($\lambda=1$). It was found, however, that the largest contribution comes from the tensor-type matrix element B_{ij} which corresponds to $\lambda=2$ and which, if present alone, would lead to a "unique" transition. The same conclusion has been drawn, after re-evaluation,[3] from the shape of the spectrum.[3,4]

These results are in accord with the relative slowness of the β transition ($\log ft=10.2$), and they indicate that the transition is not slowed down by an accidental cancellation of matrix elements but rather by a selection rule. Two such selection rules have been discussed.[5] One of these, the K-selection rule,[6] applies to collective states; it requires $\lambda\geqslant\Delta K$, where K is the projection of the total angular momentum upon the nuclear symmetry axis. The other is the j-selection rule[7–9] which can be applied to transitions between shell-model configurations whenever proton and neutron number belong to the same major shell. It permits only transitions with $\lambda\geqslant\Delta j$ where j is the total angular momentum of the transforming nucleon; if the transition changes parity and if there is no admixture from other major shells, the selection rule yields an absolute lower limit for λ.

Since Sb^{124} is not a strongly deformed nucleus, it is unlikely that it should be describable by the quantum number K. Hence, the slowness of the 2.32-Mev β transition is probably due to the j-selection rule.

As a further example, we have measured the β-γ directional correlations involving the second excited 2^+ state of Te^{124} and we find a selection rule effect also in this β transition.[10]

2. DECAY SCHEME OF Sb^{124}

The decay scheme of Sb^{124} is not yet completely known, but the levels in Te^{124} below 1.9 Mev, which are of interest here, are fairly certain (see Fig. 1).[11] The levels at 603 and 1325 kev are well established. In addition, a level at 1248 kev has become necessary to accomodate several γ transitions.[11–14] Our evidence for this level will be discussed in the Appendix. A third level at $\sim$1.35 Mev has been tentatively suggested by Girgis and Van Lieshout.[14] No higher level below 1.9 Mev has been found so far.[11,14]

The 603-kev level has been assigned spin 2^+ since this follows from systematics and since an $E2$ character for the ground-state transition follows from Coulomb excitation.[15] Measurements of K-conversion coefficients

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[1] R. M. Steffen, Phys. Rev. Letters 4, 290 (1960).
[2] G. Hartwig and H. Schopper, Phys. Rev. Letters 4, 293 (1960).
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[4] A. V. Zolotavin, E. P. Grigor'ev, and M. A. Abroian, Izvest. Akad. Nauk S.S.S.R., Ser. Fiz. 20, 289 (1956) [translation: Bull. Acad. Sciences U.S.S.R. 20, 271 (1956)].
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[9] C. E. Johnson and R. W. King, Bull. Am. Phys. Soc. 4, 58 (1959).
[10] If the Sb^{124} nucleus could be described by a quantum number K as assumed by Kotani, and if the upper 2^+ state were found to have $K=2$, then our result would *prove* that the j-selection rule rather than the K-selection rule operates in the case of Sb^{124}. This argument is due to R. W. King (private communication).
[11] C. L. McGinnis, G. Anderson, G. H. Fuller, J. B. Marion, K. Way, and M. Yamada, Nuclear Data Sheets, National Academy of Sciences (National Research Council, Washington, D. C.), 58-6-21 to 26.
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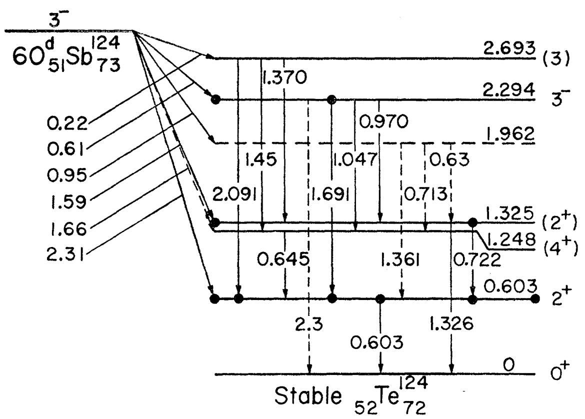

