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Spin distribution in near-barrier fusion reactions

S. Gil,
Laboratorio TANDAR - CNEA - Buenos Aires Argentina

Abstract

Despite the important progress made in the understanding of fusion reactions at near barrier energies by combining nuclear structure effects to the dynamics of the reaction, the understanding of the spin distribution of the compound nucleus still remains incomplete. Several experiments have found spin distributions that are broader than those expected from theoretical models. In this article we review the different experimental techniques that have been used to probe the spin distribution of the compound nucleus, with particular emphasis in the conversion of the experimentally measured quantities into the various moments of the spin distribution, and procedures to test the consistency of these techniques. We briefly discuss the physical ideas underlying some of the models that have been proposed to understand fusion. Finally we present some new experimental developments in the study of spin distributions and pose some questions that still remain open in this field.

I- Introduction.

In the last few years there has been considerable experimental and theoretical efforts devoted to understand the fusion process between heavy ions at near barrier energies[1, 2]. Important progress has been made by taking into account the interplay between the nuclear structure of the participant nuclei and the dynamics of the reaction. The effect of the static and dynamical deformations of the participant species has been clearly demonstrated in the studies of excitation functions of the systems $^{16}O +^{A} Sm$ [3, 4, 5, 6]. The inclusion of coupling to inelastic[7, 8] and transfer[9, 11] channels has also helped in reducing the orders-of-magnitude discrepancies between the experimental fusion cross sections and the one-dimensional penetration models. A full understanding of the fusion process in terms of coupled channels requires a complete information on all the reaction channels that compete with fusion; this detailed information is available only in very few cases[2]. In heavier systems, the number of relevant channels may be so large that it would be technically very difficult to solve the full problem with this approach, even if the appropriate coupling were known. Alternative approaches have been developed to circumvent these difficulties, for instance in the dispersion relation model, the coupling to other channels is *implicitly* taken into account by introducing an energy dependent imaginary potential that is related to the real potential by means of very general dispersion relations [12, 13, 14]. The role of new degrees of freedom, such as neck formation[15, 16, 17] in the enhancement of the fusion cross section has also been studied.

Despite all the recent progress made in the understanding of the excitation functions of the fusion cross sections, these studies alone provide only a partial information on the fusion process. Using a partial wave expansion, the fusion cross section can be written as:

$$\sigma_{fus}(E) = \sum_{\ell=0}^{\infty} \sigma_\ell(E) = \frac{\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) P_\ell(E), \quad (1)$$

where σ_ℓ (E) represents the partial fusion cross section or the spin distribution (*s.d.*) of the compound nucleus (CN). E and k are the center-of-mass bombarding energy and the wave number, respectively. $P_\ell(E)$ is the probability that the partial wave ℓ in the entrance channel leads to fusion. It is also useful to define the nth-order moment of the *s.d.* as:

$$< \ell^n > = \frac{\sum_\ell \ell^n \sigma_\ell}{\sum_\ell \sigma_\ell}. \quad (2)$$

The knowledge of *all* the moments of the distribution is equivalent to the knowledge of the distribution itself [18]. In terms of a moment expansion, the fusion cross section is proportional to the zeroth moment of the *s.d.* Therefore there can be many shapes of the *s.d.* , reflecting very different physical processes involved, that may yield the *same* fusion cross section . Consequently, more stringent tests on the theoretical models can be obtained by comparing their predictions with higher moments of the *s.d.* Indeed several experiments at near-barrier energies have yielded spin distributions of the compound nucleus that are broader than those expected from theoretical models, even when these models seem to successfully reproduce the excitation function of the fusion cross section[19, 20, 21, 22].

Also, there are some hints from these studies correlating these underpredictions of the broadening to the mass asymmetry of the nuclei involved in these reactions[21]. The role of the mass asymmetry is also important in the test of other degrees of freedom, such as neck formation[16]. Varying the asymmetry of the entrance channel may also allow us to explore how adequate the reduced mass, commonly used in most of the theoretical models, may be for describing the inertial parameter involved in the fusion process. Since the inertial parameter appears in the calculation of the quantum mechanical penetrability as well as in the centrifugal potential, it may also affect the spin distribution of the compound nucleus.

In this work we will briefly discuss the physical ideas underlying some of the models that have been proposed. We will then review the different experimental probes that have been used to obtain information about the *s.d.* and the methods for inferring the moments of the *s.d.* from experimentally measured quantities.

II- Preliminary Considerations.

The simplest approach to the fusion process is the one-dimensional penetration model . Despite its well known limitations in providing a quantitative description of the experimental results[1, 23], this model is still useful in providing an intuitive picture of the fusion process, as well as helping to achieve a physical understanding of more elaborated models. It is useful to briefly recall the usual simplifying assumptions that are made in this model. If the product $Z_1.Z_2$ is not too high (< 400), one would expect that the density overlap at the barrier maximum is not very significant. Therefore it seems appropriate to reduce the two (or many) body problem of the interacting nuclei to a one-dimensional problem in the standard way. It is then possible to use the reduced mass, $\mu(= [m_1^{-1} + m_2^{-1}]^{-1})$, as the inertial parameter that describes the system. In this case it is also reasonable to approximate the Coulomb and centrifugal potentials to those of point objects. Thus the effective potential can be written as:

$$V_{eff}(r,\ell) = V_n(r) + \frac{e^2 Z_1 Z_2}{r} + \frac{\ell(\ell+1)\hbar^2}{2\mu r^2}. \quad (3)$$

