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QUASI-FISSION REACTIONS INDUCED BY 365 MeV ^{63}Cu IONS ON A ^{197}Au TARGET

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Résumé. — Les sections efficaces des réactions de fusion complète et de quasi-fission ont été mesurées pour le système ^{63}Cu + ^{197}Au à une énergie de bombardement égale à 1,1 fois la barrière d'interaction. Comme dans le cas des réactions induites par krypton étudiées précédemment, la fusion complète est très peu probable et la section efficace de quasi-fission (250 ± 50 mb) représente la moitié de la section efficace de réaction. La masse des produits de quasi-fission varie avec l'angle de détection. La distribution angulaire des produits légers (voisins du cuivre) présente un maximum à un angle légèrement inférieur à l'angle d'effleurement. Les résultats suggèrent que, pour les faibles paramètres d'impact, un échange de masse plus important a lieu et que l'écart angulaire par rapport à la diffusion élastique est beaucoup plus fort que pour les grands paramètres d'impact. L'énergie cinétique totale est constante en fonction de l'angle (ou légèrement croissante aux faibles angles).

Abstract. — Quasi-fission and complete fusion cross sections have been measured for the system ^{63}Cu + ^{197}Au at a bombarding energy equal to 1.1 times the interaction barrier. Like the krypton case, very few complete fusion events are observed, and the quasi-fission cross section (250 ± 50 mb) is one half of the reaction cross section. A more precise determination of the mass of one of the products has been performed. The mass distribution of the quasi-fission products varies with the angle of detection. The light products (mass around that of copper) show a clear maximum at an angle slightly lower than the grazing angle. The results suggest that events found at the low angles correspond to projectiles with low *l*-values which have undergone a greater mass exchange than the high *l*-value projectiles. The total kinetic energy is constant as a function of the angle, or slightly increasing at forward angles.

Since the reaction of *quasi-fission* has been observed [1] in bombardments of heavy nuclei with ^{84}Kr ions, several features of this phenomena have been studied [2, 3] and our present experimental knowledge can be summarized as follows : two main fragments are produced, the mass of one fragment being close to the mass of the projectile and the mass of the other fragment close to that of the target nucleus. The fragment kinetic energies are close to (somewhat higher than) the values expected for fission of the compound nucleus [2] and at the energies where measurement have been made (from 1.1 to 1.3 times the interaction barrier) the cross section for quasi-fission accounts for more than one half of the total reaction cross section, while the fusion cross section is unexpectedly small. Perhaps the most puzzling feature, however, is that the angular distribution of the light quasi-fission products is strongly peaked at an angle slightly lower than the projectile grazing angle.

Since the major fraction of the reaction cross section goes into a complete fusion process for projectiles up to ^{40}Ar, the question of the relative importance of complete fusion and of quasi-fission arose for reactions induced by projectiles between Ar and Kr. An answer to this question was provided by a preliminary result from an experiment done with the first ^{63}Cu projectiles accelerated at the Orsay heavy ion accelerator ALICE. With 395 MeV ^{63}Cu ions incident on a ^{186}W target, the main observed features were found to be similar to those of the Kr case : low fission cross section, high quasi-fission cross section and an angular distribution peaked near (but slightly lower than) the grazing angle [4].

It must be kept in mind that all the results of references [1-4] have been obtained by simply measuring the kinetic energies and angles of the two final products. More intense ^{63}Cu beams allowed us to make a direct determination of the mass of one final product, by measuring its time-of-flight and energy.

The choice of the ^{197}Au target and of the bombarding energy (365 MeV) are based on the following considerations :

1) The maximum angular momentum involved in the reaction is around 100 $\hbar$ and the compound

nucleus has an excitation energy of 60 MeV. Thus all of the complete fusion nuclei that are produced are expected to undergo binary fission with a *symmetric* mass distribution [5].

2) The results will not include fission following transfer reactions. Such *ternary* processes have been observed with Ar and Kr projectiles on targets heavier than gold [8].

3) The bombarding energy is 1.1 times the interaction barrier, as was the case in situations where quasi-fission has been observed previously with Kr and Cu projectiles.