FIG. 1. Decay scheme of 60-day Sb^{124}, taken from the work cited in footnote 11. Energies are given in Mev.

are not in disagreement with the $E2$ assignment, but they tend to give too small values.[4,11] At about twice the energy of the first excited state, the collective model predicts a vibrational triplet with spins 0^+, 2^+, 4^+; of these, the level at 1326 kev should be the 2^+ level since it is de-excited by a ground-state transition, and the 1248-kev level should have spin 4^+ since it does not give rise to a ground-state transition. The ground state of Sb^{124} must be a 3^- state because of the first-forbidden, nonunique shape of the β spectrum and since no β transition to the ground state has been found. In particular, the possibility 4^+ is ruled out by the absence of a $P_4(\cos\theta)$ term in the β-γ correlation.[1]

3. EXPERIMENTAL METHOD

The measurements were performed on an automatic directional correlation apparatus designed by Steffen.[16] The β particles were detected by a plastic scintillator of 0.95-cm thickness and 3.9-cm effective diameter, mounted on a 6292 photomultiplier by means of a short light-pipe. The gamma quanta were measured with a NaI(Tl) crystal, 3-in. diam×2 in. high, on a 6363 photomultiplier (see Fig. 1 of work cited in footnote 16). The electronic equipment was largely identical to that used by Steffen, except that instead of several single-channel analyzers, one 200-channel analyzer[17] was used for the γ spectrum.

A block diagram of the electronic arrangement is shown in Fig. 2. Here, the triple coincidences of an ordinary fast-slow system open the coincidence gate of the multichannel analyzer and select the corresponding γ pulse. If the entire coincident γ spectrum is wanted, SCA_2 is set to accept all pulses. To check the performance of SCA_1, LA_3 and the multichannel analyzer can be switched to the β side. The delays inherent in the single-channel analyzers and in the slow coincidence circuit are balanced by a delay cable which forms part of LA_3.

Measuring the 0.72-Mev γ ray in the presence of the much stronger 0.60-Mev transition (see Fig. 3) required good instrumental stability. Since the γ pulse heights were found to vary by a few percent from day to day, presumably resulting from the photomultiplier, an automatic gain stabilizer[18] was incorporated in the system. This instrument uses the output rate of a single-channel analyzer (SCA_3 in Fig. 2) as a gain-sensitive signal which is fed back to change the gain of a pentode amplifier by varying its screen-grid potential. In this manner, gain variations are reduced by a factor between 30 and 50. To make calibration of the whole system by means of a pulser possible, the screen-grid potential of the stabilizer can also be fixed to any desired value, independent of the incoming pulse rate.

The remaining instability then was the result of a slow zero shift of the analog-to-digital converter in the multichannel analyzer. This shift was so small[19] as to be entirely tolerable.

The automatic cycle of the directional correlation equipment (change of angle, recording of registers, etc.) is initiated by the timer of the multichannel analyzer which also controls the automatic print-out of the coincidence spectra. Because of the stability of the equipment, fairly long times of measurement (100–200 min) could be used at every angle.

The β detector was calibrated using the conversion line of Ba^{137} and the Compton edge of the 1.69-Mev γ transition of the Sb^{124} source. For routine checks of stability, a "linear extrapolation" of the highest energy β spectrum of Sb^{124} was employed. The resolution of the β detector was 17% at 0.62 Mev. The γ detector had a resolution of 9% at 0.66 Mev; we used a peak-to-valley ratio (0.72-Mev peak to valley on its low-energy side) of the single Sb^{124} spectrum as a very sensitive function of the resolution by which small variations could be detected.

The Sb^{124} was obtained from Oak Ridge in hydrochloric acid solution. The source holders consisted of

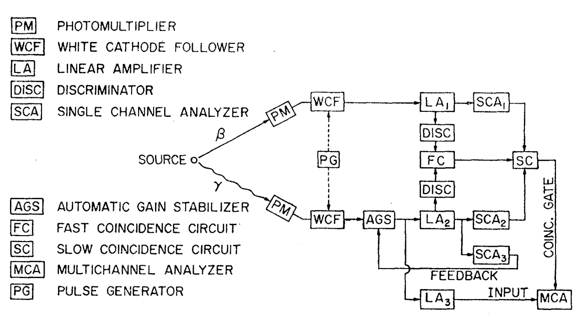

FIG. 2. Block diagram of the equipment used for measuring a γ spectrum in coincidence with a selected β energy band.