Furthermore, if we assume that fusion is the dominant reaction channel, then the problem of calculating the fusion cross section is reduced to that of calculating the penetrability of each partial wave to the effective potential. In the case of heavy ions, a good approximation of the penetrability is given by the JWKB approximation:

$$P_\ell(E) = [1 + exp(2S_\ell(E))]^{-1} \quad (4)$$

with

$$S_\ell(E) = \int_{r_1}^{r_2} \sqrt{\frac{2\mu}{\hbar^2}\{V_{eff}(r,\ell) - E\}}dr, \quad (5)$$

where r_1 and r_2 are the classical turning points. In addition if we approximate the barrier top by an inverted parabola, then it is possible to obtain a closed analytic expression for $P_\ell(E)$, given by the Hill-Wheeler formula:

$$P_\ell(E) = [1 + exp\{\frac{2\pi}{\hbar\omega_\ell}(V_\ell^\circ - E)\}]^{-1}, \quad (6)$$

where V_ℓ° is the barrier height and $\hbar\omega_\ell$ is related to the curvature at the top of the barrier, located at the the internuclear distance $R_b(\ell)$, through the expression:

$$\hbar\omega_\ell = \hbar\sqrt{-\frac{1}{\mu}\frac{\partial^2 V_{eff}(r,\ell)}{\partial r^2}}|_{r=R_b(\ell)}. \quad (7)$$

Moreover, if we assume that the barrier widths and positions are independent of ℓ, i.e., $\hbar\omega_\ell \simeq \hbar\omega_{\ell=0} = \hbar\omega$ and $R_b(\ell) = R_b(\ell = 0) = R_b$, we can write:

$$\sigma_\ell = \frac{\pi}{k^2}(2\ell+1)[1 + exp\{\frac{2\pi}{\hbar\omega}(V_b + \frac{\ell(\ell+1)\hbar^2}{2\mu R_b^2} - E)\}]^{-1}, \quad (8)$$

where $V_b = V_{\ell=0}^\circ$.

Replacing the sum over ℓ in expression (1) by an integral, we obtain the fusion cross section :

$$\sigma_{fus}(E) = \frac{R_b^2\hbar\omega}{2E} ln\{1 + exp[\frac{2\pi}{\hbar\omega}(E - V_b)]\}. \quad (9)$$

for $E \gg V_b + \hbar\omega/2\pi$

$$\sigma_{fus}(E) \simeq \pi R_b^2(1 + \frac{V_b}{E}) \quad (10)$$

which is useful for extracting the values of the parameters V_b and R_b from the above barrier fusion data.
For $E \ll V_b + \hbar\omega\ /2\pi$ we have:

$$ln(E \times \sigma_{fus}) = \{ln(\frac{R_b^2 \hbar\omega}{2}) - \frac{2\pi}{\hbar\omega} V_b\} + \frac{2\pi}{\hbar\omega} E = Constant + \frac{2\pi}{\hbar\omega} E, \qquad (11)$$

this expression allows us to obtain $\hbar\omega$ from the subbarrier fusion data.
Only in very few cases this model can reproduce the experimental results at near barrier energies, using parameters that are physically reasonable[5, 23]. On the other hand this simple model does provide some hints about some interesting effects that have been observed in near barrier reactions as we will see later.

Note that for almost any realistic potential, the barrier is usually very asymmetric about its maximum, therefore one may wonder to what extent the conclusions that are drawn from the use of the Hill-Wheeler formula, obtained for an inverted parabola, may be of any validity. It turns out that if one approximates the nuclear plus Coulomb potential by an asymmetric parabolic potential of the form:

$$V(x) = \begin{cases} V_b - \frac{1}{2}\mu\omega_1^2 x^2, & if\ x \geq 0 \\ V_b - \frac{1}{2}\mu\omega_2^2 x^2, & if\ x < 0. \end{cases} \qquad (12)$$

It can be shown from expressions (4) and (5) that the penetrability is still given by the Hill-Wheeler formula with an effective width given by: $\hbar\omega_{eff} = 2[\hbar\omega_1^{-1} + \hbar\omega_2^{-1}]^{-1}$. In fig.1 we compare the predictions of the σ_{fus} and $< \ell >$, using an asymmetric parabolic potential with numerical solution of the Shröedinger equation. The results are remarkably similar even at energies of about 20% below the barrier.

Fig.1 also illustrates the effect of saturation of the *s.d.* at subbarrier energies. This result is also implicit in expression (8). Indeed for $E \ll V_b$, the shape of the *s.d.* becomes independent of the energy (saturate), even σ_{fus} is changing exponentially, i.e.

$$\sigma_\ell = \frac{\pi}{k^2} exp\{\frac{2\pi}{\hbar\omega}(E - V_b)\} \times \{(2\ell + 1) exp\{\frac{2\pi}{\hbar\omega}\frac{\ell(\ell+1)\hbar^2}{2\mu R_b^2}\} = f(E) \times g(\ell). \qquad (13)$$

