Direct-Interaction Effects in Medium-Energy Fission of Uranium*

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The fraction of the fission events which occur after direct interactions rather than after compound nucleus formation has been determined in a number of bombardments of uranium. The projectiles used were 10.5-Mev protons, 21-Mev deuterons, and 42-Mev alpha particles. The fraction of post-direct-interaction fissions was obtained from measurements of the angular correlation of coincident pairs of fission fragments which emerged at approximately 90° to the incident particle beam. The results indicate that (2±3)% of fission events in 42-Mev alpha particle bombardments and (5±5)% in 21-Mev deuteron bombardments follow some type of direct interaction.

IN the interpretation of fission experiments performed at medium bombarding energies it is often of interest to know the relative amount of fission occurring after direct interactions (rather than after compound nucleus formation). An estimate of this fraction of events has recently been made on the basis of observations of the fission-product mass distribution.[1] One can also obtain an estimate by multiplying each of the cross sections for known types of direct interactions in heavy nuclei by the chance that the reaction leads to fission. The sum of such products, divided by the total fission cross section, would give the fraction of fissions which follow direct interactions.

The following measurement describes a more direct way to determine this fraction.[2] A "direct interaction" means, for purposes of this experiment, a reaction in which the forward momentum of the struck nucleus at the time of fission is different from what it would have been if the incident particle were initially completely absorbed. Information about the momentum of the fissioning nucleus is obtained from a measurement of the angular correlation of coincident pairs of fission fragments as shown in Fig. 1. It is seen from the diagram that $\tan\theta$ is $P/P_\perp$, where P and $P_\perp$ are the components of the momentum of the fragment reaching counter 2. If a compound nucleus is formed, P has an average value equal to that of the incident momentum, P_{IN}; otherwise it can be different, generally smaller. In any case, the observed values of P must be expected to be somewhat spread out about their average value. The main cause of this spread is the momentum given to the fissioning system by the neutrons which are evaporated before and after fission. Because the angle θ is very small at the energies in this experiment, the magnitudes of P_1 and P_2 are very nearly equal to P_f, the momentum of the fission fragments in their center-of-mass system. Indeed, it is true to a very good approximation that $\bar{\theta}=\bar{P}/\bar{P}_f$, where $\bar{P}$ is the average forward momentum of the fissioning nucleus. The object of this experiment was to determine the value of $\bar{P}$. This was done by measuring $\bar{\theta}$ and estimating $\bar{P}_f$.

To find $\bar{\theta}$, we measured the angular correlation between pairs of fission fragments. A natural uranium target was used in the experiment with each of the three projectiles available at the University of Washington cyclotron, 10.5-Mev protons, 21-Mev deuterons and 42-Mev alpha particles. The target was a thin (0.1 mg/cm^2) deposit of UO_3 on a VYNS[3] backing. The fragments were observed in a pulse ionization chamber (counter 1) and in a proportional counter (counter 2). They entered each counter through a 1/20-mil nickel window. Each window was covered with a collimator subtending an angle of about 0.8° in the plane of the counters. The opening of the collimators was about 3° in the perpendicular direction. With these apertures and normal beam intensities (~4 mμa), a coincidence rate of one count per minute was obtained at the peak of the angular distribution. The counters were able to discriminate against all particles other than fission fragments. As a result, the number of accidental coincidences was in all cases totally negligible even though the coincidence circuit employed had only a moderate resolving time (5 μsec).

Figure 2 shows the angular correlation obtained with

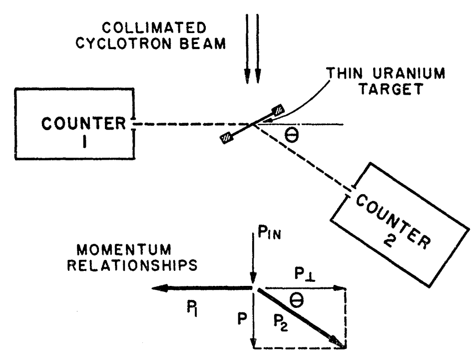

FIG. 1. The arrangement of the fission counters with respect to the beam. The angular correlation between fission fragments was measured with counter 1 at right angles to the incident beam and counter 2 movable. The relevant momentum relationships under these conditions are shown in the lower sketch.

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[1] T. T. Sugihara *et al.*, Phys. Rev. **108**, 1264 (1957).
[2] This technique has been used previously in bombardments with high-energy projectiles. V. I. Ostroumov, Doklady Akad. Nauk. S. S. S. R. **103**, 409 (1955).
[3] B. D. Pate and L. Yaffe, Can. J. Chem. **33**, 15 (1955).

