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QUASI-FISSION

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Recent experimental and theoretical investigations have led to the characterization of a new reaction mechanism called quasi-fission. This process is characterized by the emergence of fission-like fragments, which do not originate from the fission decay of a compound nucleus formed by heavy-ion fusion, but rather from the break up of a short-lived intermediate complex. The occurrence of quasi-fission processes appear to be limited to heavy reaction systems and/or large angular momenta, although the present work demonstrates that such reactions occur for somewhat lighter projectiles than previously believed. It is thus shown that measurements of fragment angular distributions provide a signature for quasifission by being sensitive to whether or not a compound nucleus was formed during the reaction. From an analysis of such data it is concluded that the possibilities for synthesizing super-heavy elements in the range Z=112-116 are reduced considerably over previous estimates.

1. EXPERIMENTAL EVIDENCE FOR QUASI-FISSION

Recent studies[1,2] of heavy ion induced fission have shown that in some cases at least a fraction of the fission cross section must be attributed to partial waves, for which the compound nucleus has no fission barrier. These results indicate that the large mass transfer necessary to achieve the observed near mass symmetry has taken place on a very short time scale since the system has not been hindered in its fission decay by a fission barrier. These studies have also shown that the mass width of the fragments increases with angular momentum lending further support to the assumption of a new process coming into play under these conditions. Several of these indications for the quasi-fission reaction are, however, somewhat indirect and it has been difficult to achieve a more precise characterization of the mechanism based on these observations.

A more direct manifestation of the quasi-fission process has recently been observed in the reaction ^{208}Pb + ^{58}Fe,[3] one can directly observe the mass drift as function of scattering angle, see Fig. 1. From the observed angular dependence of the mass distribution in this reaction one can estimate that the net mass transfer of ~75 nucleons necessary to obtain mass symmetric takes place in about 10^{-20} seconds. This observation again supports the hypothesis of a separate fast-fission or quasi-fission process.

2. THEORETICAL EXPECTATIONS

Concurrent with the experimental studies of quasi-fission, theoretical models describing heavy ion reactions in general have been developed, which support the notion of a separate quasi-fission process. Swiatecki[4] has proposed a

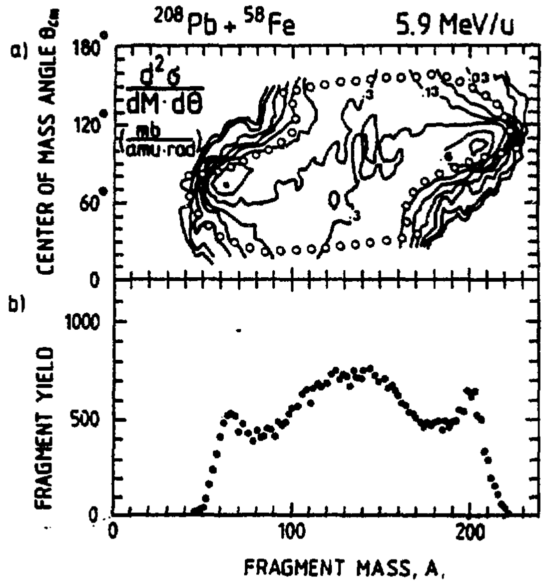

FIGURE 1. Mass and angle dependence of the cross section for the ^{208}Pb + ^{58}Fe reaction (a). The symmetric mass distribution (b) does not reveal the fast time scale of this reaction (taken from Ref. 1).

model which predicts the occurrence of quasi-fission processes and the related inhibition of heavy ion fusion. According to this model, quasi-fission takes place in cases where the two initial nuclei have sufficient radial velocity to overcome the Coulomb barrier and develop a large diameter neck between them allowing for a large net mass transfer from the heavy to the light reaction partner. If, however, the nuclear dissipative forces prevents the system from achieving shapes inside the fission barrier a rapid reseparation will take place resulting in two fission-like fragments. Similar reaction trajectories have recently been obtained also in time dependent Hartree Fock calculations.[5]

It is natural to associate the angular dependent mass drift observed in the ^{208}Pb + ^{58}Fe reaction[3] with such trajectories. Bjørnholm and Swiatecki[7] have examined the experimental data obtained by Bock et al.[3] for a range of different reactions and concluded that the quasi-fission process identified in this manner occurs only for targets heavier than ^{58}Fe when bombarded with ^{208}Pb-beams. This criterion for observation of quasi-fission relies, however, directly on the assumption that the reaction time be shorter than the rotational period, an assumption which is not necessarily fulfilled for all quasi-fission processes. One must therefore seek other signatures for quasi-fission which are more in keeping with the theoretical definition namely: that products with near symmetric masses emerge from reactions where the system has not been trapped behind the fission barrier. In the following I will try to convince you that the angular distributions[8-11] of the fragments provide this signature by being very sensitive to whether or not the system has been trapped behind the fission saddle point any time during the process. The distinction between fusion fission and quasi-fission is expected to be related to the direction of the mass flow between the two reaction participants once they have formed a neck between them, see Figure 2. It is thus intuitively expected that fusion takes place if the net mass flow goes from the light to the heavy reaction partner, whereas the oppositve direction of the mass flow is likely to lead to an intermediate complex outside the fission saddle point.

