

## Systematic analysis of average angular momenta and cross sections in sub-barrier fusion

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Average angular momenta deduced from isomer ratio, gamma-multiplicity, and fission fragment angular anisotropy measurements, and the associated cross sections for fourteen systems are analyzed with a barrier penetration model that includes the coupling of inelastic channels. Good agreement was found between the theory and the data obtained from isomer ratio and from gamma-ray multiplicity measurements with the exception of the more symmetric systems. In these cases the discrepancies with theory show correlations in cross section and angular momentum suggesting that a valid model can be found. The measurements of angular momentum using the fission fragment anisotropy technique, however, do not appear reconcilable with the energy dependence of the cross sections. This systematic overview suggests that the origin of this discrepancy lies with the deduction of angular momentum from the measured anisotropy in inclusive fission fragment angular distributions.

### I. INTRODUCTION

The measured cross sections for the fusion of heavy ions at energies near and below the Coulomb barrier can be orders of magnitude larger than the predictions of the one-dimensional barrier penetration model.<sup>1-3</sup> Theoretical studies of these enhancements have revealed the important role played by the nuclear structure of the colliding nuclei. Additional and complementary information has been obtained by measuring the moments of the angular momentum distributions leading to fusion deduced with three different techniques: gamma-multiplicity,<sup>4-10</sup> fission fragment angular distributions,<sup>11-15</sup> and very recently by measurements of isomer ratios.<sup>16,17</sup> With the latter method it was possible to observe the predicted energy-independent lower limit for the average angular momentum<sup>16</sup> ( $\ell$ ) and its expected variation with entrance channel.<sup>17</sup> Measurements of the cross sections  $\sigma_{\text{fus}}(E)$  and the deduction of  $\langle \ell \rangle$  by the isomer method are of interest because they provide an independent experimental approach to the problem that the theoretical values of  $\langle \ell \rangle$  disagree with those deduced from fission fragment anisotropies and, sometimes, from gamma-ray multiplicities. This discrepancy has been an important and perhaps the central problem in studies of sub-barrier fusion for several years.<sup>12,13,18-20</sup> Theoretical models (e.g., Refs. 19-21) must account for both the measured sub-barrier  $\sigma_{\text{fus}}(E)$  and the  $\langle \ell \rangle$ . This double requirement places a strong constraint on a model because, within a given model, the angular momentum distribution  $\sigma_{\ell}$  and the energy dependence of the cross section are intimately related.

We have investigated, following Ref. 22, all the presently available data on the first and second moments of the spin distributions leading to fusion and compared them to the *same* theoretical model. In addition, we

analyze the corresponding experimental cross sections, since the starting point in an analysis of a fusion reaction should be the understanding of the excitation functions. A simplified coupled-channel code CCFUS has been used to perform all calculations.<sup>23</sup> This model has been used extensively in describing (mostly successfully) a large number of fusion excitation functions.<sup>3</sup> We present an analysis of fourteen different systems:  ${}^3\text{He} + {}^{136}\text{Ba}$  (Ref. 17),  ${}^3\text{He} + {}^{137}\text{Ba}$  (Ref. 17),  ${}^4\text{He} + {}^{136}\text{Ba}$  (Ref. 17),  ${}^{12}\text{C} + {}^{128}\text{Te}$  (Refs. 16,17),  ${}^{16}\text{O} + {}^{144}\text{Nd}$  (Refs. 6,10),  ${}^{16}\text{O} + {}^{154}\text{Sm}$  (Refs. 4,5,22),  ${}^{28}\text{Si} + {}^{154}\text{Sm}$  (Ref. 24),  ${}^{64}\text{Ni} + {}^{96}\text{Zr}$  (Ref. 6),  ${}^{80}\text{Se} + {}^{80}\text{Se}$  (Refs. 6,7),  ${}^{64}\text{Ni} + {}^{100}\text{Mo}$  (Ref. 9),  ${}^{16}\text{O} + {}^{208}\text{Pb}$  (Refs. 11,13,14),  ${}^{12}\text{C} + {}^{236}\text{U}$  (Refs. 12,13),  ${}^{16}\text{O} + {}^{232}\text{Th}$  (Refs. 12,13), and  ${}^{19}\text{F} + {}^{232}\text{Th}$  (Ref. 15). For all these systems, the fusion cross sections and the first or second moments of their  $\sigma_{\ell}$  distributions have been measured at different bombarding energies by one of the three experimental techniques mentioned above. For a few systems:  ${}^{12}\text{C} + {}^{128}\text{Te}$  (Ref. 25),  ${}^{16}\text{O} + {}^{144}\text{Nd}$  (Ref. 26),  ${}^{16}\text{O} + {}^{154}\text{Sm}$  (Ref. 27), and  ${}^{28}\text{Si} + {}^{154}\text{Sm}$  (Ref. 28), fusion excitation functions have been measured in independent experiments.