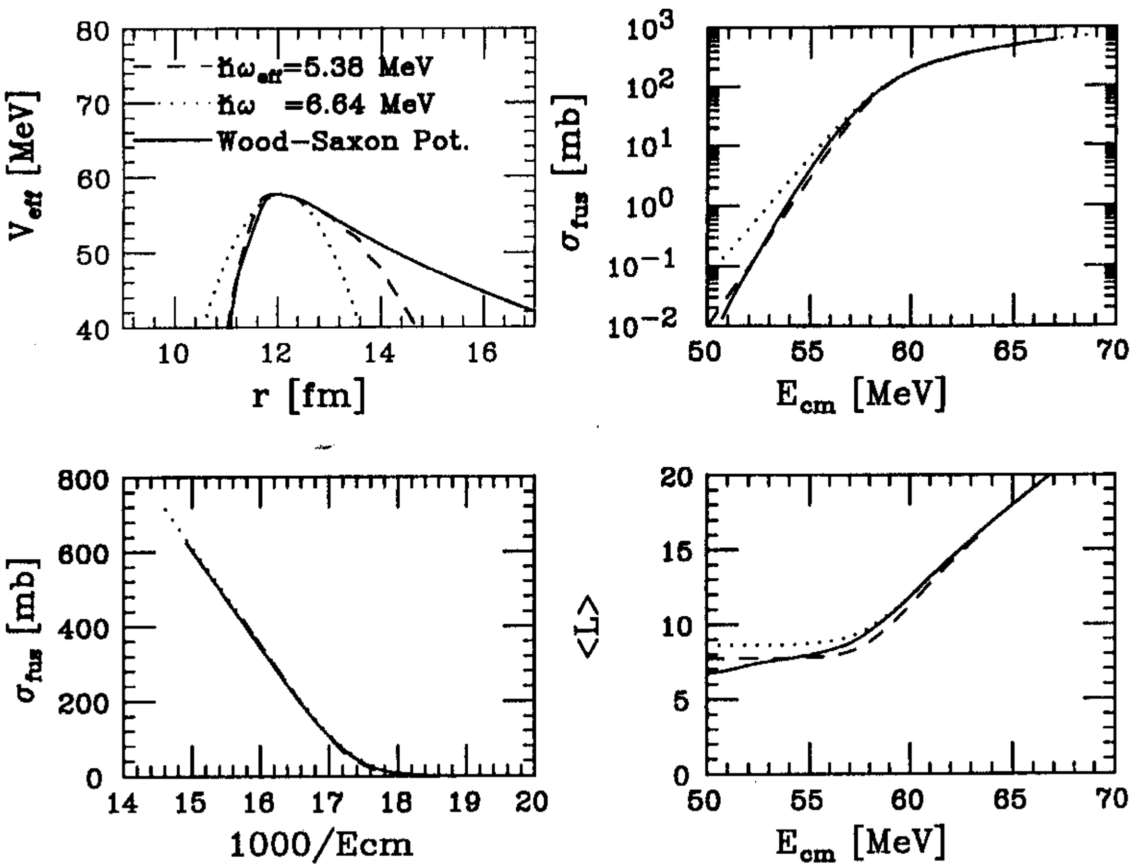

Figure 1: a) Comparison of the nuclear plus Coulomb potential for the system $^{16}O + ^{154}Sm$ using the Wood-Saxon potential (Solid lines) of ref.[13], with a symmetric (dotted line with $\hbar\omega$ =6.64 MeV) and asymmetric (dot-dash, $\hbar\omega_{eff}$=5.4 MeV) parabolic potentials. b),c) and d) predictions the one-dimensional penetration model and an optical model calculation (solid line).

These expectations of the saturation of the spin distribution have recently been confirmed experimentally in a number of systems at LBL [24, 25]. Fig.2 shows the results for the system $^{12}C + ^{128}Te$ where the change of slope of $< \ell >$ as a function of E_{cm} at about the barrier energy is very conspicuous.

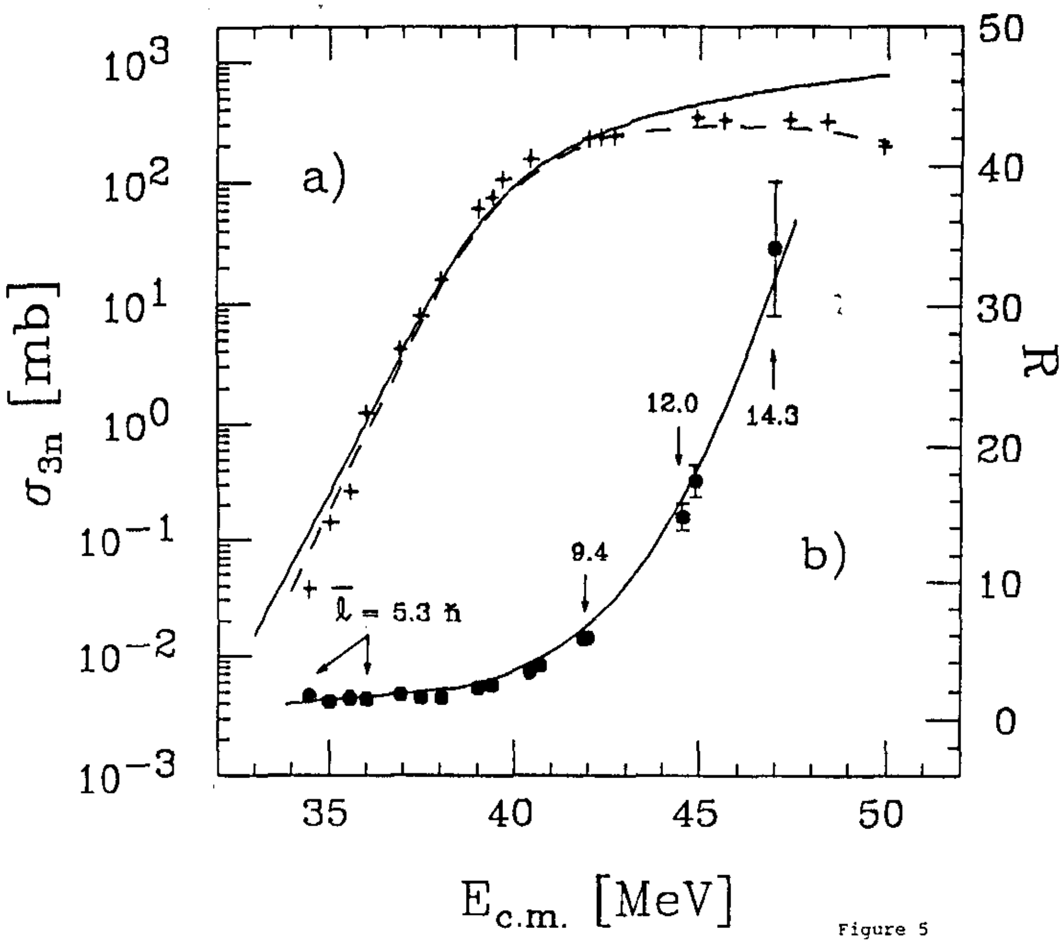

Figure 2: Experimental fusion cross section for the reaction $^{128}Te(^{12}C,3n)^{137}Ce$, and the results of $<\ell>$ obtained from the isomer ratio, R. The solid lines are the prediction of CCFUS. After ref.[24].