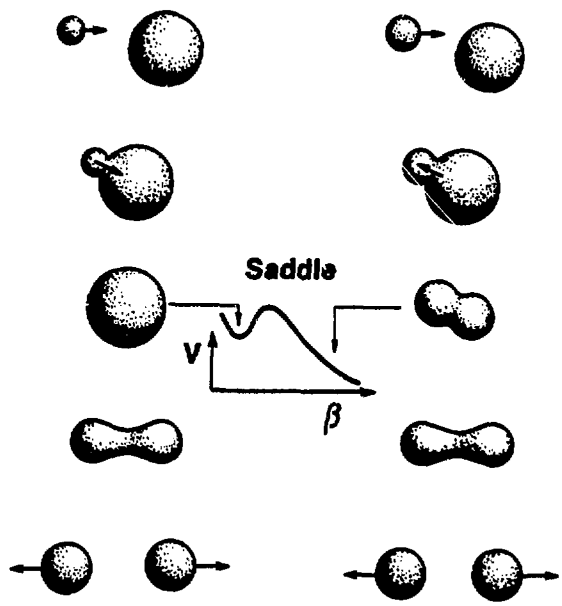

FIGURE 2. Schematic illustration of the distinction between fusion fission and quasi-fission.

3. FRAGMENT ANGULAR DISTRIBUTIONS

The angular distribution of fragments from fission of compound nuclei carry information about the shape of the nucleus at the fission saddle point[12,13] as given by the moments of inertia for axial $\mathcal{J}_\parallel$ and non-axial $\mathcal{J}_\perp$ rotations. Specifically, the angular distributions depend on the distribution of K-values (the axial component of the total spin I), which relates to the moments of inertia through the relations

$$K_o^2 = \frac{T}{\hbar^2} \mathscr{I}_{eff}; \quad \frac{1}{\mathscr{I}_{eff}} = \frac{1}{\mathscr{I}_{\parallel}} - \frac{1}{\mathscr{I}_{\perp}} \tag{1}$$

The K-distribution is assumed to be gaussian with the variance K_o^2. T is the nuclear temperature at the saddle point. A sample of experimental data are shown in Figure 3. Solid curves represent fits to the data obtained by

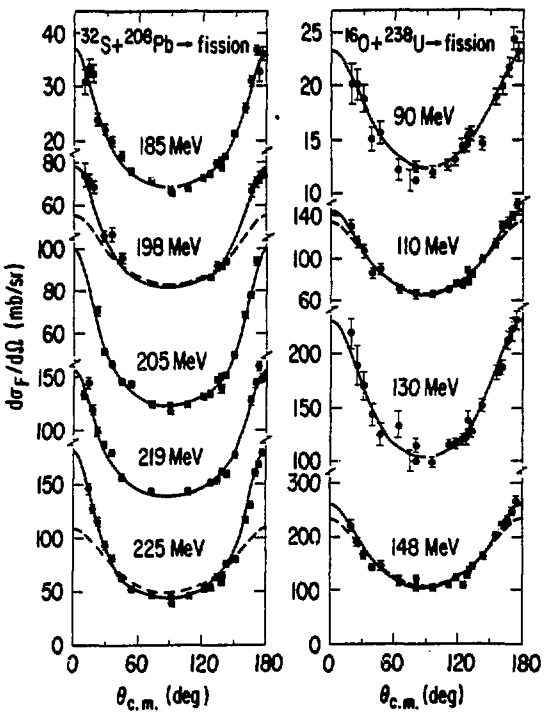

FIGURE 3. Experimental fission fragment angular distributions. Solid curves represent best fits. Dashed curves are RLDM calculations.

