Fission of Au^{197} and Bi^{209} by C^{12} and O^{16} Projectiles*

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Using a proportional counter, measurements have been made of the fission fragment angular distributions, kinetic energy spectra, and the total fission cross sections for the reactions C+Au, O+Au, C+Bi, and O+Bi at 10.5 Mev per nucleon bombarding energies and for the C+Bi reaction at energies from 72 Mev to 126 Mev. The results show the kinetic energy spectra to be independent of the excitation of the compound system and the most probable fragment kinetic energies to be 75±3 Mev and 81±3 Mev for the gold and bismuth target reactions, respectively. In all cases the fission cross sections are found to be only 60–80% of the estimated compound-nucleus formation cross sections. The angular distributions are fitted by the theory of Halpern and Strutinski, and an attempt is made to determine some of the qualitative features of these heavy-ion reactions.

INTRODUCTION

WHEN heavy nuclei in the region of gold are bombarded by heavy ions the compound systems formed are considerably neutron deficient so that for a given Z the value of Z^2/A, the fissionability parameter, is considerably larger than for isotopes which lie near the region of maximum stability. Previously, fissioning systems in the region $Z<90$ were produced by light particle bombardments, but the investigations of fission from these systems were, in most cases, carried out by radiochemical techniques because of the relatively small fission cross sections. However, by using heavy-ion projectiles, compound systems can be produced which have a large probability of undergoing fission. This makes it possible to carry out quantitative investigations of the fission process in this region using counter techniques. Also by varying the projectile it is possible to study the fission process over a region of Z that is difficult to reach with light-particle reactions because of the difficulty in obtaining suitable targets of the elements between bismuth and thorium.

Reactions between heavy ions and heavy nuclei, however, involve the production of compound systems with high excitations, since an appreciable reaction cross section is obtained only for the bombardment with ions of energies greater than the Coulomb barriers of the target nuclei. Another characteristic of these heavy-ion reactions is that due to the relatively large masses of the projectiles, the compound systems, in general, are formed in high angular momentum states. The presence of this high angular momentum in the compound system might be expected to produce effects in heavy-ion reactions that are not present in otherwise similar light-particle-induced reactions. Thus, the interaction between heavy ions and heavy nuclei can be expected to produce systems with large excitations, high angular momenta, and a large probability of undergoing fission. In addition, it should be expected that there will be other processes which compete strongly with the fission. These other processes can be divided into two general classes, direct interactions and evaporation processes. The direct interactions involve the breakup of the incident projectile before the complete formation of a compound nucleus and would, in general, leave a residual excited compound system with a lower fissionability than the system formed by the complete amalgamation of the projectile and the target nucleus. For this reason, the presence of an appreciable probability for direct interactions might be expected to decrease the probability of fission. Also the probability of direct interactions might be dependent primarily on the properties of the projectile rather than of the target. The evaporation processes, on the other hand, involve the formation of a compound nucleus with the subsequent evaporation of light particles. The evaporated particles are expected to be mainly neutrons, but since the compound systems formed are already neutron deficient there may also be an appreciable probability of evaporating protons and alpha particles. It is expected that fission will compete at each stage of the evaporation chain. Since neutron evaporation leads to larger values of Z^2/A, the probability of undergoing fission should increase as more neutrons are evaporated. Conversely, the evaporation of charged particles would lead to systems of smaller Z^2/A and might decrease the fission probability. Because of the complicated nature of these reactions, the fission observed will be due to contributions from many different compound systems, so that the analysis of the observed results should be expected to yield only information on the properties of some average fissioning nucleus in the evaporation chain. Also, because of the many different competing processes it can not be expected that measurements of the properties of the fission fragments alone will lead to unambiguous conclusions concerning the reaction mechanisms or even the fission process itself.

In this experiment the energy spectra and angular distributions of the fission fragments and the total fission cross sections have been measured for several reactions. For the C+Bi reaction these measurements have been made as a function of bombarding energy

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for incident carbon ion energies from slightly above the Coulomb barrier to the maximum energy of 126 Mev. Measurements have also been made for the C+Au, O+Au, and O+Bi reactions at the maximum bombarding energies of 10.5 Mev per nucleon in order to obtain a comparison of fission processes from various initial compound systems.

EXPERIMENTAL PROCEDURE

In this experiment the fission fragments were detected and their energy measured in a proportional counter after having passed through a grid-supported 720-$\mu g/cm^2$ nickel entrance foil. The counter was normally operated at a pressure of about one atmosphere with a maximum path length in the counter of about 3 centimeters. The counter gas used was 90% argon plus 10% methane. This path length was sufficient to stop the most energetic fission fragments but short enough so that high-energy heavy ions would not lose a large fraction of their energy in the counter. With this path length there was no background due to the longer range evaporation protons and alpha particles, and the pulse heights produced by elastically scattered heavy ions were always considerably less than the peak of the fission fragment pulse-height distributions.

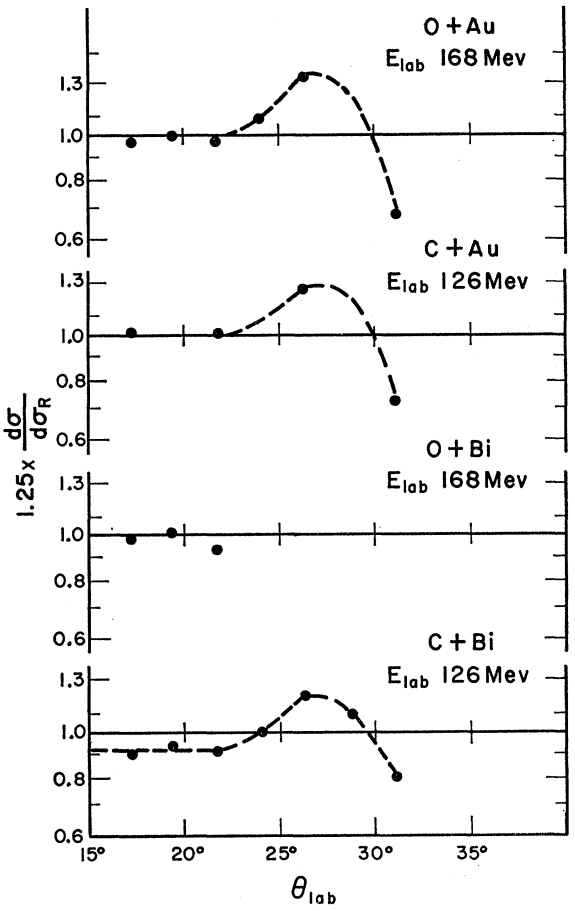

FIG. 1. The angular dependence of the ratio of the measured elastic scattering cross sections to the classical Rutherford scattering cross sections for the various reactions studied with bombarding energies of 10.5 Mev per nucleon. The quantity $d\sigma$ is the measured elastic scattering cross section determined from the integrated beam current.