Another important effect implicit in our previous discussion is the role of the reduced mass in determining the broadening of the *s.d.* To the extent that nuclear matter overlap is negligible at the top of the barrier ($Z_1.Z_2$ small), the *s.d.* will be determined by the penetrability of the centrifugal barrier. In those cases where μ is small (light projectiles) we would expect from (3) that the effective potential will change considerably from one ℓ to the next. Therefore the penetrability will change rapidly with ℓ, producing a more or less triangular shaped *s.d.* For heavier projectiles by the same arguments, the *s.d.* will broaden as μ increases; this is illustrated schematically in fig.3.

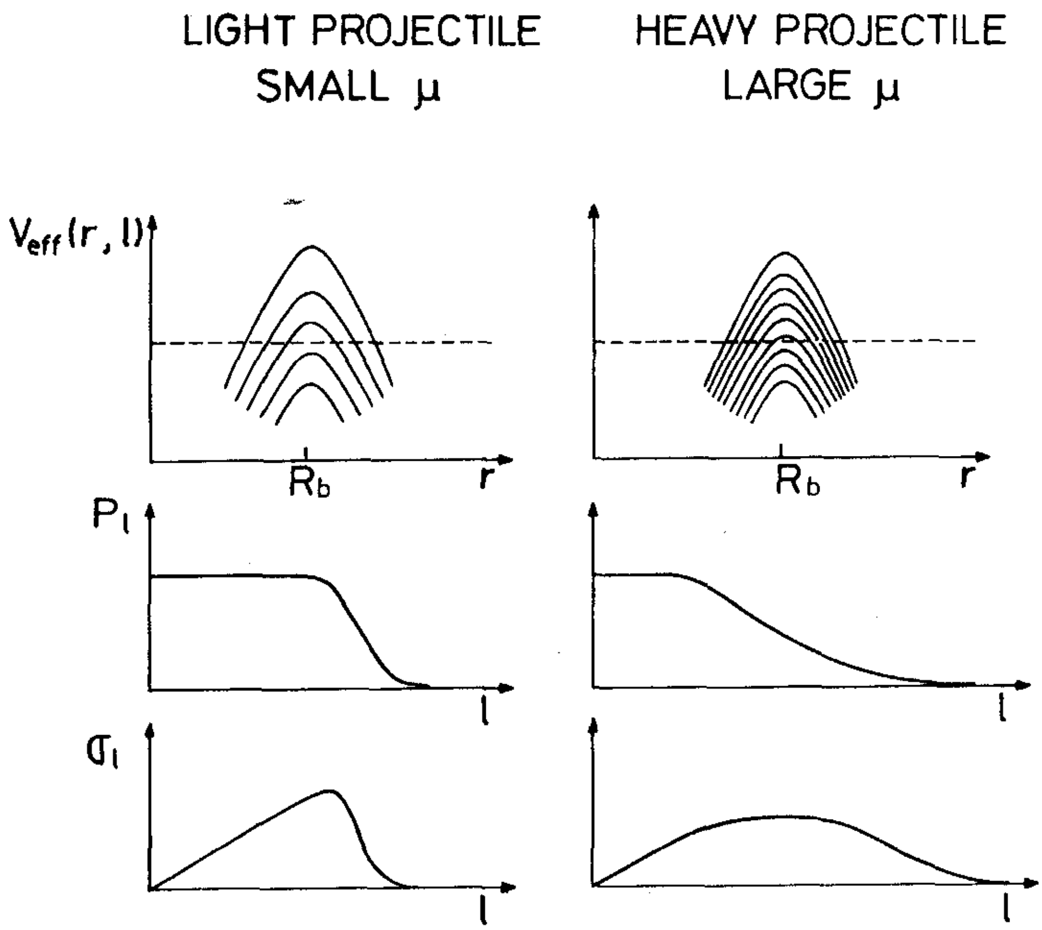

Figure 3: Schematic illustration of the effect of the reduced mass on the spin distribution.

These expectations have also been observed experimentally in an early experiment [26]. When comparing the *s.d.* to triangular shaped one, it is useful to extend the definition of the critical angular momentum, ℓ_c, to subbarrier energies:

$$\sigma_{fus} = \frac{\pi}{k^2}\ell_c(\ell_c + 1) \tag{14}$$

thus ℓ_c can be thought as the number of partial waves that should have been removed from the elastic channel to obtain the value of σ_{fus} . For a triangular shaped *s.d.* $<\ell> = \frac{2}{3}\ell_c$. Therefore, the larger the increase of $<\ell>$ over this expectation, the larger is the broadening of the *s.d.* as compared to a triangular one. Fig.4 also shows that a triangular shaped *s.d.* is a good approximation for very asymmetric systems, particularly at above barrier energies. This result is useful when one is trying to establish the connection between the experimentally measured quantities and the moments of the *s.d.* .