[16] R. M. Steffen, Phys. Rev. Letters 3, 277 (1959). I am very grateful to Professor Steffen for giving me the opportunity to use his equipment.

[17] Model 3302, manufactured by Radiation Instrument Development Laboratory, North Lake, Illinois.

[18] H. Paul (to be published).

[19] With the analyzer in good operating condition, the zero position shifted gradually by a total of 1.1 v over 50 days.

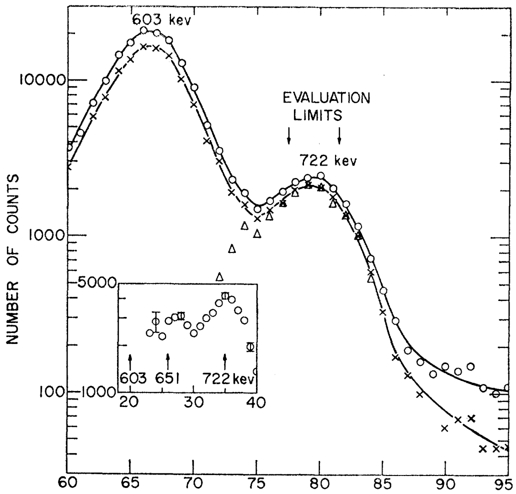

FIG. 3. Portion of the γ spectrum of Sb^{124} in coincidence with 1.02 ± 0.07 Mev β particles, at 180°. Circles indicate the original spectrum; crosses, the spectrum after subtraction of $\gamma\gamma$ and chance coincidences; and triangles, the spectrum after subtraction of the 0.6-Mev peak. The insert shows a control measurement (see Appendix), after subtraction of chance coincidences and of the 0.6-Mev coincidence peak; here, the spectrum to be subtracted (γ quanta in coincidence with β particles of $E_\beta \gtrsim 1.7$ Mev) was measured simultaneously; a few representative errors are shown.

thin Al rings of 5-cm diam, covered by 1.8 mg/cm² Mylar. Sources were prepared by slowly evaporating to dryness a small drop of the solution placed in the center of the source holder and covering the ring by another piece of Mylar to prevent contamination of the equipment by flaking.

4. MEASUREMENTS AND RESULTS

We have measured the directional correlation of the 0.72-Mev γ quanta in coincidence with β particles of 1.02-, 1.16-, 1.30-, and 1.44-Mev median energy. The β pulse-height range selected corresponded to 0.14 Mev in every case. The entire γ spectrum in coincidence with the selected β particles was recorded by the multichannel analyzer at 90°, 180°, and 270°. This simplified the correction for first-order chance coincidences (see below) and for contributions resulting from other γ rays. The total single-γ counting rate was used for normalization, to correct for geometrical variations.[20] The rate of selected β particles remained practically constant, except for source decay.

The measured spectrum was first corrected for $\gamma\gamma$ coincidences and second-order chance coincidences.[21] The former were measured by inserting a β absorber, the latter by delaying the pulse from SCA_1 by an amount large compared to the resolving time of the slow coincidence circuit. Then the single-γ spectrum was normalized to the coincidence spectrum at the 1.69-Mev peak and subtracted; since the 1.69-Mev γ peak can result from chance coincidences only, and since the first-order chance coincidence spectrum has the same shape as the single-γ spectrum, this is the proper correction for first-order chance events. To correct the height of the 0.72-Mev peak for a small contribution due to the tail of the 0.6-Mev peak, the shape of the latter was obtained by measuring the γ spectrum in coincidence with β particles of a kinetic energy >1.7 Mev. A correction for the contribution of the 1.32-Mev γ ray was applied by extrapolating the Compton distribution of that transition from higher energies down.

