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ANGULAR CORRELATIONS IN HIGH ENERGY FISSION*+

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I. INTRODUCTION

It seems to be now established that when a high energy nucleon collides with a heavy nucleus, and the collision leads to fission, the events take place in the following way:

The incoming nucleon develops inside the heavy nucleus a nucleonic cascade.

The nucleonic cascade can be absorbed in the nucleus or can come out from it. From the work of Belovitskii et al.[1], it seems that the change from one case to the other takes place around incident nucleon energy of 150 Mev.

The nucleus is left with a large excitation energy forming a compound nucleus which decays by fission and by the emis-

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sion of many neutrons.

We can assume, as Blatt and Weisskopf[2] do in a similar case, that all the reactions of the decay of the excited nucleus take place through elementary reactions in which only two products are formed. This will be true if the time between reactions is longer than the transit time of nucleons over the nucleus.

The decay of the excited nucleus can now take place according to three different schemes.

In scheme I, the first event is the fission of the heavy nucleus, with the emission of the neutrons taking place from the excited fission fragments. The reactions will be as follows:

$$H_0 = F_0 + G_0$$

$$F_0 = F_1 + n \qquad G_0 = G_1 + n$$

$$F_1 = F_2 + n \qquad G_1 = G_2 + n$$

$$\text{etc.} \qquad \text{etc.}$$

Here H means heavy nucleus, F and G are fission fragments. This scheme has been suggested already[3].

In scheme II there are neutrons emitted before fission, and neutrons emitted from the fission fragments. The reactions will be as follows:

$$H_0 = H_1 + n$$

$$H_1 = H_2 + n$$

$$\text{etc.}$$

$$H_n = F_0 + G_0$$

$$F_0 = F_1 + n \qquad G_0 = G_1 + n$$

$$F_1 = F_2 + n \qquad G_1 = G_2 + n$$

etc. etc.

A third scheme proposed by Goeckermann and Perlman[4], in which all the neutrons were emitted before fission, seems to ruled out by the experiment of Harding and Farley[5]. They irradiated U with 147 Mev protons and measured the ratio $N_0(f,n)/N_{90}(f,n)$ of the intensity of neutrons emitted at an angle of 0° with the fission fragments, and at an angle of 90° with the fission fragments, and found 1.27 ± 0.11. Although they interpreted their result as meaning that, of the 13 neutrons emitted in the process, 2.5 were emitted after fission, it has been shown[6] that their result is compatible with the emission of all the neutrons after fission, according to scheme I.

II. ANGULAR CORRELATIONS

Wolke[7] has measured the angular correlation of one of the fission products of Bi when irradiated with 450 Mev protons, and he found the distribution $N_\theta(p,f) = 1 + 0.13\cos^2\theta$ between the proton and the fragments. Loshkin et al.[8] have measured in plates the angular distribution of the fission of U with 660 Mev protons and found the correlation $N_\theta(p,f) = 1+0.29\sin^4\theta$ between the proton beam and the fragments.

From the data of Steiner and Jungerman[9], we extrapolate that the fission cross section for Bi with 450 Mev protons is about 0.23 barn and for U with 660 Mev protons about

$\pi\bar{\lambda}^2$ for protons of 450 Mev is 1.17 mb and for protons of 660 Mev it is 0.73 mb. This means that, to add up to the experimental cross sections, we have to take the partial waves to $\ell = 13$ and $\ell = 41$ respectively. Even if there is some angular momentum leaving with the nucleonic cascade, the compound nucleus will have a large spin.

On schem I, the existence of the angular correlation **can be** understood readily. This angular correlation means quantum mechanically that the fission fragments are emitted with orbital angular momentum of 0 and 1 in the case of Bi and 0,1 and 2 in the case of U.

Since the average direction of the nucleonic cascade is the same as the direction of the incoming proton, it does not matter for defining a direction whether the cascade comes out or is absorbed in the nucleus. If the first event to happen to the excited nucleus is the fission, this will have a direct angular correlation with the direction of the incoming proton.

There are still several questions to be answered, such as why the coefficients have the values that they have, and why the angular correlation of U is peaked at 0° below proton energy of 60 Mev and at 90° above proton energy of 60 Mev.

On this scheme it can also be calculated the angular distribution $N_\Theta(p,n)$ of neutrons with respect to the incident proton beam, and it turns out $1 + 0.004\cos^2\theta$ for Bi, and $1 - 0.003\cos^2\theta$ for U. As can be seen, they are practically symmetric. A forward cone due to the neutrons from the nucleonic cascade will be superimposed on this distribution.

It is also possible in scheme I that there is an angular correlation $N_\theta(f,n)$ between the fission fragment and the emitted neutrons due to the emission of the first neutron with angular momentum equal or greater than one. We guess that this correlation is small, strongly reduced by the remaining neutrons, and cannot be separated from the correlation due to the motion of the fission fragments. There might be also a small correlation $N_\theta(n,n)$ between any two neutrons, due to the emission of two consecutive neutrons from the same fission fragment with angular momentum equal or greater than one. We guess also that this correlation would be small and strongly reduced by the remaining neutrons.

In scheme II, the angular correlation between the incident proton or the nucleonic cascade and the fission fragments has to be preserved through the angular correlation of the intermediary neutrons. That means that all the neutrons evaporated before fission are emitted with angular momentum equal or greater than one.

The first neutron emitted would have to have a strong angular correlation $N_\theta(p,n)$ with the proton beam or the nucleonic cascade. Each emitted neutron would have to have a strong angular correlation $N_\theta(n_i,n_{i+1})$ with the following neutron, and the last neutron emitted before fission would have to have a strong angular correlation $N_\theta(n_n,f)$ with the fission fragments.

We have made calculations considering all the emissions until fission with $\ell = 1$. The three distributions mentioned in the previous paragraph would have the form $a_0 + a_2\cos^2\theta$. We found that, with values for the coefficients in the range of other measurements of nuclear angular distributions, the number of neutrons emitted before fission would be zero. We also found that, in the best of cases, the number of neutrons emitted before fission in Bi would be 4 and in U would be 2.

We then made calculations considering all the emissions before fission with $\ell = 2$. The three distributions would have the form $a_0 + a_2\cos^2\theta + a_4\cos^4\theta$. We found again that, with values of the coefficients in the range of other measurements, the number of neutrons emitted before fission would be zero, or perhaps one, and the largest number of neutrons emitted before fission would be 4 in U and 7 in Bi.

In the case of scheme II, there should be also an angular correlation $N_0(p,n)$ between the incoming proton and any neutron. We found that $N_{180}(p,n)/N_{90}(p,n) - 1 = 0.12\ n$, where n is the number of neutrons emitted before fission and the relation is true within 40%. There would be superimposed on this correlation the forward cone of neutrons from the nucleonic cascade.

In the case of scheme II, there should be also an angular correlation $N_\theta(n,n)$ between any two neutrons if there were two or more neutrons emitted before fission. If three or more neutrons were emitted before fission, this angular correlation should be more assymetric than the angular correlation between the proton beam and the fission fragments, in spite of the smearing from the neutrons emitted after fission.

In conclusion, there are 4 kinds of angular correlations in high energy fission. They are $N_\theta(p,f)$, $N_\theta(p,n)$, $N_\theta(f,n)$ and $N_\theta(n,n)$. There are measurements of the first and third, but there is not any measurement of the other two correlations. All the experimental data are compatible with scheme I and indicate contradictions with scheme II. A few more measurements could settle the problem of the qualitative mechanism of high energy fission, which is certainly a previous step to any attempt at a quantitative theory of high energy fission.

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