### II. DEDUCTION OF THE MOMENTS OF THE SPIN DISTRIBUTION

The deduction of the moments of the spin distribution of the compound nucleus from the *measured quantities* is different for each experimental technique employed: isomer ratio measurements, gamma-ray multiplicity, and fission fragment angular distributions.

#### A. Isomer ratio

In the isomer ratio technique, the relationship between the spin distribution in the compound nucleus and the

measured relative population of the ground and isomeric states in the evaporation residue is established through statistical model calculations.<sup>16,17,29</sup> Starting with the experimental value of the isomer ratio, we deduce the average angular momentum of a smooth cutoff distribution for  $\sigma_\ell$  represented by a Fermi function with fixed  $\Delta\ell$  and variable  $\ell_0$ .<sup>17</sup> The statistical calculations were performed with the use of the Monte Carlo code PACE,<sup>30</sup> which treats the effects of successive evaporation of neutrons leading to the evaporation residue, and the subsequent gamma-ray emission leading to the isomer or ground state. The code allows one to incorporate explicitly the low-lying levels of the residual nucleus and, thereby, to treat the last steps of the gamma-ray deexcitation realistically.

### B. Gamma-ray multiplicity

Average gamma-ray multiplicities were obtained in early experiments,<sup>4-6</sup> while the advent of detector arrays<sup>7-10</sup> has made it possible to measure full multiplicity distributions. In either case, the measured multiplicities have to be converted to angular momenta to determine either the full  $\sigma_\ell$  distribution or the  $\langle\ell\rangle$ . The conversions from the number of gamma rays detected (coincidence fold) to multiplicity and then to angular momentum depend on instrumental effects such as the response function of the detector system and on a knowledge of the decay of a compound nucleus, respectively. Therefore, one needs to know the average angular momentum removed per photon, the average angular momentum carried off by the evaporated particles and the statistical gamma rays, and the corrections for the internal conversion of the gamma rays.<sup>8,9</sup> Some of these quantities have been estimated using statistical model calculations.<sup>9</sup>

### C. Fission fragment anisotropy

The second moment of the compound nuclear spin distribution can be obtained from the measured fission fragment angular distributions. In the standard transition-state theory<sup>31</sup> the anisotropy of the fission fragment angular distribution is related approximately to the second moment of the spin distribution (mean-square spin) by the following expression:

$$\frac{W(180^\circ)}{W(90^\circ)} \simeq 1 + \frac{\langle\ell^2\rangle}{4K_0^2}, \quad (1)$$

where  $K_0$  is the width of the distribution of the spin projection along the symmetry axis and is determined by the nuclear temperature and the effective moment of inertia at the saddle point,  $K_0^2 = J_{\text{eff}}T/\hbar^2$ . By measuring the fission fragment anisotropies, the ratio  $\langle\ell^2\rangle/K_0^2$  can be determined, and thus one has to assume a value for  $K_0^2$  to deduce  $\langle\ell^2\rangle$ , or vice versa. At this point there are two approaches to follow in the interpretation of the anomalously large measured anisotropies. Vandenbosch

*et al.*<sup>12,13,18</sup> have deduced the value of  $K_0^2$  from the above-barrier  $^4\text{He} + ^{244}\text{Cm}$  anisotropy<sup>32</sup> in order to obtain  $\langle\ell^2\rangle$  for the reactions  $^{12}\text{C} + ^{236}\text{U}$  and  $^{16}\text{O} + ^{232}\text{Th}$  leading to the same compound nucleus,  $^{248}\text{Cf}$ . Dasso *et al.*,<sup>19,20</sup> however, argue that the energy dependence of the fusion cross section determines the content of  $\sigma_\ell$ , and thus a model which describes  $\sigma_{\text{fus}}(E)$  has to give reasonable values of  $\langle\ell^2\rangle$ . Consequently, the large measured anisotropies should be taken as evidence for a small value of  $K_0^2$ . Complicating the interpretation of the experimental anisotropies is the possibility of contamination due to transfer reactions and sequential fission of the target.<sup>13</sup>