The time of flight has been measured by means of a plastic scintillator (Ne^{111} 145 $\mu g/cm^2$) associated with a photomultiplier, and with a heavy ion surface barrier detector. The overall mass resolution was 3 amu for a mass of $\sim$ 60 amu and 7 amu for a mass of 130 amu. For heavier masses, the resolution was even worse, and thus the results presented here are for masses lower than 130 (i.e. for masses lighter than half of the mass of the compound nucleus). It must be noted that no coincidence was required with another reaction product in this analysis.

Figure 1 shows a typical two-dimensional spectrum of the masses of the detected products versus the laboratory kinetic energies. Three main areas can be noted. Two of them are rather sharp and contain the elastically and inelastically scattered ^{63}Cu or ^{197}Au nuclei as well as the light or heavy quasi-elastic transfer products. A large area contains the quasi-fission and fission fragments. This area is well separated from the light quasi-elastic transfer area. It is not well separated from the heavy quasi-elastic transfer area, due to the lack of mass and energy resolution for these heavy and slow products. Also, if one calculates the angular distribution of the heavy quasi-fission products corresponding to the observed angular distribution of light products (given in figure 3*d*), none asymmetric ones are expected to be found at this angle (56°). They can be observed only at lower angles where measurements are difficult.

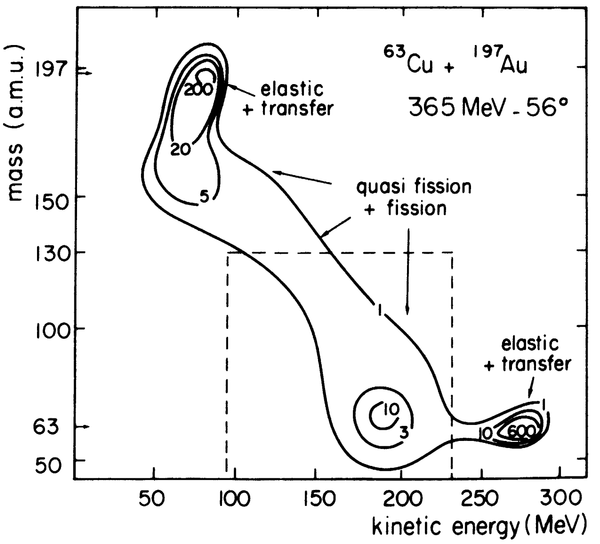

FIG. 1. — Distribution of the reaction products received at 56°. The abscissa is the laboratory kinetic energy and the ordinate the mass of the product, deduced from its time-of-flight and energy. The long-dashed rectangle is the area of quasi-fission and fission events studied in this paper.

We will then describe in this letter the main results obtained for products of quasi-fission and fission that have a mass lower than 130 (half of the mass of the compound nucleus), i.e. events in the long-dashed rectangle in figure 1. It must be remembered that :

1) No coincidence with any other product was required.

2) The measured mass is that of the product after possible particle evaporation.

In figure 2, are displayed the mass distributions at seven laboratory angles. Their main features are :

a) A low number of fragments which can be attributed to fission of a complete fusion nucleus, since the mass distribution of such fragments is expected to peak around mass 126.

b) The maxima in the distributions are around mass 60 (i.e. very close to 63 before de-excitation) at the high angles, and they shift to higher masses at low angles. This result is at variance with the result reported by Wolf *et al.* [3] for the system Kr + Bi at 600 MeV.