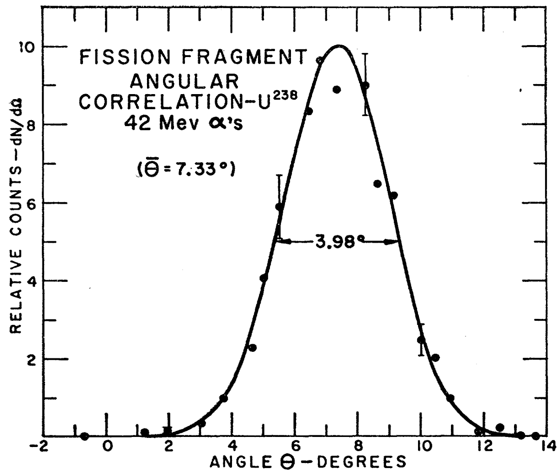

FIG. 2. The angular correlation between coincident pairs of fission fragments in the alpha-particle bombardment of uranium. The angle θ is defined in Fig. 1.

42-Mev alpha particles. It is based on four independent runs. Similar curves were obtained in the proton and deuteron bombardments. In the latter case, where the neutron background was expected to be the most serious, it was verified that only a negligible fraction of the fissions were being produced by neutrons. The angle $\theta=0$ was located both with a jig constructed for the purpose and on the basis of the proton bombardments. The latter determination, which was the more precise, was based on the assumption that *all* of the fissions in bombardments with 10.5-Mev protons, follow compound nucleus formation. Both methods of locating $\theta=0$ agreed within 0.1°.

In order to obtain a value of $\bar{P}$ from the measured $\bar{\theta}$ it is necessary to have information about the value of $\bar{P}_f$ and about any angular dependence that $\bar{P}_f$ may have. For this reason complete pulse-height spectra of the fission fragments were taken in counter 2 at all angles. It was found, as one would expect from kinematic considerations, that the average value of P_f decreased as θ increased. The effect on $\bar{P}$ was small and was easily taken into account. For the protons, an appropriate value of $\bar{P}_f$ was determined from the assumption that the average kinetic energy release, roughly twice $(1/2M)(\bar{P}_f)^2$, with M the mass of a typical fragment, was 169 Mev. This value is the average of the measured values[4] in the thermal neutron fission of U^{235} and Pu^{239}. In using a value for $\bar{P}_f$ based on low-energy measurements, we are using the apparent fact that the mean kinetic energy release is quite insensitive to the bombarding energy.[5] Although it was not possible for us to measure absolute values of the kinetic energy release, it was possible to show, from measurements of fission pulse-height spectra, that this energy release changed by less than 3 Mev when the energy of bombarding alpha particles was raised from 26 to 42 Mev. In the same way it was possible to show that $\bar{P}_f$ for the proton, deuteron, and alpha particle bombardments in this experiment had the relative values 1.0 to 0.995 to 0.995 where the error of the measurement was about 1%.

The first column in Table I lists the observed values of $\bar{\theta}$ with their estimated errors. The second column gives the computed values of the same quantity based on the assumption that all reactions leading to fission are taking place through compound nucleus formation. In computing the "compound nuclear" $\bar{\theta}$, exact kinematic expressions were used in place of the small angle approximations with the above mentioned value for the mean fragment kinetic energy. The estimated uncertainty of the computed values of $\bar{\theta}$ is about $1\frac{1}{2}\%$, or roughly the same as the errors in the measurements of $\bar{\theta}$. It comes mostly from uncertainties in the values of the kinetic energies of the fission fragments.

Column 3 in Table I gives the measured widths of the angular correlations between fission fragments (see Fig. 2). The fourth column gives the expected widths on the basis of the geometry of the experiment and the calculated smearing of the correlation due to the neutron evaporation which takes place before and after fission. In each case at least half the estimated width is due to the neutron evaporation. It is seen from the table that the actual widths are within 10% of the estimated ones. The small discrepancy may indicate that the mean kinetic energies of the neutrons or their angular distribution (assumed isotropic) with respect to the fragments was misestimated. It is clear that, desirable as it might be to learn about higher moments of the P distribution by measuring the higher moments of the angular correlation, it would be difficult to do so. The loss in angular resolution due to the evaporation of neutrons is too severe at the bombarding momenta of the present measurement.

It is seen from the table that the estimated values of $\bar{\theta}$ agree with the measured ones within their errors in all three cases. Within 2 to 3% for deuterons and about $1\frac{1}{2}\%$ for alpha particles, the average forward momentum deposit is therefore the same as it would be if compound nuclei were always formed. Any difference in the two values could be expressed as a product of two factors: (the fraction of the fission events that follow direct

TABLE I. The average angle in degrees between coincident fission fragments and the widths of the distributions in angle.