## III. MODEL CALCULATIONS

The calculations of the fusion cross sections and angular momentum distributions are based on the matrix diagonalization method of Ref. 23 which solves the multidimensional barrier penetration problem and includes finite range effects. Its accuracy has been tested against exact coupled-channel numerical calculations.<sup>23</sup> The code can treat coupling to collective degrees of freedom (surface vibrations) of the target and/or projectile nuclei and to transfer channels. A new version of the program (CCDEF) has been implemented recently to treat static deformations in nuclei such as  $^{154}\text{Sm}$ ,  $^{232}\text{Th}$ , and  $^{236}\text{U}$  (Ref. 33). Coupling to transfer channels has not been included in any of the calculations presented in this work. The nuclear potential used in the code has a Woods-Saxon shape with parameters as given by Ref. 34. This potential together with the Coulomb potential determines the height and the curvature of the parabolic barrier.

The analysis of the systems  $^{19}\text{F} + ^{232}\text{Th}$  (Ref. 15),  $^{64}\text{Ni} + ^{100}\text{Mo}$  (Ref. 9),  $^{12}\text{C} + ^{128}\text{Te}$  (Refs. 16,17),  $^3\text{He} + ^{136,137}\text{Ba}$  (Ref. 17), and  $^4\text{He} + ^{136}\text{Ba}$  (Ref. 17) with the CCFUS program is described in previous publications. For all other systems considered here the procedure was to (1) determine the barrier parameters ( $V_b$ ,  $R_b$ , and  $\hbar\omega$ ) for each system by adjusting the depth of the nuclear potential to fit the measured total fusion cross sections at energies above the Coulomb barrier; (2) include known values of electromagnetic transition probabilities for the lowest excited states of the target and/or projectile nuclei for each system.<sup>35-37</sup>

## IV. COMPARISON BETWEEN EXPERIMENT AND THEORY

Figure 1 displays the ratio of the experimental fusion cross section  $\sigma_{\text{expt}}$  to the theoretical value  $\sigma_{\text{theo}}$  (upper frame) and the ratio of the experimental value  $\langle\ell\rangle_{\text{expt}}$  to the theoretical value,  $\langle\ell\rangle_{\text{theo}}$ , (lower frame) as a function of the ratio of the bombarding energy to the Coulomb barrier, for the isomer ratio measurements. Note that the cross sections and the average angular momenta for  $^{12}\text{C} + ^{128}\text{Te}$ ,  $^3\text{He} + ^{136}\text{Ba}$ ,  $^3\text{He} + ^{137}\text{Ba}$ , and  $^4\text{He} + ^{136}\text{Ba}$  are fairly consistent with the theoretical expectations at bombarding energies above and well below the barrier.

In Fig. 2 we make a similar comparison for the gamma-

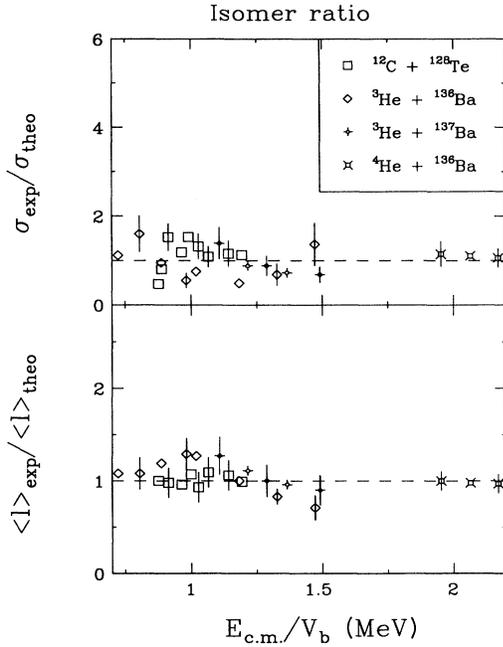


FIG. 1. Comparison of experimental and theoretical cross sections, and average angular momenta, as a function of bombarding energy relative to the Coulomb barrier for the results of isomer ratio measurements. Error bars have been included for representative data points.