In the scattering chamber used the proportional counter subtended an angle of about 2° at the target and could be placed at any laboratory angle from 8.5° to 171.5°. However, due to counting rate limitations in the proportional counter, reliable fission fragment spectra could not be obtained at angles where elastic scattering predominated. For this reason angular distributions were usually measured from 171.5° to the elastic scattering cutoff angle, i.e., to about 40° at 10.5 Mev per nucleon bombarding energies. A more detailed description of the equipment used in this experiment has been given elsewhere.[1]

The targets used were an unsupported 300-$\mu g/cm^2$ gold foil, and 300 $\mu g/cm^2$ and 550 $\mu g/cm^2$ of bismuth evaporated onto 25-$\mu g/cm^2$ Formvar backings. For the fission fragment spectra from the bismuth targets it was found that there was no significant background due to the Formvar backings.

The heavy-ion accelerator used in this experiment yielded full energy beams of 10.5 Mev per nucleon. When the full-energy beam was used, it was analyzed and its energy determined by use of two magnets each of which deflected the beam through an angle of 45°. For the reduced energy C+Bi experiments the beam energy was degraded by passing the beam through beryllium absorbers which were placed between the two magnets. In these cases the beam energies were determined from the currents in the second magnet. In all cases the beam energies were determined to an accuracy of about 2%. The beam was collimated at the entrance to the scattering chamber by two $\frac{1}{4}$-in. collimators placed 17 in. apart.

The energy scale for the proportional counter was calibrated by using a Cf^{252} spontaneous fission source and comparing to the results of Milton and Fraser.[2] Window and target thickness corrections were made using both Fulmer's data[3] and some measurements made in this laboratory on the absorption of Cf^{252} fragments in air and nickel. The calibration is believed to be reliable for fragments with energies above 60 Mev, but due to uncertainties in target and window corrections is somewhat in doubt for lower energy fragments.

The beam was monitored by collecting it in a Faraday cup which was connected to an integrator. Cross sections were then determined by two methods. In one case they were calculated using the integrated beam current, the target thicknesses known from weighings, and the calculated solid angle subtended by the counter

[1] C. E. Anderson, A. R. Quinton, W. J. Knox, and R. Long, Nuclear Instr. and Methods 7, 1 (1960).
[2] J. C. D. Milton and J. S. Fraser, Phys. Rev. 111, 877 (1958).
[3] C. B. Fulmer, Phys. Rev. 108, 1113 (1957).

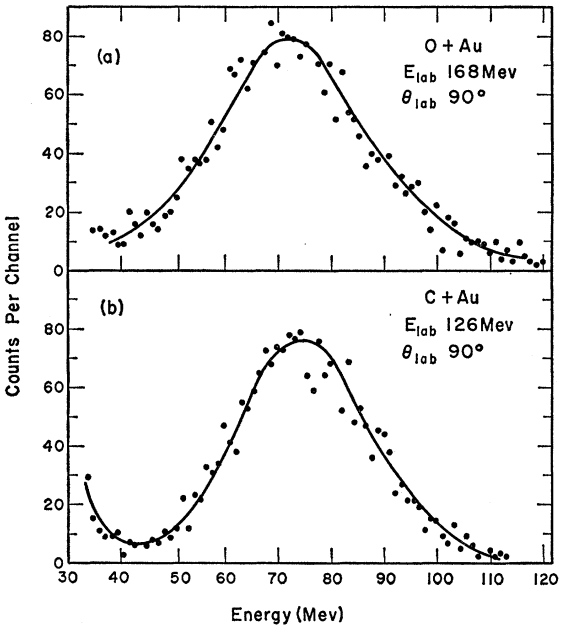

FIG. 2. The fission fragment energy spectra at 90° in the laboratory system for the C+Au and O+Au reactions.

at the target. The second method involved a normalization to Rutherford scattering. Using the same detection system as for the fission measurements, elastic scattering was observed for each reaction at a few angles which were far enough forward so that the $\csc^4(\theta/2)$ angular dependence was obtained. The cross sections obtained by this method were found to be about 25% higher than those calculated by the first method. This difference is expected to be due mainly to faulty charge collection in the Faraday cup. Figure 1 shows the angular dependence of the ratio of the experimentally measured elastic scattering cross sections to the calculated classical Rutherford scattering cross sections for 10.5 Mev per nucleon carbon and oxygen beams. In this case $d\sigma$ is the differential cross section determined from the integrated beam current. These results show that if a normalization factor of 1.25 is used the average value of 1.25 $d\sigma/d\sigma_R$ is close to 1 at small angles for the C+Au, O+Bi, and O+Au cases but that this quantity is 0.93 for the C+Bi measurements. However, other elastic scattering measurements for the C+Bi system gave average values for 1.25 $d\sigma/d\sigma_R$ at small angles of 1.04 and 0.98 for incident carbon ions with energies of 105 and 85 Mev, respectively. As a result of these measurements, the experimental fission cross sections were in all cases determined from the integrated beam current and then increased by a normalization factor of 1.25. From the scatter in the average values of $d\sigma/d\sigma_R$ at small angles for the various reactions and energies, it is estimated that the absolute fission cross sections determined by this method are accurate to about 10%. The angular dependence of $d\sigma/d\sigma_R$ is similar to the results reported for the elastic scattering of 120-Mev carbon ions by gold[4] and of 157-Mev oxygen ions by gold,[5] but the results are not directly comparable due to the difference in bombarding energies.

The results presented here were obtained from data taken on ten different days over a period of about five months. As a check on the internal consistency of the equipment, measurements were made during each run at a few angles for the full energy C+Bi reaction. These measurements always gave the same results to within the counting statistics.