Bombardment	$\bar{\theta}$[a] measured	$\bar{\theta}$ computed	Half-width measured	Half-width computed
10.5-Mev protons	1.86[b]	1.86	1.43±0.10	1.32
21-Mev deuterons	3.66±0.08	3.74	1.72±0.12	1.59
42-Mev alpha particles	7.33±0.08	7.43	1.99±0.07	1.78

[a] $\bar{\theta}$ is the difference between the average angular separation of a pair of coincident fission fragments and 180° (see Fig. 1).

[b] The $\bar{\theta}=0$ position was chosen such that the measured and computed $\bar{\theta}$ for protons were equal.

[4] W. E. Stein, Phys. Rev. **108**, 94 (1957).

[5] J. Jungerman and S. C. Wright, Phys. Rev. **76**, 1112 (1949).

interactions rather than compound nucleus formation) $\times$ (the difference between the mean forward momentum deposit in the direct interactions and compound nucleus formation). For example, if the direct interactions happened to result in deposits of the same average momentum as in the normal reactions, they would not be detectable in the present measurement.

It is reasonable to assume, however, that the forward momentum deposits in direct interactions are appreciably smaller than compound nuclear deposits. Angular distribution measurements of some specific direct interactions like stripping and inelastic scattering tend to support this assumption. We have found, for example, that the inelastically scattered alpha particles in $(\alpha,\alpha' f)$ reactions appear predominantly forward of 60°, leaving, on the average, only about $\frac{1}{4}$ of the incident momentum with the nucleus. According to all indications, this number, $\frac{1}{4}$, should apply in good approximation to all of the direct interactions which are induced by alpha particles. Using this number, the figures in Table I imply that $(2\pm3)\%$ of the fission events follow direct interactions of some sort. This conclusion is consistent with one based on the summation of those reactions reported by Vandenbosch *et al.*[6] that appear, from the nature of their excitation curves, to involve direct interactions.

It would appear from an analysis of deuteron stripping angular distributions[7] that at most half of the incident momentum is left in the nucleus of these reactions. This, together with our measurements of $\bar{\theta}$, leads to an estimate of $(5\pm5)\%$ for the amount of direct interaction preceding fission for the deuteron bombardments.

It would be desirable to relate the above results to the quantity σ_D/σ_R, the ratio of the direct-interaction cross section to the reaction cross section. However, because we use fission as an indicator, we can at best learn something about $(\sigma_D/\sigma_R)_{>6}$, where the subscript means that the measurement involves excitation energies which lie above the fission threshold (~6 Mev). Actually we measured $(\sigma_{DF}/\sigma_{RF})_{>6}$, that is, the ratio of the fission-producing parts of the direct and total cross sections. But one can easily show that in the alpha-particle bombardment, for example, $(\sigma_D/\sigma_R)_{>6} \cong 1.3(\sigma_{DF}/\sigma_{RF})_{>6}$. The factor 1.3 is obtained from the known fissionabilities[8] of the nuclei involved in the reactions. On the basis of our result that $(\sigma_{DF}/\sigma_{RF})_{>6} = (2\pm3)\%$, it follows that $(\sigma_D/\sigma_R)_{>6} = (3\pm4)\%$.

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[6] R. Vandenbosch *et al.*, Phys. Rev. **111**, 1358 (1958).

[7] N. S. Wall, Phys. Rev. **96**, 670 (1954).

[8] J. R. Huizenga, Phys. Rev. **109**, 484 (1958).

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Measurement of Primary Directions in Extensive Air Showers*

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The abilities of various extensive shower arrays to detect possible departures from isotropy of the directions of incidence of very high-energy cosmic-ray primaries are analyzed. The effects of angular resolution, selectivity of total energy and sensitivity to the nature of the primary are discussed. A simple method of analyzing variation in intensity with declination is given and applied to some recent experimental results. It is shown that in two well-known cases these are not consistent with the hypothesis of isotropy of incoming directions.

I. INTRODUCTION

EXTENSIVE air showers of cosmic radiation are due to primary particles of great total energy. The assignment of the lower limit to this energy is a matter of definition of what constitutes an extensive air shower. One might reasonably choose 10^{14} ev. No upper limit to the total energy is known. Showers whose total energy was as high as 10^{18} ev. have been reliably reported and even higher energies have been claimed. The origin of particles of such high energy is of great interest and an obvious way to obtain information about this is to study the directions of arrival of these showers and to try to see if any particular directions in space are preferred or not. The experiment, however, is greatly complicated by a number of factors, one being the very small flux of high-energy particles.

II. NATURE OF THE PROBLEM

The nature of the primaries producing extensive air showers is not known. Conservatively one may expect that these include all nuclei from hydrogen to iron

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