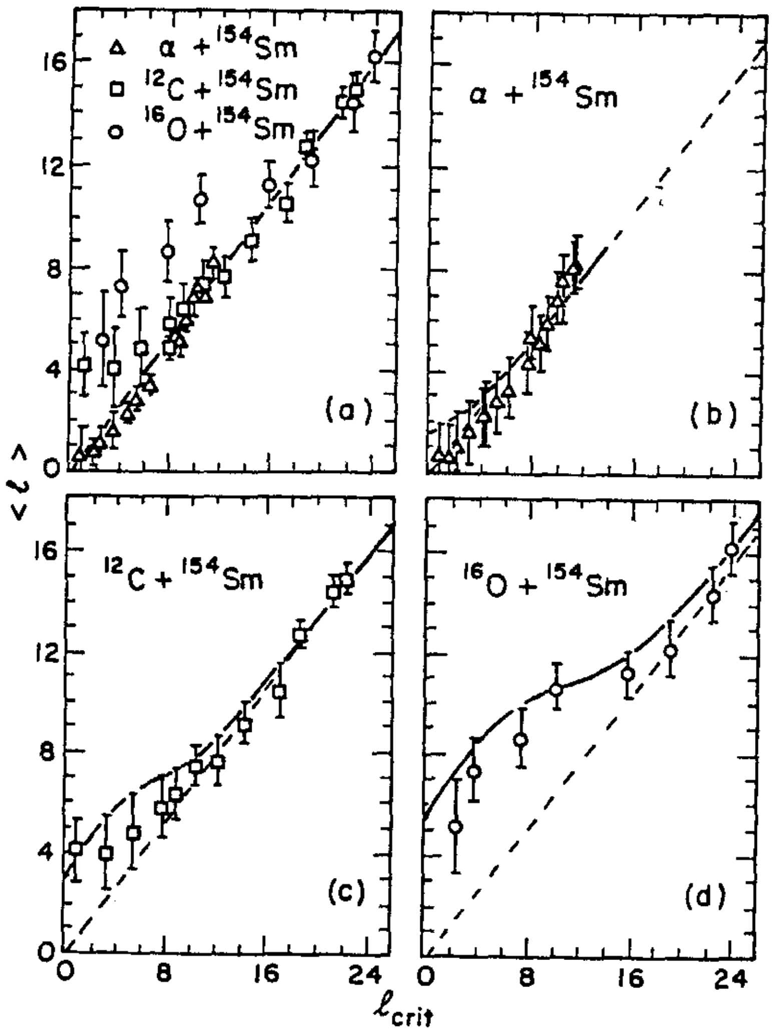

Figure 4: Experimental results of $< \ell >$ vs. ℓ_c. The values of $< \ell >$ were obtained from M_γ measurements and those of ℓ_c were deduced from σ_{fus} . The dashed lines are the expectation for a triangular *s.d.* , the solid lines are the expectation of the Wong model. From ref.[26]. In these experiments, only the 4-n decay channels were studied for the two heavier systems. At lower energies the 3n channel begin to be more important, therefore these experimental results only provide a lower limit on the the width of the *s.d.* [42], but still illustrate the effect of the reduced mass.

Nuclear structure effects. Several years ago, Wong [3] extended the one-dimensional penetration model so as to include the static deformation of the participant nuclei. Assuming that the rotational motion is much slower than the collision time, the penetrability can be calculated for a frozen orientation of the projectile and target, and then averaging over all the orientations. Esbensen [6] following a similar idea, extended this treatment so as to include the case of vibrational nuclei. Due to the zero-point motion (ZPM), spherical nuclei can acquire an instantaneous deformation. Again assuming that the change of shape is slow compared to the collision time, each individual collision samples a given shape. Penetrabilities are then calculated by taking an ensemble average over all the possible shapes. The net result of including the static deformations or the ZPM vibrations is to enhance the subbarrier fusion and to broaden the spin distribution. Fig.5 illustrate this effect.

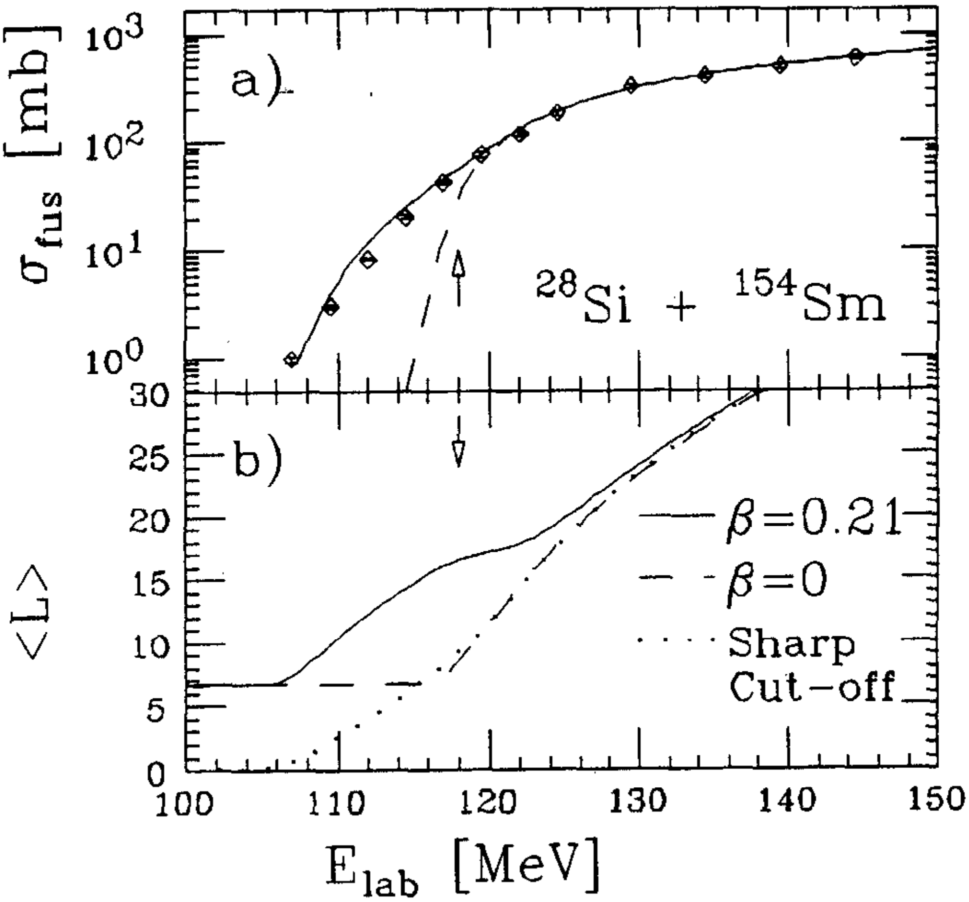

Figure 5:Illustration of the effect of deformation on the σ_{fus} and $< \ell >$. The introducing of ZPM or coupling to other channels produce qualitatively similar results [20, 2]. These effects can also be simulated with a fluctuating barrier. Note that below the lowest barrier thus generated, the same saturation value is obtained. The experimental result are from ref.[35]