DATA ANALYSIS

In order to transform an observed laboratory angular distribution to the rest system of the fissioning nuclei, it is necessary to know the center-of-mass velocity of the fissioning nucleus, the mass of the detected fragment, and the energy of the fragment in either the laboratory or the center-of-mass system. Because of the uncertainty in the energy calibration for low-energy fragments, there was some uncertainty in the fragment energy spectra at far backward angles. However, in all cases it was found that the movement of the peaks of the energy spectra with angle was consistent with an average velocity for the fissioning nucleus equal to the velocity of the original compound system, assuming full momentum transfer between projectile and target.

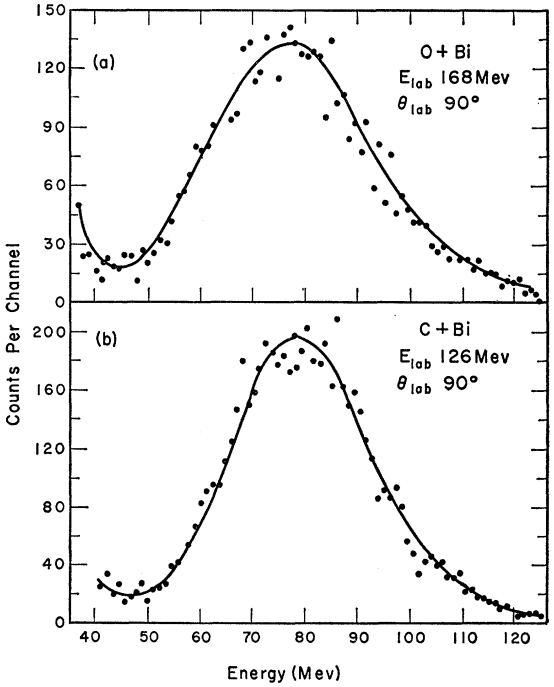

FIG. 3. The fission fragment energy spectra at 90° in the laboratory system for the C+Bi and O+Bi reactions.

[4] E. Goldberg and H. L. Reynolds, Phys. Rev. 112, 1981 (1958).
[5] J. A. McIntyre, S. D. Baker, and T. L. Watts, Phys. Rev. 116, 1212 (1959).

Using this value for the center-of-mass velocity and assuming a mass for the fragments, the center-of-mass energy spectrum for the fragments could be determined from the data taken at angles where the peak of the laboratory energy spectrum was above 60 Mev. Then the data for the backward angles could be transformed under the assumption that the center-of-mass energy spectrum is independent of the center-of-mass angle.

For each reaction the transformation was carried out assuming that all the fragments had a single mass and a single center-of-mass energy. The mass used was estimated from the peaks of the mass distributions obtained for similar heavy-ion reactions by radiochemical means.[6] The energy used was obtained from the peaks of the observed laboratory energy spectra. An analysis of the possible errors introduced due to transforming by this method, instead of using a spectrum of masses and energies for the fragments, and due to the uncertainty in the most probable mass for the fragments, indicates that in all cases the error introduced into the points in the center-of-mass angular distributions is less than 2%.

RESULTS AND DISCUSSION

A. Energy Spectra

The shapes of the fragment energy spectra were all found to be similar. Figures 2 and 3 show the energy spectra at 90° in the laboratory with 10.5 Mev per nucleon bombarding energies for the various reactions studied. These spectra have full widths at half maximum of 39% for the C+Au and C+Bi reactions and 47% for the O+Au and O+Bi reactions. This difference in the widths of the spectra for the carbon and oxygen induced reactions seems significant and possibly indicates that the widths of the energy spectra are somewhat dependent on either projectile or angular momentum. The energy spectra from the C+Bi reaction show no significant variation with incident energy in either shape or peak position (see Fig. 4). This indicates that in this case the fragment energy spectra do not depend strongly on either the initial excitation or the angular momentum of the fissioning nucleus. The most probable center-of-mass energies for the fragments from the reactions studied are listed in Table I.

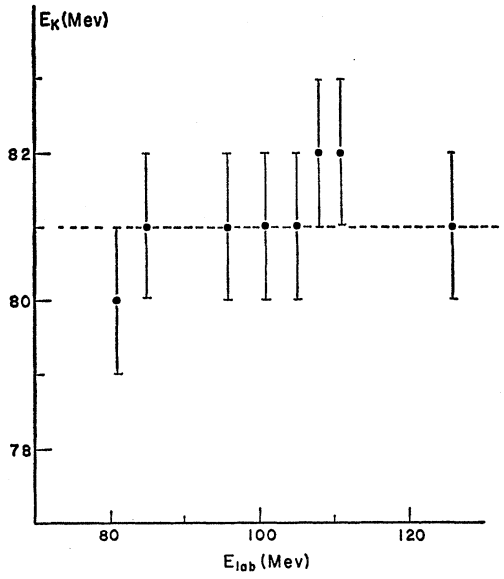

FIG. 4. The most probable center-of-mass energy versus the laboratory bombarding energy for the fragments from the C+Bi reaction.

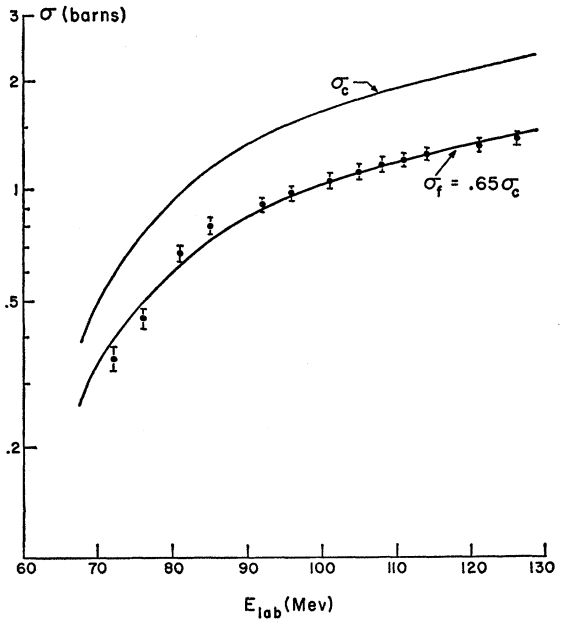

FIG. 5. The total experimental fission cross section and the estimated compound-nucleus formation cross section versus the laboratory bombarding energy for the C+Bi reaction. The estimated compound-nucleus cross section is obtained from reference 8.