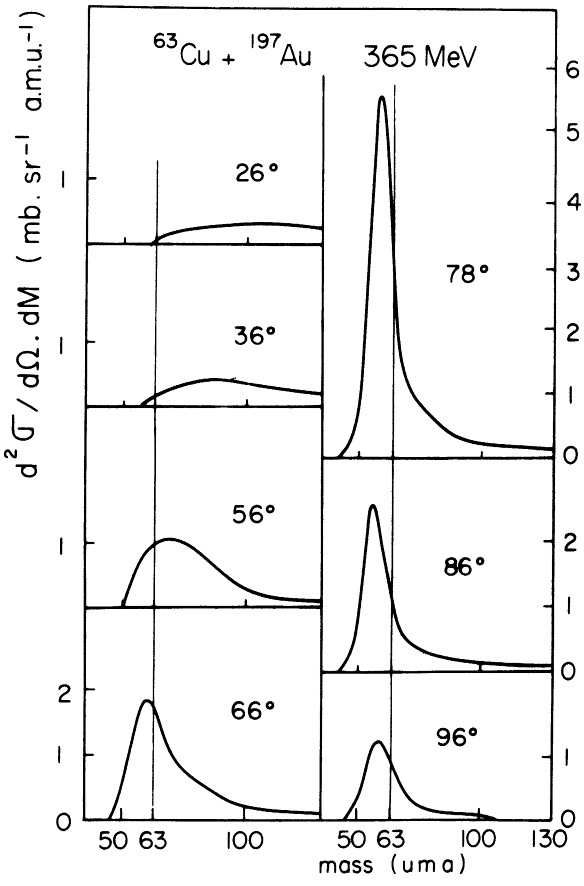

FIG. 2. — Mass distributions of the light quasi-fission and fission products detected at 7 laboratory angles.

c) The width increases as the mass exchange becomes more important, i.e. as the peak of the mass distribution shifts toward more symmetric mass divisions.

These last two results (*b*) and *c*) above) seem to indicate that the reaction time has been longer for the products detected at low angles than for the products detected at larger angles. As the phonon energy of the mass asymmetry degree of freedom is typically about 1-2 MeV [6] this means that the reaction time is of the order or slightly less roughly than the oscillation time of this degree of freedom, which is 2-4 $\times 10^{-21}$ s.

Another way to show the experimental result is the evolution of the shape of the angular distribution with the amount of mass transferred which appears in figure 3*a-d*. For a mass region close to that of the projectile, the distribution is strongly peaked. This peak is not as sharp for a mass region $70 \leqslant M \leqslant 90$ and it disappears completely for more important mass transfers. These data suggest a continuous evolution of the mechanism as the mass transfer increases. However, for masses around 130, the distribution could be that of fission fragments issued from a complete-fusion nucleus. If we assume this to be the case and also that the width of the mass distribution is around 50-60 amu, we obtain the angular distribution labelled *fission* in figure 3*e*. If we assume a $1/\sin\theta$ shape for this distribution, in the center-of-mass system (a shape which is consistant with the experimental point reported here), we can deduce a maximum of 30 mb $\pm$ 12 mb for fission following complete fusion (our results are not to be taken as evidence for a $1/\sin\theta$ shape because we have not made measurements at forward and backward c.m. angles). The full curve in figure 3*e* is the angular distribution of the light quasi-fission events which results when the complete-fusion fission events are substracted. The total cross section of these quasi-fission events is 250 $\pm$ 50 mb, which is one half of the total reaction cross section estimated to be 500 mb. This ratio is very similar to the one already observed in references [2-4].