varying K_o^2. Since the K_o^2-values are related to the nuclear deformation at the saddle point it is appropriate to compare the data with calculations based on moments of inertia $\mathcal{J}_\parallel$ and $\mathcal{J}_\perp$ predicted by the Rotating Liquid Drop Model.[14] Such calculations are represented by dashed curves in Figure 3. We observe that the angular distributions calculated in this manner give a fairly good representation of the $^{16}O + {}^{238}U$-data, but fails rather dramatically in accounting for the large anisotropies observed in the $^{32}S + {}^{208}Pb$ reaction. These two reactions, if fusion occurs, would produce compound nuclei with almost identical fissilities $X \approx 0.84$. This means that the fission barriers in the two cases should be almost identical in terms of both barrier height and deformation. The substantially larger than expected anisotropy observed for the $^{32}S + {}^{208}Pb$ reaction means that the K-distribution in this case is determined at a deformation larger than that of the fission saddle point. Since the two reactions are so similar, both with respect to the shape of the fission barrier, the angular momentum input and the nuclear temperature, it appears inconceivable that the K-distribution in the $^{32}S + {}^{208}Pb$ should be determined at a point way outside the fission saddle point unless, of course, this reaction never led to the formation of a compound nucleus. We are therefore led to conclude that $^{32}S + {}^{208}Pb$ reaction, probably due to the dynamic features of the process, does not lead to compound nucleus formation. The major fraction of the observed near symmetric fission fragments must consequently be ascribed to the quasi-fission reaction since they have exactly the characteristics expected for this reaction mechanism.

The parameter $\mathscr{I}_{sph}/\mathscr{I}_{eff}$, where $\mathscr{I}_{sph}$ is the rigid moment of inertia of a sphere, can be determined from the angular distributions via eq. 1. Note that this parameter is monotonically related to the nuclear deformation. The extracted values of $\mathscr{I}_{sph}/\mathscr{I}_{eff}$ are shown in Figure 4

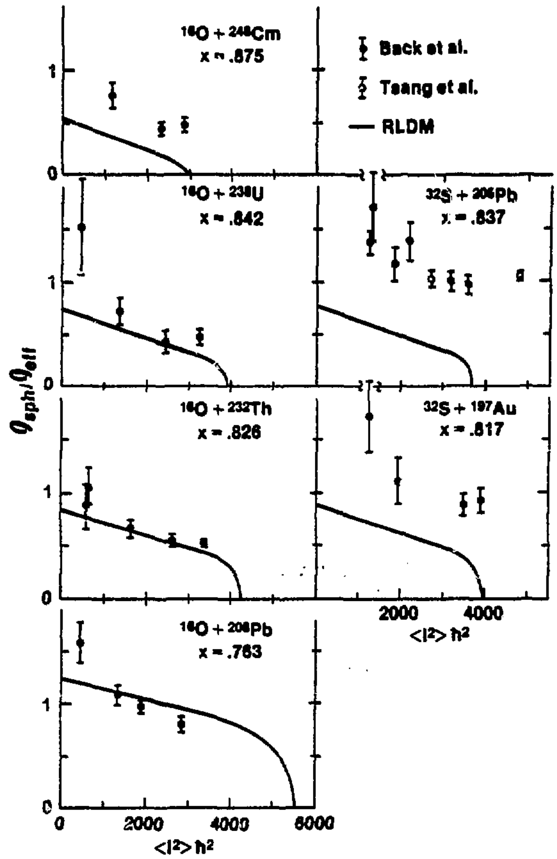

FIGURE 4. Comparison of experimental $\mathscr{I}_{sph}/\mathscr{I}_{eff}$ values with RLDM estimates. Solid points are from the present work, open circles from Ref. 10.

plotted as a function of the mean square spin $\langle I^2 \rangle$ of the system. This latter parameter is determined from the fission cross section assuming a diffuseness of the partial wave distribution obtained from optical model transmission coefficients. The value of $\mathscr{I}_{sph}/\mathscr{I}_{eff}$ at the fission saddle point can be readily estimated from the rotating liquid drop model and is shown in Figure 4 as solid curves. This model predicts that $\mathscr{I}_{sph}/\mathscr{I}_{eff}$ decreases, not only with increasing fissility x of the system, but also with increasing average spin. The experimental values of $\mathscr{I}_{sph}/\mathscr{I}_{eff}$ extracted from the angular distribution agree quite well with theoretical expectations for the ^{16}O + ^{208}Pb, ^{232}Th, ^{238}U reactions, which indicates that these reactions proceed through a compound nucleus stage with subsequent decay over the fission saddle point. The discrepancy for the ^{16}O + ^{248}Cm reaction can possibly be attributed to a breakdown of the theory for very small fission barriers, which in this case is predicted to be less than 1 MeV. In such cases one must expect that the significance of the fission saddle point is lost.