Also listed in Table I are values for the average total kinetic energy release divided by $Z^2/A^{\frac{1}{3}}$. A compilation of the results available for the average total kinetic energy of the two fragments from various spontaneous and neutron-induced fission reactions has been made by Terrell.[7] Terrell showed that all the available results could be fitted fairly well by a linear function of $Z^2/A^{\frac{1}{3}}$. The best fit was obtained for the function

$$E_T = 0.121 Z^2/A^{\frac{1}{3}},$$

where E_T is the average total kinetic energy of the two fragments. For this experiment the values for $2E_K/(Z^2/A^{\frac{1}{3}})$ listed in Table I agree very well with the above dependence even though the values of $Z^2/A^{\frac{1}{3}}$ for

[6] N. I. Tarantin, Iu. B. Gerlit, L. I. Guseva, B. F. Miascedov, K. V. Fillippov, and G. N. Flerov, J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 316 (1958) [translation: Soviet Phys.—JETP 34(7), 220 (1958)].

[7] J. Terrell, Phys. Rev. 113, 527 (1959).

TABLE I. The most probable kinetic energies for fission fragments from the various reactions studied.

Reaction	E_K (Mev)	$2E_K/(Z^2/A^{\frac{1}{3}})$
C+Au	75±3	0.123
O+Au	75±3	0.119
C+Bi	81±3	0.123
O+Bi	81±3	0.119

the compound systems formed in these reactions are somewhat lower than the values for the reactions compiled by Terrell.

B. Cross Sections

The fission cross sections determined in this experiment by integrations of the angular distributions and normalizations to Rutherford scattering have been compared with theoretical total compound-nucleus formation cross sections. For the C+Au and O+Au reactions the calculations have been done by Thomas.[8] Interpolations of these results have been used for the C+Bi and O+Bi reactions. The experimental results are summarized in Table II. This small amount of data hints at the possibility that σ_f/σ_c may be dependent upon the projectile. These data would be consistent with a significant part of the reaction cross section being taken up by direct interactions, which do not lead to fission, and these processes being more important for incident carbon ions than for incident oxygen ions. This interpretation is somewhat substantiated by some preliminary results on the measurement of the direct interactions produced in the bombardment of gold by 168-Mev oxygen ions.[9] These results indicate that the total cross section for the production of B, Be, C, and N fragments is 0.5±0.1 barn which is approximately the value found in this experiment for $\sigma_c-\sigma_f$. Most of this cross section is taken up by C and N fragments which would leave a residual compound system with a fissionability that is very low compared to the O+Au compound system so that the probability of fission occurring after one of these direct interactions should be very small.

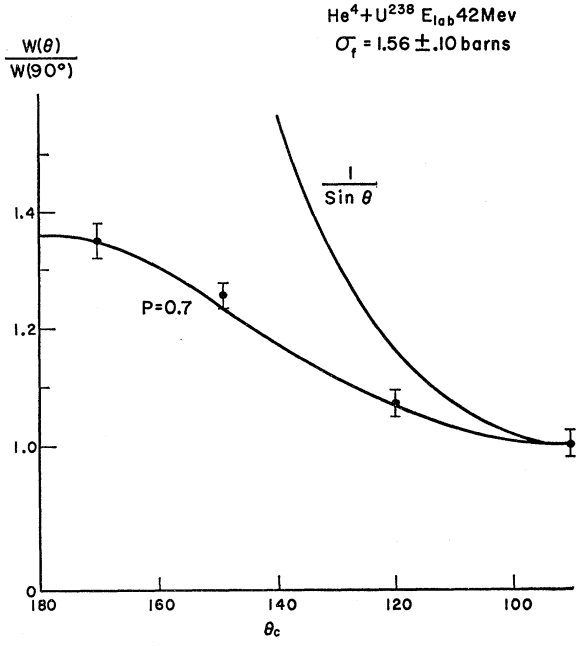

FIG. 6. The center-of-mass angular distribution of fission fragments for the 42-Mev He^4+U^{238} reaction.

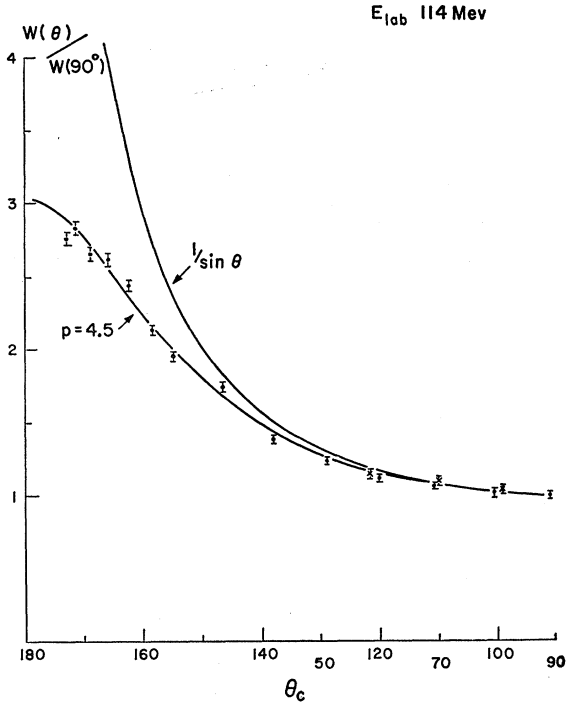

FIG. 7. The center-of-mass angular distribution of fragments from the C+Bi reaction at a laboratory bombarding energy of 114 Mev. Points for the angles 0°–90° are indicated by × and points for angles 90°–180° by ●.

The variation of the fission cross section with bombarding energy for the C+Bi reaction is illustrated in Fig. 5. Within the experimental errors these points can

TABLE II. The fission cross sections and theoretical compound-nucleus formation cross sections for the various reactions studied with 10.5 Mev per nucleon bombarding energies. The absolute fission cross sections are estimated to be accurate to about 10%. The values for σ_c have been obtained from Thomas.[a]

Reaction	E_{lab} (Mev)	$\sigma_c(b)$	$\sigma_f(b)$	σ_f/σ_c
C+Bi	126	2.2	1.38	0.63
C+Au	126	2.2	1.35	0.61
O+Bi	168	2.3	1.63	0.72
O+Au	168	2.3	1.80	0.79

[a] See reference 8.

[8] T. D. Thomas, Phys. Rev. **116**, 703 (1959).

[9] W. J. Knox and C. E. Anderson (private communication).