ray multiplicity measurements. For the systems  $^{28}\text{Si} + ^{154}\text{Sm}$ ,  $^{16}\text{O} + ^{154}\text{Sm}$ , and  $^{16}\text{O} + ^{144}\text{Nd}$ , both the  $\sigma_{\text{expt}}$  and the  $\langle \ell \rangle_{\text{expt}}$  are well described by the CCFUS calculations. On the other hand, when the theory underestimates the cross section for  $^{64}\text{Ni} + ^{100}\text{Mo}$  it also underesti-

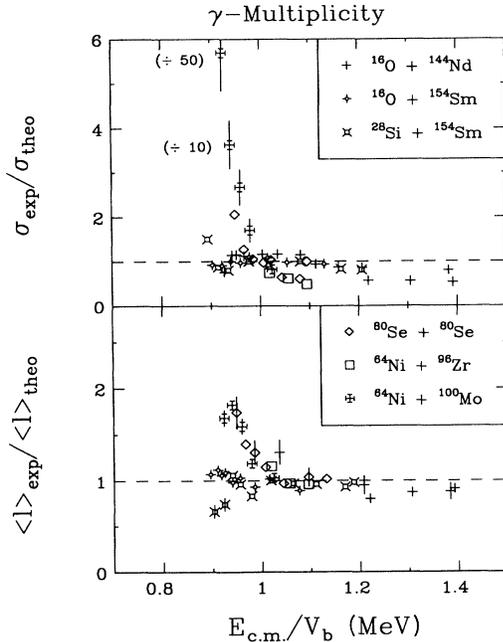


FIG. 2. Same as Fig.1 but for gamma-multiplicity measurements.

mates the average angular momentum. More precisely, it is the slope of the cross sections (the logarithmic derivative) that the theory overestimates. This corresponds to an underestimate of the angular momentum, which is also observed. If the barrier can be approximated by a parabolic shape, then the mean-square angular momentum and the energy dependence of the cross section are related by<sup>20</sup>

$$\langle \ell^2 \rangle = \frac{2\mu R_b^2}{\hbar^2} \epsilon, \quad \epsilon^{-1} = \frac{d}{dE} [\ln(E\sigma_{\text{fus}}(E))], \quad E \ll V_b. \quad (2)$$

Thus, the deviations of theory with experiment are in the *same direction* for both cross section and average angular momentum. Indeed, Halbert *et al.*<sup>9</sup> have obtained a better fit to the cross sections and the angular momentum by increasing the strength of the coupling for all the inelastic channels by a factor of 1.5. Note that there is also a discrepancy between experiment and theory in the  $\langle \ell \rangle$  values for  $^{80}\text{Se} + ^{80}\text{Se}$  at energies below the barrier. Although the corresponding cross sections do not show a clear deviation, it is necessary to point out that only relative cross sections were reported in Ref. 7, and, therefore, in the present analysis they have been arbitrarily normalized to the theory at bombarding energies above the barrier. In any case, it is apparent from this comparison that theory fails to satisfactorily describe the angular momentum and the cross sections at energies below the barrier for the more symmetric systems. Recently, Fröbrich *et al.*<sup>38</sup> have reported a consistent description of the measured  $\sigma_{\text{fus}}(E)$  and  $\langle \ell \rangle$  for  $^{64}\text{Ni} + ^{100}\text{Mo}$  using a transport model for solving Langevin equations based on a surface friction model.

The comparison between theory and experiment for the case of fission fragment angular distributions is shown in Fig. 3. In this case we have plotted the ratio of the root-mean-square values  $\langle \ell^2 \rangle^{1/2}$  rather than the mean values. As noted by Vandenbosch,<sup>22</sup> the ratios (experiment to theory) for the mean angular momentum and the ratios for the root-mean-square angular momentum are not very different for plausible  $\sigma_\ell$  distributions. For  $^{12}\text{C} + ^{236}\text{U}$  and  $^{16}\text{O} + ^{232}\text{Th}$  the experimental values of  $\langle \ell^2 \rangle$  are those given in Refs. 12 and 13, and were derived using empirical values of  $K_0^2$  from the measured anisotropy of  $^4\text{He} + ^{244}\text{Cm}$  (Ref. 32). For  $^{16}\text{O} + ^{208}\text{Pb}$  (Refs. 11,13,14) and  $^{19}\text{F} + ^{232}\text{Th}$  (Ref. 15), the values of  $\langle \ell^2 \rangle$  were determined by deducing  $K_0^2$  from the prediction of  $J_0/J_{\text{eff}}$  given by the diffuse surface liquid-drop model of Sierk.<sup>39</sup> Figure 3 shows that the experimental cross sections are well reproduced by the CCFUS calculations, but that the theoretical root-mean-square values deviate significantly at energies around and below the barrier for all the systems. Given that the model reproduces the slope of the cross sections, it is hard to see how it can be so inconsistent with the experimental angular momentum. Similar conclusions were reached by Fröbrich *et al.*<sup>38</sup>

On the other hand, if we follow the arguments of Refs.