A more quantitative and complete approach to the fusion process can be obtained with the coupled-channel formalism. Perhaps the most attractive feature of this model is that it provides a simultaneous understanding of all reaction processes (fusion, elastic and inelastic scattering, transfer, etc). Futhermore the nuclear structure of the participant nuclei can be incorporated in a flexible and natural way. The physical effect of coupled-channels in fusion reactions has been nicely explained by Dasso et al. [27]. Using a simplified two-level model, they showed that the effect of channel coupling is to split the original barrier into a higher and lower one, resulting in both an enhancement of subbarrier fusion and a broadening of the *s.d.* , similar to the effect shown in fig.5.

Perhaps an oversimplified but useful way of thinking about the general effect of incorporating nuclear structure degrees of freedom is the following. Coupling to other reaction channels can be simulated by a fluctuation of the interaction barrier, which result in both an enhancement of the fusion cross section and a broadening of the *s.d.* .

Only in very few systems it has been possible to do a complete analysis using a coupled-channel formalism. One of these systems is $^{16}O + ^{208}Pb$ [29]. In this case the theory succeeds in reproducing the inelastic plus transfer data together with the fusion excitation function, but it underestimates the width of the *s.d.* [10, 30, 11]. Similar disagreements have been observed in other systems as well [19, 22].

Frobrich and coworkers have explored the fusion process from a different approach. Using a classical transport theory based on a surface friction model [31, 32] they can give a consistent description of σ_{fus} and the *s.d.* for a number of systems. However severe discrepancies still remain between this approach and the experimental results at subbarrier energies, particularly for those systems where the CN undergoes fission after fusion.

III- Experimental Probes of the Spin Distribution.

The experimental information about the spin distribution of the CN at subbarrier energies is not very abundant. For those systems where the CN produced in the reaction de-excites primarily by the emission of a few neutrons followed by γ-rays, it is possible to infer information about the different moments of the *s.d.* by studying the γ-ray multiplicities. In particular, the first moment of the spin distribution, $< \ell >$, has been obtained using a high resolution Ge detector in combination with at least one NaI in coincidence. In the discrete photon technique, the Ge detector is used for tagging the different evaporation residues produced in the reaction, the coincidence to singles ratio is proportional to the average γ multiplicity, M_γ . When using this technique it is important to include as many decay channels of the CN as possible (ideally all). Otherwise significant bias may be present in the results due to spin fractionation. This effect is associated with the fact that different decay channels sample different region of the spin distribution of the compound nucleus[22].

The conversion of M_γ to $< \ell >$ has often been accomplished by using a simple relation of the form:

$$< \ell > = a(M_\gamma - b). \tag{15}$$

The constant a and b are determined empirically through measurements of M_γ and σ_{fus} for systems in the same region of the periodic table and at bombarding energies well above the barrier. The constant b is associated with the number of statistical

γ-rays emitted early in the cascade. Typical values of b are between 2 and 4. The constant a is the average angular momentum carried off by the non-statistical γ-rays. Typical values of a are between 1.5 and 2. This relation is probably adeq... when relatively large amounts of the angular momentum are involved. For near-barrier reactions, the values of angular momentum involved are usually rather modest and a more specific connection is necessary. We have explored a number of empirical approaches for this conversion, and have adopted a procedure similar to that of Halbert et al. [22], which seems more appropriate in these cases:

$$< \ell_i > = 2(M_\gamma^{(i)} + 1 + BB_i - < M_s^i >) + < M_s^i >< \Delta J_i > + M_n < \Delta J_n > + J_h^i. \quad (16)$$

where the first term describes the angular momentum carried away by stretched quadrupole non-statistical gammas, the second term describes the (modest) amount of angular momentum carried off by the statistical gammas, and the third term accounts for angular momentum carried away by the evaporated neutrons. $J_h(i)$ is the angular momentum of the band head. The index i denote the different evaporation residues produce in the reaction under study. The $1 + BB_i$ term corrects for the γ-ray used as a tag in the Ge detector and for transitions that are either too low in energy for the corresponding γ-ray to be detected in the NaI, or that proceed by internal conversion.

The values of $< M_s^i >, < \Delta J_s >$ and $< \Delta J_n >$ are taken from statistical evaporation models. Finally, the value of $< \ell >$ is obtained as the weighted average over all the decay channels.

$$< \ell > = \sum_i f_i < \ell_i > \quad (17)$$

where f_i is the relative yield for the channel i at each energy. These values have been measured for a number of systems[4, 33]. An important constraint on the statistical model, is that it should reproduce these relative yields.

In our investigations we have devised a technique to empirically test (or "calibrate") the validity of this conversion. For example in a recent reexamination of the system $^{16}O +^{154} Sm \rightarrow (^{170}Yb^*)$ we produced the same CN by using the reaction $^4He +^{166} Er$ [42], which explores the same region of excitation energy and spin at near barrier energies, but with bombarding energies well above the barrier. Thus in this later reaction, one can more safely predict the spin distribution by measuring σ_{fus} and M_γ and then use it as a bench mark for testing the validity of the conversion of M_γ to $< \ell >$.

Using large array γ-detector, the above procedure can be used to extract higher moments of the spin distribution, which consequently helps to obtain a deeper insight into the fusion process[22].