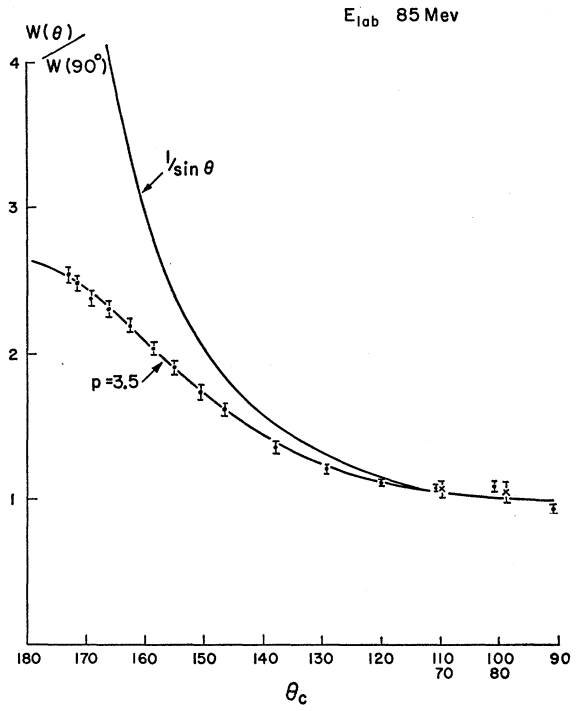

FIG. 8. The center-of-mass angular distribution of fragments from the C+Bi reaction at a laboratory bombarding energy of 85 Mev. Points for the angles 0°–90° are indicated by × and points for angles 90°–180° by ●.

be fitted to a curve of the form

$$\sigma_f = 0.65\sigma_c,$$

where again σ_c is due to Thomas.[8] This result suggests several possible interpretations: (1) that direct interactions take up a fixed fraction of the cross section; (2) that the cross section not leading to fission is taken up by a combination of direct interactions and evaporation chains that do not lead to fission with the direct interactions being most important at high bombarding energies and the evaporation that does not lead to fission being greatest at low excitation energies; (3) that the ratio of the fission to neutron widths is very small at high excitations so that the probability of all the excitation energy being given up to evaporation products without fission occurring is independent of the excitation energy at high excitations. However, the results of the analysis of the angular distributions, which is given below, seem to indicate that at high excitations the average fission occurs from a system that is still highly excited which would not be consistent with this last possibility.

In order to substantiate this rather surprising cross section data, the cross section for the fission of U^{238} by 42-Mev He^4 ions was also measured. From the four-point angular distribution shown in Fig. 6 a total fission cross section of 1.56±0.10 barns is obtained. This result is in good agreement with the value of 1.6 barns reported by Vandenbosch *et al.*[10] This value depends, as in all cases, on a normalization to Rutherford scattering at small angles. Although its effect on the cross section is slight, the value obtained for the anisotropy $W(180°)/W(90°)$ is less than that reported by Coffin and Halpern.[11]

C. Angular Distributions

Fission fragment angular distributions for the C+Bi system were measured for incident energies of 121, 114, 95, 85, and 72 Mev, and the laboratory anisotropies $W(180°)/W(90°)$ were measured for several other energies. In the center-of-mass frame these angular distributions are of similar form as is illustrated by Figs. 7–9. The angular distributions obtained from the reactions C+Au, O+Au, and O+Bi at bombarding energies of 10.5 Mev per nucleon are shown in Figs. 10–12. These results show that the anisotropies are much greater for the gold target reactions than for the bismuth target reactions with the same projectile and bombarding energy. The angular distribution for the C+Au reaction agrees well with the results of Gordon, Larsch, and Sikkeland.[12]

All the angular distributions have been fitted by curves of the shape predicted by Halpern and Strutinski.[13] The parameter obtained by such a fit is

$$p=\left(\frac{I_m}{2K_0}\right)^2=\left(\frac{\hbar^2}{2j_{\text{eff}}}\right)\frac{I_m^2}{2T},$$

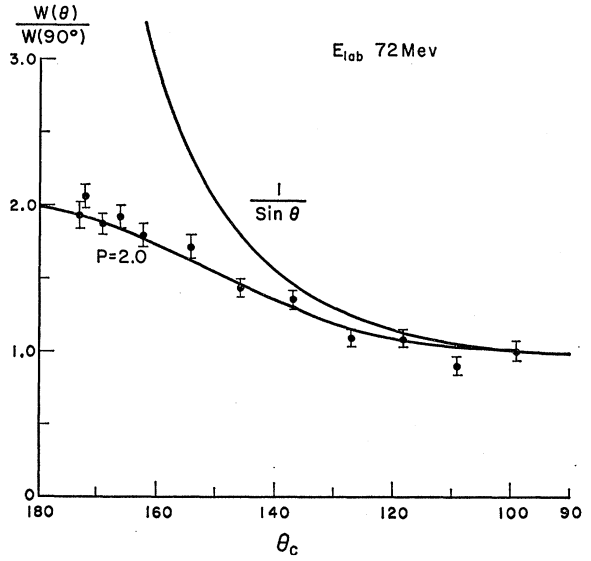

FIG. 9. The center-of-mass angular distribution of fragments from the C+Bi reaction at a laboratory bombarding energy of 72 Mev.

[10] R. Vandenbosch, T. D. Thomas, S. E. Vandenbosch, R. A. Glass, and G. T. Seaborg, Phys. Rev. 111, 1358 (1958).
[11] C. T. Coffin and I. Halpern, Phys. Rev. 111, 536 (1958).
[12] G. E. Gordon, A. E. Larsch, and T. Sikkeland, Phys. Rev. 118, 1610 (1960).
[13] I. Halpern and V. M. Strutinski, *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 398.