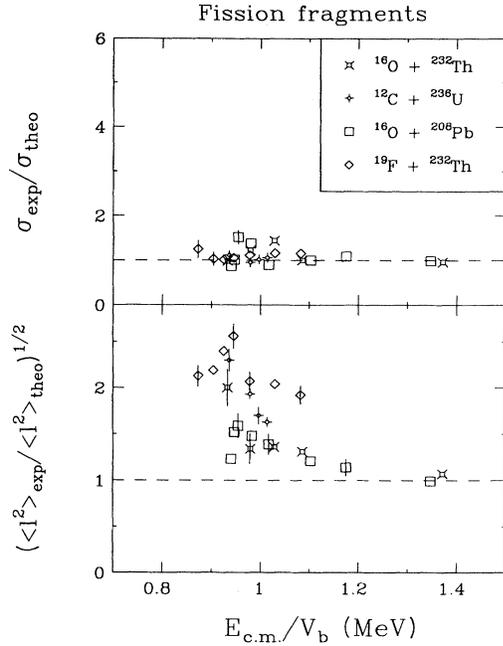


FIG. 3. Same as Fig.1 but for fission fragment anisotropy measurements.

19 and 20, we can take the values of  $\langle \ell^2 \rangle$  given by the theory (since calculations with CCFUS reproduce the excitation function) and deduce values of  $K_0^2$  from the measured anisotropies for  $^{12}\text{C} + ^{236}\text{U}$ ,  $^{16}\text{O} + ^{232}\text{Th}$ ,  $^{16}\text{O} + ^{208}\text{Pb}$ , and as was done in Ref. 15, for  $^{19}\text{F} + ^{232}\text{Th}$ . Figure 4 shows the values of  $K_0$  deduced in this approach for these four systems. We find that the values of  $K_0$  are

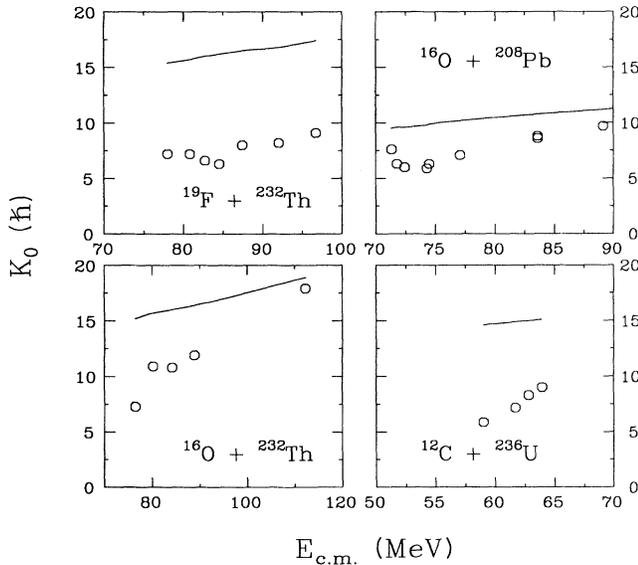


FIG. 4. Values of  $K_0$  deduced from the measured fission fragment anisotropies and  $\langle \ell^2 \rangle$  calculated from CCFUS,<sup>23</sup> as a function of the ratio of bombarding energy to the Coulomb barrier. The solid lines represent the values of  $K_0$  calculated with  $J_0/J_{\text{eff}}$  obtained from Sierk's model.<sup>39</sup>

a factor of 2–3 smaller than those determined by using the values of  $J_0/J_{\text{eff}}$  of a rotating liquid-drop given by Sierk's model.<sup>39</sup>

The present analysis thus indicates that our overall theoretical understanding of the measured cross sections and fission fragment angular distributions is incomplete. Either one or more of the main elements—the calculations of fusion in the entrance channel, the assumption of the formation of an equilibrated compound nucleus, the assumptions in the standard transition-state model for fission, or the calculations of  $K_0^2$  from the rotating liquid-drop model—is not adequate.