Figure 3 shows a portion of the γ spectrum in coincidence with β particles of 1.02-Mev energy, taken at 180°. The spectrum is also shown after subtraction of $\gamma\gamma$ and chance coincidences, and again after subtraction of the 0.6-Mev peak. The coincidence spectrum shows peaks at 0.60, 0.72 ± 0.01, and (not shown in the figure) 1.32 ± 0.02 Mev, in agreement with the decay scheme (Fig. 1). Here, the 0.60- and the 1.69-Mev peaks have been used for calibration. Evidence for the 0.65-Mev transition is discussed in the Appendix.

Since the 1.6-Mev β transition can be expected to be first-forbidden, the β-γ correlation is of the form

$$W(\theta)=1+\epsilon P_2(\cos\theta), \qquad (1)$$

at any given β energy. After all corrections including normalization had been applied to the coincidence spectra, the sum of four adjacent analyzer channels (see Fig. 3) was taken as a measure of the intensity of the 0.72-Mev peak. The contribution of the 0.65-Mev γ ray to the counts in this region should be small. The anisotropy $A'=[W'(180°)-W'(90°)]/W'(90°)$ thus obtained[22] was corrected for finite detector solid angles[23,24] using the correction factors $Q_\beta=0.89$ and $Q_\gamma=0.95$, where $Q_\beta Q_\gamma$ is the ratio between the uncorrected and the corrected correlation coefficient ϵ.

The results are shown in column 3 of Table I. In

TABLE I. Measured β-γ directional correlations in the decay $Sb^{124}\rightarrow Te^{124}$. The values for $E_\gamma=0.60$ Mev were not corrected for the presence of the triple cascade. The errors are standard errors based on counting statistics only.

β energy (Mev)	Coefficient ϵ in $W=1+\epsilon P_2(\cos\theta)$ $E_\gamma=0.60$ Mev	$E_\gamma=0.72$ Mev	$E_\gamma=1.32$ Mev
1.02	-0.221 ± 0.012	0.20 ± 0.02	
1.16	-0.252 ± 0.011	0.18 ± 0.02	
1.30	-0.272 ± 0.011	0.19 ± 0.03	
1.44	-0.320 ± 0.009	0.22 ± 0.06	
1.0–1.6			-0.28 ± 0.08

[20] These usually amounted to $\pm1.5\%$.

[21] For a discussion of higher-order chance coincidences, see H. Paul, Nuclear Instr. (to be published).

[22] The primed symbols indicate quantities before correction for finite solid angle.

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

[24] H. I. West, Jr., University of California Radiation Laboratory Report UCRL-5451 (unpublished). I would like to thank Dr. West for calculating the correction factor for our particular geometry.

column 2 of this table, the coefficient ϵ for the correlation between the highest energy β and the 0.60-Mev γ transition is also given which was obtained from the same measurements.[25] The latter results are fairly close to Steffen's[1] and give us confidence in our results concerning the 0.72-Mev γ transition; no complete agreement is expected since we did not correct the data in column 2 for the presence of the triple cascade $\beta(E_{\max}=1.6\text{ Mev})-\gamma(E=0.72\text{ Mev})-\gamma(E=0.6\text{ Mev})$.

In a separate measurement, we also obtained the anisotropy for the 1.32-Mev γ transition in coincidence with the 1.6-Mev β group. There, single-channel analyzers were used to select 1.0- to 1.6-Mev β rays and 1.32 ± 0.06 Mev γ pulses; the multichannel analyzer was not used. A second pulse-height analyzer set to accept all β particles with $E_\beta>1.7$ Mev was simultaneously employed, and its coincidences with the same selected γ pulses were also recorded. This served as a chance coincidence monitor.