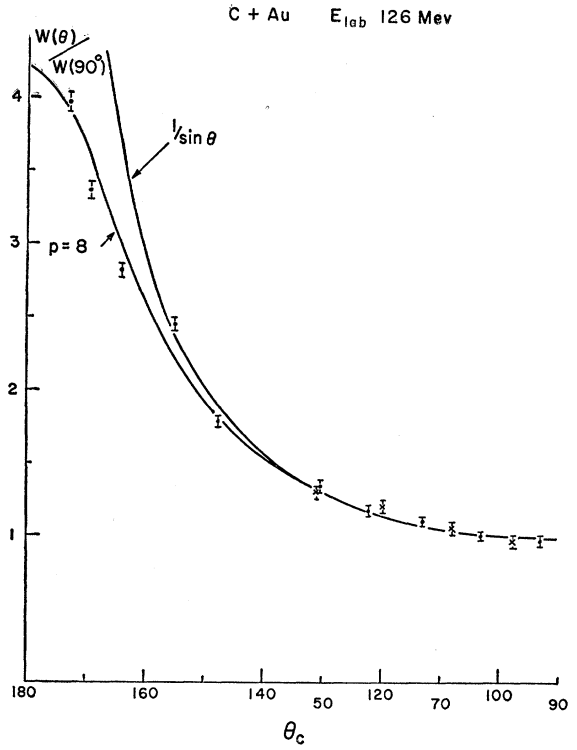

FIG. 10. The center-of-mass angular distribution of fragments from the C+Au reaction at a laboratory bombarding energy of 126 Mev. Points for the angles 0°–90° are indicated by × and points for the angles 90°–180° by ●.

where I_m is the maximum angular momentum of the fissioning system, T its temperature, and K_0^2 the mean of the square of the projection of I on the fission axis. In the above expression j_{eff} is the effective moment of inertia at the saddle point shape and is defined by

$$\frac{1}{j_{\text{eff}}}=\frac{1}{j_{\parallel}}-\frac{1}{j_{\perp}},$$

where $j_{\parallel}$ and $j_{\perp}$ are the saddle point moments of inertia about axes parallel and perpendicular to the fission axis.

Because of the high excitation energies in these experiments, particle evaporation, especially of neutrons, is likely to compete with fission. The result is that an observed angular distribution is a composite of several curves of the type predicted by the theory. In the absence, at this time, of any detailed information on the evaporation chains, the analysis of the results has been carried out in terms of the average fissioning nucleus in the chain.

Clearly evaporation lowers the temperature from an initial value T_i, corresponding to an initial excitation E_i, because of a loss, on the average, of an amount of excitation energy ΔE before fission occurs. It is also expected, on level density grounds, that evaporation should tend to lower the angular momentum from an initial maximum value of I_i. Then for the average fissioning nucleus p can still be written in terms of initial values as

$$p=\frac{\hbar^2}{2j_{\text{eff}}}\frac{I_i^2}{2T_i}\frac{1-\Delta I^2/I_i^2}{(1-\Delta E/E_i)^{\frac{1}{2}}},$$

where ΔI^2 is the typical lowering of I_i^2. If neutron evaporation is the most important competitor to fission, then ΔI^2 should be small in comparison with I_i^2 and the change in excitation energy would be the more important effect. If this is true, then the anisotropies should be greater for cases where a large fraction of the excitation energy is lost before fission than for cases where the fission occurs without much evaporation. Since fission is expected to compete more strongly with evaporation as Z^2/A of the compound system increases, the observed anisotropy should decrease with increasing target A for the same projectile and excitation. Qualitatively this is what has been observed.

For each case studied the initial temperature was calculated using

$$T_i=(10E_i/A)^{\frac{1}{2}},$$

where the tables of Cameron[14] were used for estimating E_i. Values of I_i were estimated from the calculations of Thomas[8] for carbon and oxygen on gold. Using these values estimates can be made of the rotational quantity

$$R=(\hbar^2/2j_{\text{eff}})f(\Delta E,\Delta I^2),$$

where

$$f(\Delta E,\Delta I^2)=(1-\Delta I^2/I_i^2)/(1-\Delta E/E_i)^{\frac{1}{2}}$$

is the quantity which determined the effect of evaporation on the angular distributions of the fragments.

For the C+Bi reaction the results of this analysis are shown in Fig. 13 which illustrates the dependence of p and R on the initial excitation energy. In Fig. 13 the indicated errors include only the estimated experimental errors and not the uncertainties in the estimates of T_i and I_i. If the assumption is made that $\hbar^2/2j_{\text{eff}}$ is approximately a constant for this reaction, then the observed variation in R would be due mainly to a variation in $f(\Delta E,\Delta I^2)$. If $\Delta I^2 \ll I_i^2$, which should be the case if the evaporation is mainly neutron evaporation, then a decrease in $f(\Delta E,\Delta I^2)$ with increasing initial excitation energy indicates a corresponding decrease in $\Delta E/E_i$. If the saddle-point shape is not strongly dependent on excitation or angular momentum, i.e., if $\hbar^2/2j_{\text{eff}}$ is approximately constant, then from the theoretical calculations of Swiatecki[15] it might be expected that in this region of Z^2/A the saddle-point shape should have a major to minor axes ratio of the order of 2:1. Using rigid-body moments of inertia, this would indicate that the value of $\hbar^2/2j_{\text{eff}}$ should be approximately 3 kev. If this value is roughly correct, then the C+Bi results indicate that for high initial excitations the average fission takes place

[14] A. G. W. Cameron, Chalk River Laboratory Report CRP-690, AECL-433, December, 1958 (unpublished).
[15] W. J. Swiatecki, Phys. Rev. 104, 993 (1956).

TABLE III. A tabulation of various quantities for the reactions studied with bombarding energies of 10.5 Mev per nucleon. The values for I_i^2 have been obtained from Thomas.[a]

Reaction	E_i (Mev)	p	I_i^2	T_i (Mev)	R (kev)	$(Z^2/A)_i$
C+Au	102	8.0±0.5	4800	2.2	7.4	34.6
O+Au	126	7.0±0.5	8360	2.7	4.5	35.5
C+Bi	82	4.5±0.5	4450	1.9	3.9	35.8
O+Bi	108	5.0±0.5	8360	2.1	2.5	36.8

[a] See reference 8.

from a system that is still rather highly excited. If this is true, then for the cases where a compound nucleus is formed the probability of all the excitation energy being dissipated in evaporation products without fission occurring should be small. This would be consistent with the previously mentioned possibility that at high excitations the fraction of the total cross section that does not go into fission is taken up primarily by direct interactions.

A similar analysis for the other reactions studied with 10.5 Mev per nucleon beams is given in Table III. The values of $(Z^2/A)_i$ for the initial compound system have been tabulated to show explicitly the correlation between $(Z^2/A)_i$ and R. If again $\hbar^2/2j_{\text{eff}}$ is assumed to be approximately constant and of the order of 3 kev, these results would indicate that the ratio of the fission to evaporation widths varies continuously and very rapidly with $(Z^2/A)_i$. This would seem to indicate that for the C+Au reaction the average fission occurs at a relatively low excitation while for the O+Bi reaction the average fission occurs at close to the initial excitation. Qualitatively these results seem to be consistent with a Z^2/A dependence for the ratio of the evaporation to fission widths that is similar to the results that have been compiled by Vandenbosch and Huizenga[16] for the variation of the ratio of the neutron to fission widths with Z^2/A for light-particle-induced fission reactions.