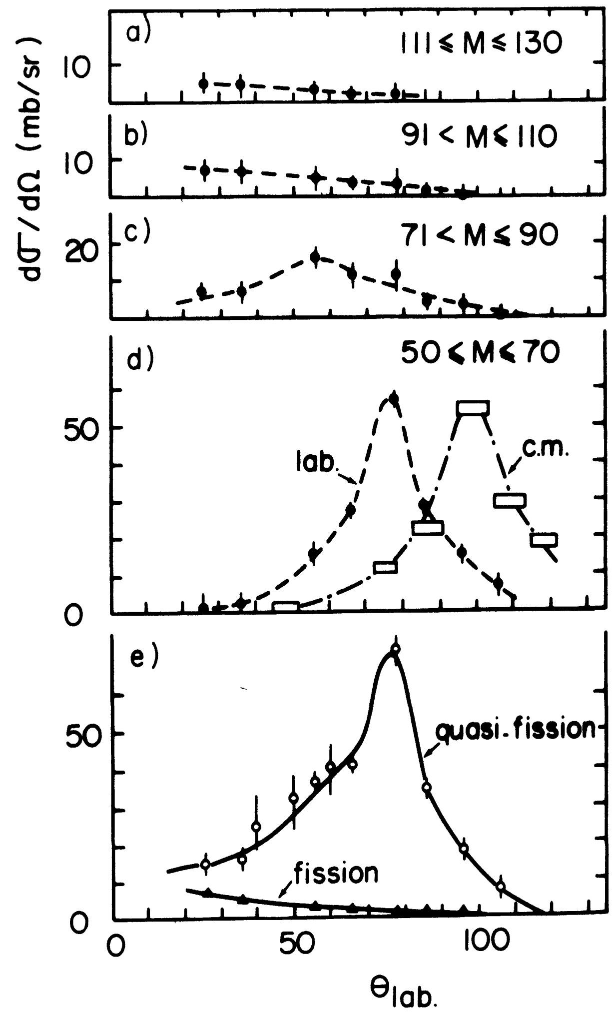

FIG. 3*a*, *b*, *c*, *d*. — Angular distributions of the quasi-fission and fission products in the laboratory, for several ranges of mass values. In addition, the center-of-mass angular distribution is given for the mass range 50-70.

FIG. 3*e*. — Angular distributions of the fragments which may be attributed to fission from a fusion nucleus, and to quasi-fission reactions.

In figure 3*d*, the dot-dashed curve is the center-of-mass angular distribution. It was obtained from the laboratory angular distribution (given by the dashed curve) by a method of transformation that involved averages. The c.m. curve peaks near 100°, which is slightly smaller than the 110° grazing angle for ^{63}Cu, consistant with other cases in which quasi-fission has been observed.

Let us consider the extent to which the various *l*-waves contribute to the different processes that make up the total reaction. For this purpose we shall restrict ourselves to the sharp cut-off approximation. If we make the usual assumption that fusion takes place for the lowest *l*-waves, then the observed fusion cross section of 30 mb corresponds to a critical angular momentum $l_{\text{crit}}\ \hbar \approx 25\ \hbar$, beyond which complete fusion does not take place. At the other extreme, for partial waves of $l \gtrsim 100$, only elastic scattering occurs. For partial waves $25 < l < 100$ two processes take place : quasi-elastic transfer for partial waves greater than about 75, and quasi-fission for $25 \lesssim l \lesssim 75$.

For elastic scattering and for quasi-elastic transfer processes the relationship between *l*-values and the emission angle is well known. For transfer reactions, the products are peaked at the projectile grazing angle, and for elastic scattering the emission angle decreases with increasing *l*. In the case of quasi-fission we need to explain at the same time the shapes of both the angular distribution and of the corresponding mass distribution of figures 2 and 3. The qualitative conclusion that we are led to is that, contrary to elastic scattering, the light-product emission angle increases with increasing *l*. Thus for relatively low *l*-values (near 30) the penetration of the nuclei is deep and the reaction time is relatively large, which allows equilibrium in the mass-degree of freedom to be more nearly achieved and which also allows a relatively large rotation of the system before scission. The light products are then observed at forward angles (26-36°) and their mass distribution is wide. The differential cross section at these angles is small, since partial cross sections for low l-waves are small. For relatively high l-values (near 70), the nuclear penetration is less deep, the time of reaction is shorter, the extent of mass transfer is less, and the angle of rotation is smaller before re-separation. Thus the light products are observed at a greater emission angle in this case, and the cross section is higher, due to the greater partial cross sections at higher l-values. This explains the rather narrow mass distribution peaked at 60 amu which is observed near 78°. Since the above explanation of our results requires that a partial rotation of the composite system takes place, it is not surprising to find the peak of the overall angular distribution of the light quasi-fission products to be at an angle that is smaller than the grazing angle.