Of the coincidences recorded at 180°, only 29% were true β-γ coincidences, the rest was first- (47%) and second- (12%) order chance coincidences and $\gamma\gamma$ coincidences (12%). Evidently, the relative scarceness of true coincidences not only produces a high rate of chance coincidences, but also increases the relative contribution of the second-order effects. For our evaluation, we used the following approximate formula[21]:

$$_3C^t={}_3C-D-{}_3C_t'', \tag{2}$$

where $_3C^t$ are the true triple coincidences, $_3C$ is the measured triple coincidence rate, D is the rate measured by delaying one of the pulses that enter the double coincidence circuit (resolving time τ) by an amount $>\tau$, and $_3C_t''$ are the second-order triple chance coincidences due to true double coincidences. The chance coincidence monitor mentioned in the foregoing was used as an independent check upon the rates D and $_3C_t''$.

The result of this measurement is given in column 4 of Table I.

5. EVALUATION AND DISCUSSION

For the evaluation of our results in terms of nuclear matrix elements, we use Kotani's[5] expression for ϵ:

$$\epsilon=(p^2/W)k(R_3+eW)[C(W)]^{-1}, \tag{3}$$

where p and W are electron momentum and total energy, respectively, in relativistic units; $k(R_3+eW)$ contains the spins, β matrix elements, and γ mixing ratio; and $C(W)$ is the shape correction factor. Formulas for these terms are given in the work cited in footnote 5.

Since the two correlations which we have measured (columns 3 and 4 of Table I) involve the same β transition, there is a simple relation between the values ϵ for the $3\rightarrow2\rightarrow0$ and for the $3\rightarrow2\rightarrow2$ cascade:

$$\frac{\epsilon(3\rightarrow2\rightarrow0)}{\epsilon(3\rightarrow2\rightarrow2)}=\frac{F_2(2202)(1+\delta^2)}{F_2(1122)-2F_2(1222)\delta+F_2(2222)\delta^2}=\frac{-0.598(1+\delta^2)}{-0.418+1.224\delta+0.128\delta^2}, \tag{4}$$

where the F_2 are F coefficients[26] and δ is the mixing ratio (quadrupole/dipole) of the 0.72-Mev γ transition.

Within our limits of error, $\epsilon(3\rightarrow2\rightarrow2)$ is independent of energy; we therefore use an average value $\epsilon(3\rightarrow2\rightarrow2)=0.19\pm0.01$. By substituting this value together with $\epsilon(3\rightarrow2\rightarrow0)=-0.28\pm0.08$ into Eq. (4), we obtain

$$\delta=+0.8_{-0.2}^{+0.7}.$$

This is in agreement with the value $\delta^2=1.0\pm0.2$ obtained by Lindqvist and Marklund[27] using $\gamma\gamma$-directional correlation measurements.

The essential question to be answered by our measurements is whether or not the B_{ij} matrix element contributes essentially to the 1.6-Mev β transition. In Kotani's notation, the four nuclear parameters (combinations of matrix elements) that can contribute to a $3^-\rightarrow2^+$ decay are u, x, Y, and z, where the first three contain the vector-type matrix elements and the last is proportional to $\int B_{ij}$. To prove our point, assume $z=0$ in $\epsilon(3\rightarrow2\rightarrow0)$, as given by Eq. (3), and substitute $W_0=4.11$ and (as an approximate average energy) $W=3.2$. One then gets

$$B\equiv\frac{\epsilon W}{p^2}=\frac{0.0278(2\gamma-\beta)(-1.47+1.18\beta+2.94\gamma)}{1.09(\beta-0.6)^2+3.94(\gamma-0.32)^2+0.20}, \tag{5}$$

where $\beta=u/Y$ and $\gamma=x/Y$. The experimental value is $B=-0.10\pm0.03$. It can be shown, however, that Eq. (5) reaches a value $B=-0.03$ for $Y=0$, $x=0.05u$ and never becomes smaller. The possibility $z=0$ can therefore be excluded. This shows that the B_{ij} element is necessary to explain the large negative correlation coefficient, and further, that a selection rule effect slows down the 1.6-Mev β transition just as it slows down the 2.3-Mev transition.

Finally, one might try to fit the measured correlation coefficients by a combination of matrix elements. The problem offers many solutions, of course, but assuming $u=x=0$ as for the 2.3-Mev transition[1,2] one can fit our data by either $Y/z=1.2$ or $Y/z=0.04$. In both these cases, the dependence of ϵ on energy is very small, in agreement with our results.