Recently a LBL Group has devised a novel technique for probing the spin distribution below the barrier. They measured the isomer ratio of the cross section for populating a high spin isomeric state to that of a low spin ground state. Since the high spin states produced in the reaction will preferentially feed the high spin isomer, it is clear that the isomer ration, R, is related to the spin distribution of the compound system. This group has studied the *s.d.* far below the barrier and found evidence for the saturation effect (Fig.3). Perhaps a serious limitation of this approach is that for converting R into $< \ell >$ one has to rely,rather heavily, on some kind of statistical evaporation model. Since the isomer ratio is measured only in one of all the several open channels, caution should be exercised to avoid the effect of the spin fractionation. This conversion is also sensitive to details of the level scheme of the isomer nucleus. Perhaps when using this technique, the use of a "calibration" reaction of the type described before, would be very valuable for establishing the connection between R and $< \ell >$.

During the last few years, at the Nuclear Physics Laboratory of the University of Washington, we have devised a new technique to obtain $< \ell >$ by using an electrostatic deflector. Since the fusion products are strongly peaked at 0 degree, large detection efficiency can be achieved with these deflectors whenever it is possible to separate and suppress the beam-like particles from the fusion products. Furthermore, by directly using the fusion products as a tag for the fusion process, the effect of channel fractionation can be diminished.

This deflector when used in conjunction with several NaI detectors and a large particle detector (a Breskin counter [34]) allowed us to measure the γ-ray multiplicities. The Breskin counter, when operated with a pulsed beam, provides a time of flight (TOF) of the particles, which was used to separate the fusion products from the elastic and quasi-elastic products.

In Fig. 6 we show typical TOF spectra, both singles and in coincidence with the NaI detectors. The larger peak in the singles spectrum is associated with the beam-like particles. At low bombarding energies, when the fusion cross section is close to a few mb, the magnitude of the tail of this peak under the recoil peak is the main source of uncertainty in extracting the area of the recoil peak from the singles spectrum. Considerable improvement was achieved in reducing this tail by carefully tuning the beam so as to minimize the amount of beam hitting the collimators. The enhancement of the recoil peak in the coincidence spectrum as compared to the beam-like peak, can be readily understood as arising from the larger M_γ associated with fusion as compared with inelastic, transfer, and quasi-elastic processes.

Gamma multiplicities are then obtained from the ratio of the areas of the recoil peak in the coincidence and singles spectra, in a manner similar to the discrete photon tag case. An important property of the multiplicities thus obtained, is that they are *independent of the efficiency of the electrostatic deflector.* Using this technique we have been able to measure M_γ at bombarding energies below those using the discrete photon method.

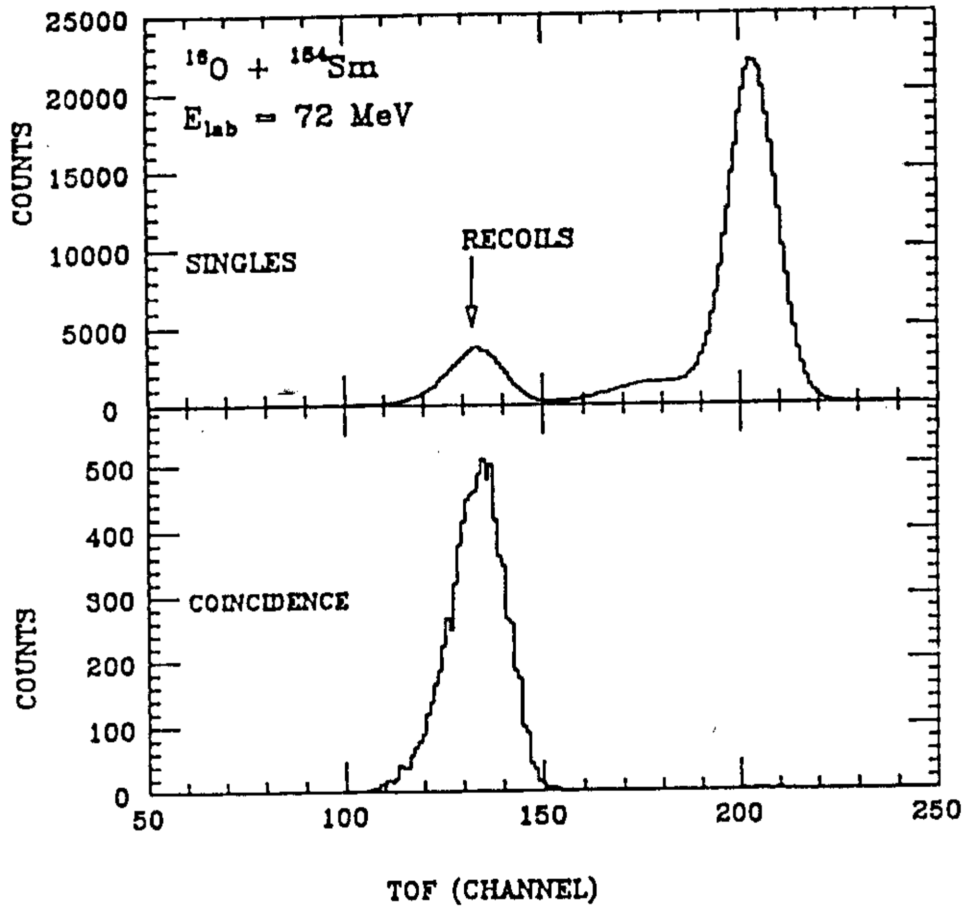

Figure 6: TOF spectra for the system $^{16}O + ^{154}Sm$ at E_{lab}=72 MeV, using the University of Washington electrostatic deflector, in singles (top) and coincidence (bottom) with the NaI detectors.