This view given above is different from the one of Wolf *et al.* [3], since it is based on a very different experimental result for the variation of the mass distribution with the angle. Our results imply a much larger rotation angle for low l-wave events than those of Wolf *et al.*

Let us now look at the information given by the kinetic energies of the quasi-fission fragments. For this, we have chosen products of mass 60 amu. The center-of-mass kinetic energy $\bar{E}_{60}$ of these products can be easily calculated on the assumption that they emit no particle before detection. Assuming that quasi-fission is a two-body reaction, the center-of-mass energy $\bar{E}_{\mathrm{H}}$ of the heavy product emitted in coincidence can then also be obtained. It is found that the final total center-of-mass kinetic energy $\bar{E}_{60} + \bar{E}_{\mathrm{H}}$ is lower than the initial kinetic energy of the system by 90 MeV. We have assumed that this energy has been dissipated through neutron evaporation and photon emission : 9 neutrons could be emitted. Some of these neutrons may have been emitted by the product which has a measured mass of 60 amu, and its c.m. kinetic energy $\bar{E}_{\mathrm{L}}$ due to the quasi-fission process may thus be higher than $\bar{E}_{60}$. We have made the correction for neutron emission according to three hypotheses and have calculated $\bar{E}_{\mathrm{L}}$ and $\bar{E}_{\mathrm{H}}$ in each case :

1) All the neutrons are evaporated before the separation of the two fragments (open points in figure 4) :

$$\bar{E}_{\mathrm{L}} = \bar{E}_{60}, \bar{E}_{\mathrm{H}} = \bar{E}_{\mathrm{L}} \times 60/191 .$$

2) All the neutrons are emitted after full acceleration from the heavy product only (closed circles) :

$$\bar{E}_{\mathrm{L}} = \bar{E}_{60} , \quad \bar{E}_{\mathrm{H}} = \bar{E}_{\mathrm{L}} \times 60/200 .$$

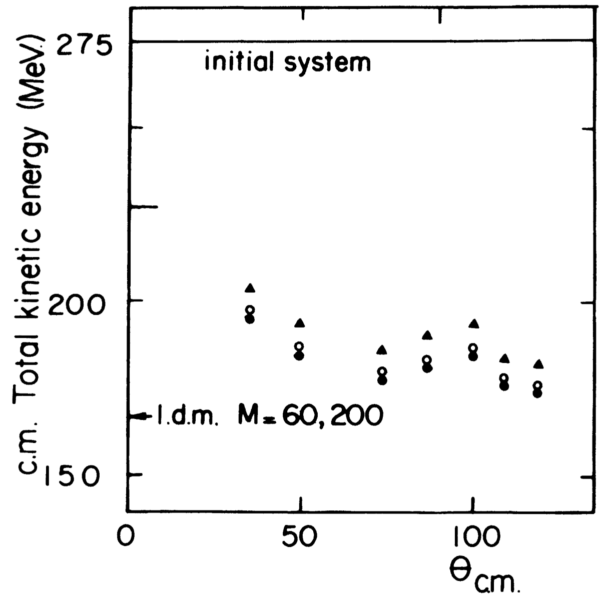

FIG. 4. — Total kinetic energy in the center-of-mass for quasi-fission events producing a light product of mass 60, versus the angle at which this product is detected. The different points correspond to three possible hypothesis concerning the numbers of neutrons emitted by the fragments (details in the text). The arrow indicates the value predicted for this couple of fragments by the liquid drop model adjusted to fit experimental values of fission kinetic energies in this region of nuclei.

3) They are emitted after full acceleration from both fragments in proportion to their respective masses (triangles) :

$$\bar{E}_{\mathrm{L}} = \bar{E}_{60} \frac{260}{251} ,$$

$$\bar{E}_{\mathrm{H}} = \bar{E}_{\mathrm{L}} \left(60 \times \frac{260}{251}\right) \Big/ \left(260 - 60 \times \frac{260}{251}\right) .$$

Figure 4 shows the total kinetic energy of both fragments before de-excitation as a function of the angle. It seems to be constant, or slightly increasing at forward angles. The experimental uncertainties do not allow us to make a definite conclusion, and we will, therefore, not discuss the possible reasons for an increase in the total kinetic energy at low angles.

The average value is higher than expected for the fission of the complete-fusion nucleus (calculated with the liquid drop model adjusted to fit the experimental data for similar nuclei [7]). This seems to indicate that the shape at the neck connecting the two fragments near scission is different, or that the velocity of the two fragments before scission may be greater than in fission, or both.

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