ACKNOWLEDGMENTS

The author would like to thank Professor R. W. King and Professor J. O. Rasmussen for illuminating

[25] The correlation of the 1.32-Mev γ ray cannot be obtained from these measurements, since the coincidence efficiency was set too low for higher energy γ rays.

[26] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957).

[27] T. Lindqvist and I. Marklund, Nuclear Phys. **4**, 189 (1957).

discussions, Mr. J. Alberghini for his help with some of the measurements and evaluations, and Mrs. M. Speer, Mrs. J. Laraway, and Miss K. McJelton for their help in reducing the large amount of data.

APPENDIX. EVIDENCE FOR THE 1.25-MEV LEVEL

When the 0.6-Mev peak was subtracted from the composite coincident γ spectrum, there was always a remainder (see Fig. 3) which might have been ascribed to the 0.65-Mev γ transition. To check this point more carefully, we measured the γ spectrum simultaneously in coincidence with β particles of 1.2–1.46 Mev, and with β particles of $E_\beta > 1.7$ Mev. That was done by externally routing the coincident pulses into one of the two halves of the multichannel analyzer, depending on the β pulse height. Since the γ pulses for both spectra went through the same circuits up to and including the analog-to-digital converter, there can be no relative pulse-height shift between the two spectra. Indeed, they matched perfectly at 0.60 Mev. The additional peak was still present after subtraction (see insert of Fig. 3), it appeared with an intensity about 0.7 times that of the 0.72-Mev peak, at an energy of 651 ± 16 kev. In view of the large inaccuracies involved in the subtraction, this is in good agreement with the energy and intensity expected for that transition[11,13,14] and presents additional evidence for the existence of the 1.25-Mev level in Te^{124}.

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Asymmetric Fission of Bismuth*

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An asymmetric mode of mass division in the mass region 66–73 has been observed in the fission of Bi^{209} with 36-Mev protons. About 0.3% of the fissions contribute to this mode. At 58 Mev no evidence for asymmetric fission (<0.05% of total fissions) as a separate mode could be found. The fission cross sections at 36 and 58 Mev are 1.9 and 11.3 mb, respectively. The narrowness of the 36-Mev asymmetric peak leads to the suggestion that the asymmetric fission of bismuth results from the fission of a single nuclear species and from a closed-shell effect, similar to the fine structure observed in low-energy fission of heavy elements. This asymmetric fission is considered to occur from states of relatively high excitation energy. However, the possibility of asymmetric fission also occurring from states of low excitation energy, whether following neutron evaporation or as a consequence of an inelastic proton interaction, cannot be ruled out. The symmetric fission observed with both 36- and 58-Mev protons is consistent with the results obtained by Fairhall in the fission of bismuth with 22-Mev deuterons.

I. INTRODUCTION

THE low-energy (<30 Mev excitation) fission of bismuth and radium has been shown by Fairhall and co-workers[1,2] to be strikingly different in mass distribution from that of thorium and heavier nuclei. Bismuth fission with 22-Mev deuterons[1] results in a narrow, symmetric mass distribution while 11-Mev proton fission of radium[2] exhibits a "three-humped" distribution. The center peak corresponds closely to the narrow, symmetric bismuth distribution while the two outside humps resemble the asymmetric modes that might be obtained for thorium fission, suitably adjusted for the difference in mass number. More recently Fairhall, Jensen, and Neuzil[3] have shown that symmetric fission is very sensitive to excitation energy but not to target mass number while asymmetric fission exhibits much greater sensitivity to mass number and less to energy.

We felt it conceivable that bismuth might also display an asymmetric mode, no doubt of small probability, if studies could be made at an excitation energy sufficiently low that it is not overwhelmed by the more probable symmetric mode. On the other hand, since the fission cross section drops rapidly with decreasing energy in the particle energy region of 20–40 Mev, there is a practical lower limit as well.

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[3] A. W. Fairhall, R. C. Jensen, and E. F. Neuzil, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva,* (United Nations, Geneva, 1958), Vol. 15, p. 452.