Concerning the entrance channel, the prediction of the fusion cross sections for relatively light projectiles such as  $^4\text{He}$ ,  $^{12}\text{C}$ , and  $^{16}\text{O}$  is generally satisfactory for all three experimental methods. The assumption of compound nucleus formation followed by equilibrium fission would seem to be reasonable for the relatively asymmetric entrance channels, low angular momenta and excitation energies, and small values of  $Z_1Z_2$  encountered here. However, nonequilibrium or dynamic contributions to fission have been observed for much heavier systems such as  $^{40}\text{Ar} + ^{197}\text{Au}$  (Ref. 40), and  $^{40}\text{Ar}$ ,  $^{50}\text{Ti}$ , and  $^{56}\text{Fe} + ^{208}\text{Pb}$  (Ref. 41,42). These reactions also show much larger anisotropies than expected on the basis of the transition-state model, and for mass-asymmetric fission decays, exhibit angular distributions that are asymmetric about  $90^\circ$  in the rest system. While it would seem unlikely that these quasifission mechanisms would persist for projectiles as light as  $^{16}\text{O}$ , similar radiochemical measurements for reactions with lighter projectiles would be needed to rule out completely any nonequilibrium processes. For example, Ref. 43 reports cross sections and fission fragment anisotropies for reactions induced by  $^{10}\text{B}$ ,  $^{12}\text{C}$ ,  $^{16}\text{O}$ , and  $^{19}\text{F}$  on heavy targets at bombarding energies above the barrier. They find anomalously large anisotropies for the  $^{16}\text{O}$ - and  $^{19}\text{F}$ -induced reactions, which have entrance channel mass asymmetries smaller than the Businaro-Gallone critical value. They conclude from this that the large anisotropies are consistent with a mixture of compound nucleus and nonequilibrium fission mechanisms being present for the heavier projectiles. Measurements in the forward hemisphere to test for asymmetries about  $90^\circ$  could check this suggestion.

The use of empirical values of  $K_0$ , deduced from the decay of the same compound nucleus populated in a light ion reaction at energies above the barrier<sup>12,13,32</sup> (where one believes one knows the average angular momentum from the measured cross section), avoids the problem of calculating a value of  $K_0^2$  from a model. Since such empirical values of  $K_0^2$  tend to be smaller than the theoretical values, this reduces the discrepancy somewhat. Recent experimental studies<sup>44,45</sup> show that corrections for the contributions from sequential fission (i.e., fission following transfer) to the fission fragment anisotropies reduce the discrepancies between experiment and theory, but they do not eliminate them.

Thus, we are left with a situation in which straight-

forward entrance channel models for fusion (of  ${}^4\text{He}$ ,  ${}^{12}\text{C}$ , and  ${}^{16}\text{O}$ ) are able to account for the cross sections and the average angular momenta with one exception—when the average angular momenta are deduced from fission fragment anisotropies. Barring unsuspected nonequilibrium contributions to fission, this suggests that the problem is in the deduction of angular momenta from measured fission anisotropies. The discrepancy is consistent with the fissioning system having a more elongated shape at the point where the distribution of  $K_0$  becomes *fixed*. Indeed, the question of when and how the distribution of angular momenta projected along the symmetry axis is determined and fixed as the fissioning nucleus proceeds from saddle to scission has received extensive discussion.<sup>11, 46–49</sup>

## V. CONCLUSIONS

In summary, we have analyzed all the existing data on the first or second moments of the spin distributions

leading to fusion along with the corresponding experimental cross sections and compared them to the same model. All these calculations were performed with the coupled-channel code CCFUS.<sup>23</sup> A fairly good agreement was found between the theory and the data obtained from isomer ratio measurements and gamma-ray multiplicity for all the systems with the exception of the more symmetric ones,  ${}^{64}\text{Ni} + {}^{100}\text{Mo}$  and, less clearly,  ${}^{80}\text{Se} + {}^{80}\text{Se}$ . In those cases when the theory overestimates the slope of the cross section it also underestimates the angular momentum. And finally, although the theoretical fusion-fission cross sections show very good agreement with experiment, there is a discrepancy with the average angular momenta. The present systematic overview suggests that the origin of the discrepancy may lie in the deduction of the angular momentum from the measured inclusive fission fragment angular distributions.

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