The results for the ^{32}S-induced reactions indicate that the K-distributions in these cases are determined at substantially larger deformations supporting the conclusion arrived at earlier that these reactions do not proceed via compound nucleus formation, but rather via a quasi-fission process. The products of the ^{32}S reactions are, however, indistinguishable from normal fission fragments in terms of mass and kinetic energy distributions.

4. LIMITATIONS TO HEAVY ION FUSION

The observation of clear signatures for quasi-fission in the reactions $^{32}S + {}^{197}Au$, ^{208}Pb implies that the compound nucleus formation in these cases is inhibited. Theoretical calculations[4-6] indicate that this may be due to the dynamics of the process. In the extra push model of Swiatecki[4-5] this inhibition of compound nucleus formation is controlled by the parameter x_{cliff}, which has been tentatively assigned a value of 0.85 by Bjørnholm and Swiatecki.[7] They arrived at this value for x_{cliff} by assuming that angular dependent mass distributions constitute a good signature for quasi-fission. We hope to have demonstrated however, that quasi-fission can occur also for lighter systems, which do not exhibit this feature and a re-adjustment of the x_{cliff} parameter may therefore be in order. The experimental fission cross sections are compared with extra push model estimates in Figure 5. The fractions of the cross section going to fusion-fission (FF), quasi fission (QF) and deep inelastic collisions (DIC) are indicated. We observe that a readjustment of the x_{cliff} parameter to a value of 0.78 will qualitatively account for the present observation of quasi fission in ^{32}S induced reactions even near threshold. This readjustment of x_{cliff} has the effect of reducing the predicted fusion cross section for heavy ion reactions and in particular it will severely reduce the possibilities for synthesizing super heavy elements.

It is then appropriate to ask whether this reduction of x_{cliff} generates a conflict with other data, in particular the observation of evaporation residues from

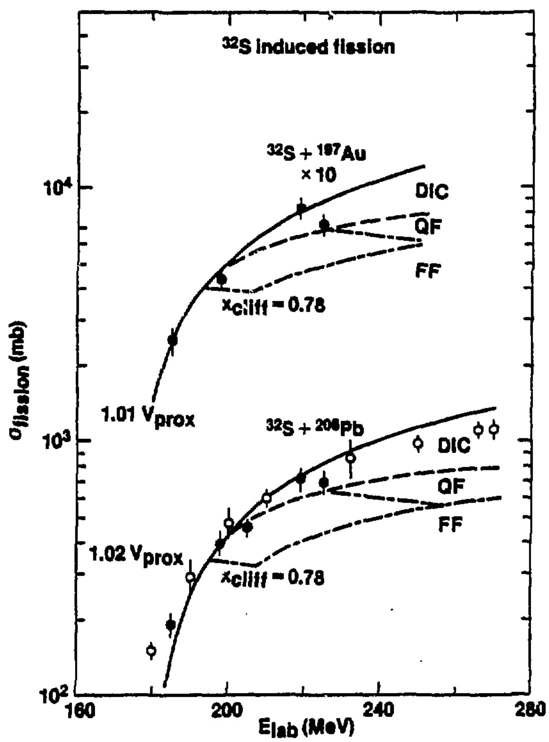

FIGURE 5. Experimental fission cross sections for ^{32}S induced reactions. Solid points are from the present work, open circles from Ref. 10.

fusion of ^{40}Ar, ^{50}Ti + ^{208}Pb as illustrated in Figures 6 and 7. Münzenberg et al.[17] have observed evaporation residue products from the ^{40}Ar + ^{208}Pb reaction, for which the fission cross section has been measured by Oganessian et al.[18] We observe that the evaporation residue cross section peaks near the reaction threshold where the fusion reaction is still uninhibited, because of the small angular momenta involved in this region. In the ^{50}Ti + ^{208}Pb