In the previous discussion it has been assumed that $\hbar^2/2j_{\text{eff}}$ is approximately constant so that the observed variations in R were due mainly to variations in $f(\Delta E,\Delta I^2)$, i.e., to variations in the competition between fission and evaporation. It might be expected for fissioning systems with high angular momenta that the saddle-point distortions would be somewhat decreased due to the relatively large rotational energy of the system. As the fissioning nucleus is distorted, the rotational energy will decrease and thus the addition of a rotational energy term to the total energy of a liquid drop could lead to a decrease in the distortion of the drop at the saddle-point shape. A decrease in the saddle-point distortion would lead to a corresponding decrease in $\hbar^2/2j_{\text{eff}}$ and, therefore, $\hbar^2/2j_{\text{eff}}$ should be expected to decrease with increasing angular momentum. Similarly the presence of high angular momenta should tend to decrease the fission barrier as has been shown theoretically by Pik-Pichak.[17] This should cause an increase in the ratio of the fission to evaporation widths and thus a decrease in $f(\Delta E,\Delta I^2)$ with increasing angular momentum. Therefore, because of both these effects R should be expected to decrease with increasing angular momentum.

For the reactions listed in Table III the fissioning systems produced by oxygen bombardment have an average angular momentum of about 60 $\hbar$ in contrast to a value of about 45 $\hbar$ for the carbon induced reactions. However, the values of R obtained for these reactions do not show any strong correlation with the angular momentum for the carbon and oxygen induced reactions. For the results from the C+Bi reaction as a function of energy it is possible that some of the variation in R may be due to these angular momentum effects, but it would seem unlikely that this is the major effect because of the absence of any noticeable angular momentum dependence in the reactions listed in Table III.

CONCLUSION

The information on the general characteristics of heavy-ion fission reactions which has been obtained from these results is somewhat crude due mainly to the

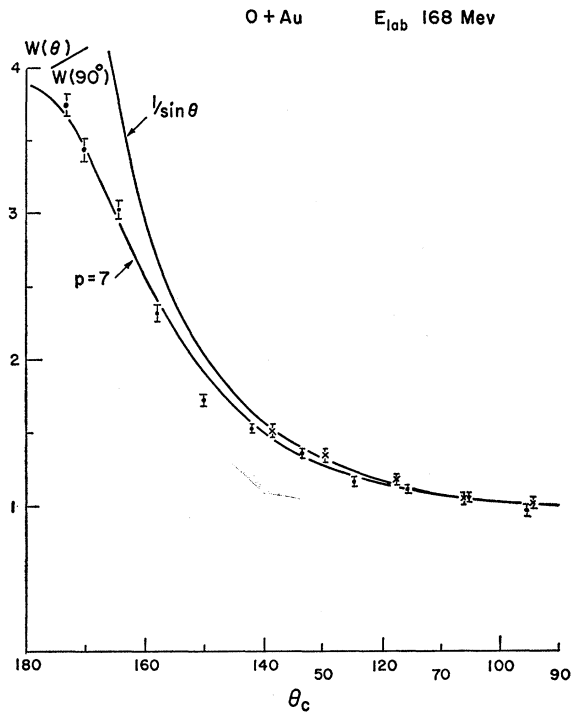

FIG. 11. The center-of-mass angular distribution of fragments from the O+Au reaction at a laboratory bombarding energy of 168 Mev. Points for the angles 0°–90° are indicated by × and points for the angles 90°–180° by ●.

[16] R. Vandenbosch and J. R. Huizenga, *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 284.

[17] G. A. Pik-Pichak, J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 341 (1958) [translation: Soviet Phys.—JETP 34(7), 238 (1958)].

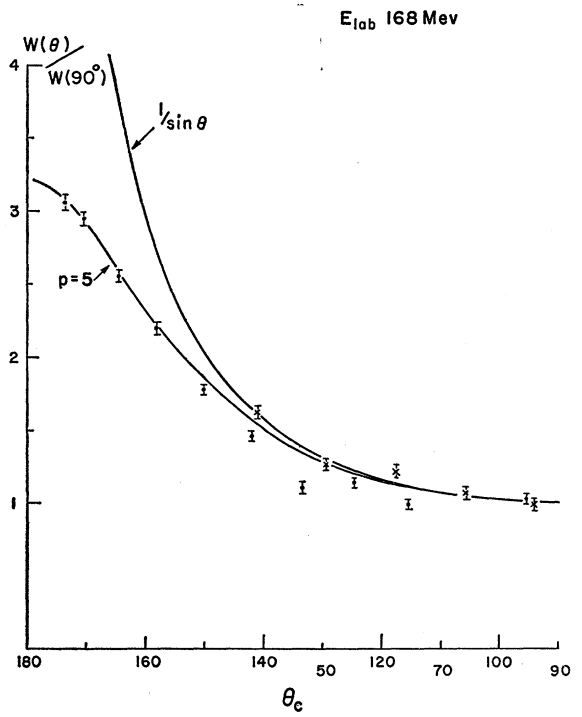

FIG. 12. The center-of-mass angular distribution of fragments from the O+Bi reaction at a laboratory bombarding energy of 168 Mev. Points for the angles 0°–90° are indicated by × and points for the angles 90°–180° by ●.

lack of detailed information concerning the other competing processes. Nevertheless, these results do indicate some of the general characteristics of the reaction mechanisms for the interactions between heavy ions and heavy nuclei.

The comparison of the fission cross sections to the theoretical compound-nucleus formation cross sections indicates that an appreciable fraction of the total cross section does not end up in fission. Furthermore, the indications that the ratio σ_f/σ_c may be projectile dependent and that in some cases the average fission probably occurs from a system that is still highly excited seem to suggest that the fraction of the total reaction cross section that does not lead to fission may be, at least in some cases, taken up mainly by direct processes involving the break-up of the projectile which would leave a residual excited system of low fissionability. This conclusion is somewhat substantiated for the O+Au reaction by some preliminary measurements on the direct interactions from this reaction which indicate that the total direct-interaction cross section is approximately equal to the difference between the compound-nucleus formation cross section and the total fission cross section.[9]

The general characteristics of fission from systems formed by heavy ion bombardment seem very similar to the results that have been found for other types of fission reactions. The lack of a dependence for the fragment energy spectra on the excitation of the compound system and the dependence of the total kinetic energy release on $Z^2/A^{\frac{1}{3}}$ are similar to the results from spontaneous and light-particle-induced fission reactions. The analysis of the angular distributions seems to indicate that the dependence of the ratio of the evaporation to fission widths on Z^2/A is qualitatively similar to the results obtained for light-particle-induced fission reactions. This result is rather interesting since the fissioning systems formed in these heavy-ion reactions have values of Z^2/A which are similar to systems which have been produced in light particle reactions. However, the systems produced in light-particle reactions have a Z and A somewhat greater than those formed by heavy-ion reactions. This similarity between fissioning systems of different Z and A but the same Z^2/A seems to indicate the validity of Z^2/A as the parameter which determines the fissionability of a system. Conversely, the systems formed in these heavy-ion reactions undergo primarily symmetric fission as is the case for systems with these values of Z formed in light-particle reactions. This seems to indicate that it is the Z of the fissioning system that determines whether or not asymmetric fission will be probable as has been previously suggested

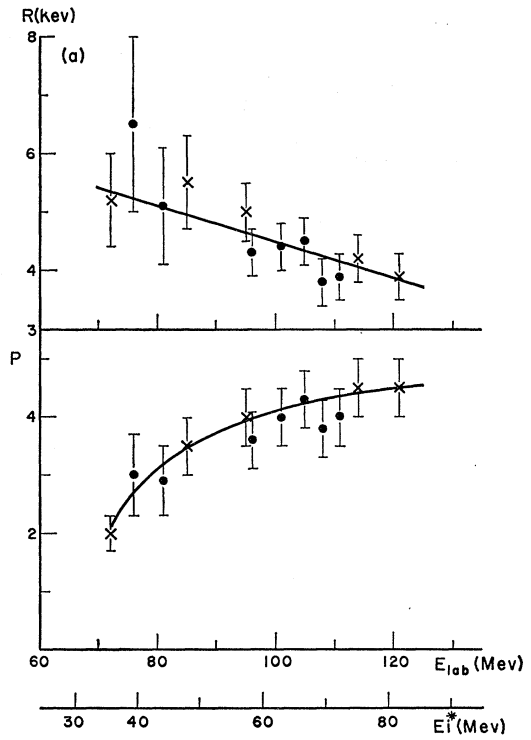

FIG. 13. The variation of p and R with the laboratory bombarding energy and the initial excitation energy of the compound system for the C+Bi reaction. The quantities p and R are obtained by fitting the angular distributions with the theory of Halpern and Strutinski (see reference 13). The points obtained from the analysis of complete angular distributions are indicated by × and the points from the laboratory anisotropies $W(180°)/W(90°)$ are indicated by ●.

by Fairhall, Jensen, and Neuzil.[18] These results are also interesting as they do not seem to show a strong dependence for the ratio of the evaporation to fission widths on angular momentum. This dependence of the fissionability on angular momentum, if present, must be consideraby less than the dependence on Z^2/A.

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

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Nuclear Orientation of Iodine by Electric hfs Alignment*

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Nuclear alignment of iodine in a single crystal of copper *p*-iodobenzenesulfonate at a temperature of about 0.03°K has been detected by measurement of the anisotropic angular distribution of gamma radiation from aligned I^{131}. No evidence was found for a nuclear spin-lattice relaxation time longer than a few seconds. The spin of the 637-kev level in Xe^{131} was established as 5/2, and the $E2/M1$ mixing ratio of the 364-kev transition was found to be $\delta=-6.7\pm0.5$. The quadrupole coupling constant eQq/h was found to be -950 ± 190 Mc/sec.

I. INTRODUCTION

THE electric-field gradient $q=(\partial^2 v/\partial z^2)_0$ at a nucleus arises from electrons that have nonspherically symmetrical charge distributions, i.e., from those outside closed shells and subshells. It may sometimes be as large as 10^{16} esu/cm^2. If the nucleus has a spin I of 1 or more it will have an electric quadrupole moment Q associated with its spheroidal shape. The interaction between the nuclear quadrupole moment and the electric-field gradient gives rise to hyperfine structure where the $2I+1$ nuclear magnetic substates are split so that their energies are given by

$$E(M)=\frac{3eQq}{4I(2I-1)}[M^2-\tfrac{1}{3}I(I+1)].$$

Pound has pointed out that this coupling could be used to produce nuclear alignment provided a crystal could be found in which the axis of symmetry of the crystalline field has the same direction for similar nuclei throughout the crystal.[1] By cooling the crystal to low temperatures such that $\Delta E\sim kT$, the nuclei will become aligned with respect to a crystal axis. Quadrupole coupling then offers a method for aligning nuclei of diamagnetic atoms, where magnetic hyperfine structure is not available. Dabbs *et al.* have employed this method to align nuclei in uranyl salts above 1°K,[2] and the extension to demagnetization temperatures seemed desirable.

In 1954 Daniels attempted to align I^{131} nuclei by this method.[3] Quadrupole-resonance measurements show that for I^{127} covalently bonded to carbon atoms in benzene rings, eQq/h is typically of the order of -2000 Mc/sec. The negative sign indicates that the lowest state has $M=\pm I$, corresponding to alignment of the nuclear spin along the bond rather than in the plane perpendicular to it. For I^{131}, which has a smaller quadrupole moment by a factor of about two, the coupling should be of the order of -1000 Mc/sec. The over-all splitting will be about 0.022°K and the nuclei must be cooled to temperatures in this region to obtain sufficient alignment to produce a measurable γ-ray anisotropy. The salt used was zinc *p*-toluenesulfonate, which has a monoclinic structure with all the $C-CH_3$ bonds making a small angle (about 12 deg) with the a axis. To reach the required temperatures this salt was grown in a mixed crystal with cobalt *p*-toluenesulfonate from a solution containing I^{131} in *p*-iodobenzenesulfonate ions and cooled by adiabatic demagnetization. The cobalt ions were cooled to about 0.1°K. No anisotropy of the gamma rays greater than 1% was observed,[3] and this was attributed to insufficient cooling of the crystal. However the possibility could not be definitely excluded that the iodine nuclei did not reach the temperature of the cobalt ions owing to a long spin-lattice relaxation time.

We have performed a similar experiment using copper *p*-iodobenzenesulfonate as the magnetic coolant.

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[3] J. M. Daniels, Can. J. Phys. **32**, 662 (1954).