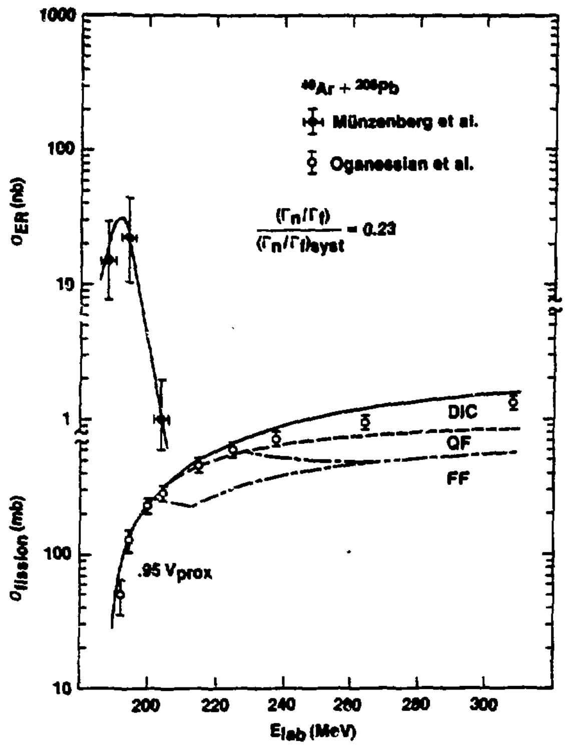

FIGURE 6. Fission[17] and evaporation residue cross sections[18] for the ^{40}Ar + ^{208}Pb reaction. See Fig. 5 concerning theoretical curves.

reaction[3,19] we find, however, that the complete fusion cross section is predicted to be strongly inhibited by the extra-push model when the readjusted value of x_{cliff} = 0.78 is used. By comparing the measured value of Γ_n/Γ_f (neutron - to fission decay widths) to the ones obtained from systematics, it appears that the compound nucleus formation is indeed strongly inhibited in this reaction, see Figure 7. It should in this connection be kept in

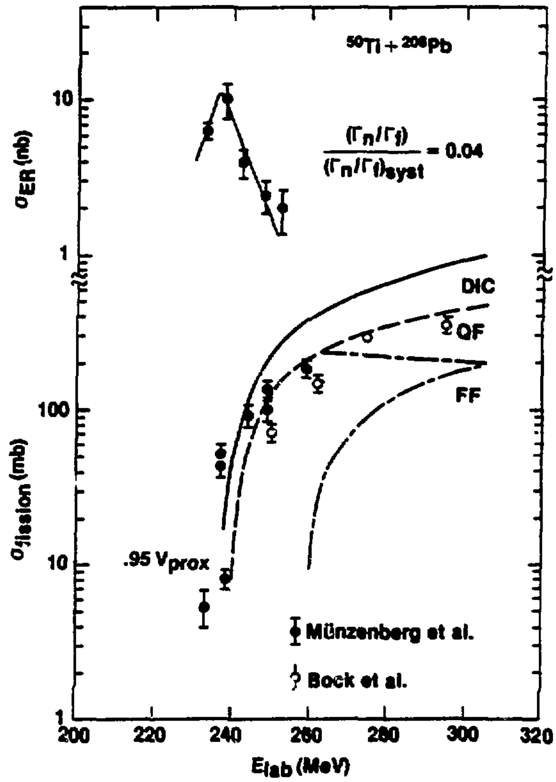

FIGURE 7. Fission and evaporation residue cross sections are shown for the $^{50}Ti + ^{208}Pb$ reaction, solid points are from Ref. 15 and open circles are from Ref. 3. See Fig. 5 concerning theoretical curves.

mind that the extra push model cannot be expected to produce reliable estimates of the cross sections in the near-barrier region since it does not include several effects, such as barrier penetration, zero point vibration[20] etc., which are believed to increase the fusion cross section at near barrier energies.

The recent observations[21,22] of evaporation residues from $^{54}Cr + ^{209}Bi$ and $^{58}Fe + ^{209}Bi$ reaction do, however, uniquely prove the feasibility of compound nucleus formation, even with such heavy projectiles. These cross sections are, however, extremely small and one should not expect the extra push model, which is only designed to reproduce the main features of heavy ion reactions, to account for this small reaction channel.

It therefore does not appear that the proposed readjustment of the x_{cliff} parameter in the extra push model generates any conflict with available experimental data.

5. CONCLUSION

It has been shown that quasi-fission or fast-fission processes constitute a general feature of heavy ion reactions. Several experimental signatures for these processes have been observed including fission cross sections exceeding the RLDM limit,[12] angular dependent mass distributions[3,7] and abnormally large angular anisotropies.[8-11] Of these three observables, only the fragment angular distributions are sensitive to the occurrence of quasi fission in reactions with ions of mass A<40, since the quasi-fission fragments are indistinguishable from normal fission fragments in terms of mass and kinetic energy alone. The occurrence of quasi-fission has the consequence of exhausting the part of the reaction cross section which would otherwise lead to compound nucleus formation.

It is shown that a slight readjustment of the x_{cliff} parameter in the extra push model[4,5,7] is necessary in order to account for the observation of quasi-fission in ^{32}S induced reactions. This readjustment has the consequence of posing more stringent theoretical limitations on the heavy ion fusion reaction in general and in, particular, it severely reduces the predicted possibilities for synthesizing super-heavy elements using heavy ion fusion reactions, even if such species were quite stable in their ground states.

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