With the electrostatic deflector we have recently measured M_γ for the system $^{28}Si + ^{154}Sm$. This is a natural extension of the previous studies with a ^{154}Sm target with lighter projectiles[26]. The values of σ_{fus} were obtained from a delayed X-ray activity experiment[4, 33] at the Tandar laboratory. The same measurements were made to the system $^{16}O + ^{166}Er$, that leads to the same CN as $^{28}Si + ^{154}Sm$, at bombarding energies that explore the same region of excitation energies and spin. To achieve this, the last reaction was performed with bombarding energies well above the barrier. According to our previous discussion it is expected that for $^{16}O + ^{166}Er$ the spin distribution can be more safely predicted from the σ_{fus} data. Therefore this reaction can be used as a "calibration" or bench mark for obtaining the connection between the measured quantities M_γ and $< \ell >$. We were able to obtain good fits of the fusion cross sections for both systems using the Wong model[35]. The values of $< \ell >$ were obtained following a procedure similar to the one discussed in connection with the discrete photon technique. The comparison of the values of $< \ell >$ obtained with this procedure for $^{16}O +^{166} Er$, with those expected from the values σ_{fus} , nicely agree. Our preliminary results of $< \ell >$ for $^{28}Si +^{154} Sm$ are shown in fig. 7 together with the results of the Wong model calculation that successfully reproduce the fusion cross section . This is a surprising result since in view that in an earlier of the system $^{16}O +^{154} Sm$ [21, 42] we found *s.d.* broader than the one expected from a theoretical model that reproduced the fusion excitation function. Consequently, for this more asymmetric system we would have expected even a larger discrepancy.

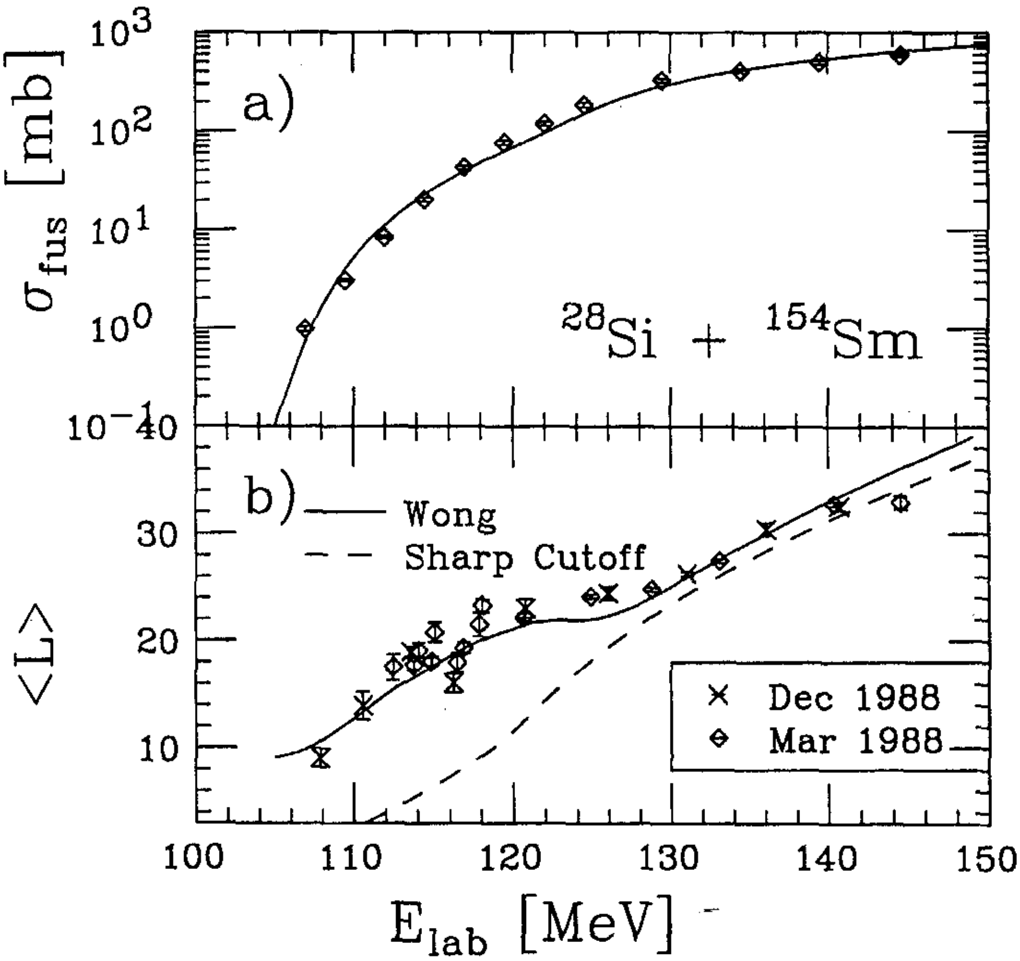

Figure 7: Preliminary results of $< \ell >$ obtained from M_γ measurements using an electrostatic deflector. The solid line are Wong model predictions, using parameters the also fit the fusion excitation function for this system (see fig. 5). From ref.[35].

In heavier CN, where fission is the main decay channel, it is possible to obtain information about the spin distribution of the CN by measuring the angular distribution of the fission fragments [19, 30]. In particular $< \ell^2 >$ is given approximately by

$$\frac{W(0^\circ)}{W(90^\circ)} = 1 + \frac{<\ell^2>}{8K_0^2} \quad (18)$$

where

$$K_0^2 = \frac{J_{eff}T}{\hbar^2} \quad (19)$$

The values of K_0^2 can be obtained from a calibration reaction [19] or from systematics [30]. In fig.8 we show the results of $<\ell^2>$ using this technique for the systems: $^{16}O+^{208}Pb, ^{16}O+^{232}Th$ and $^{12}C+^{236}U$[19, 30]; together with the theoretical predictions. These were among the first systems where large underpredictions of $<\ell^2>$ have been observed.

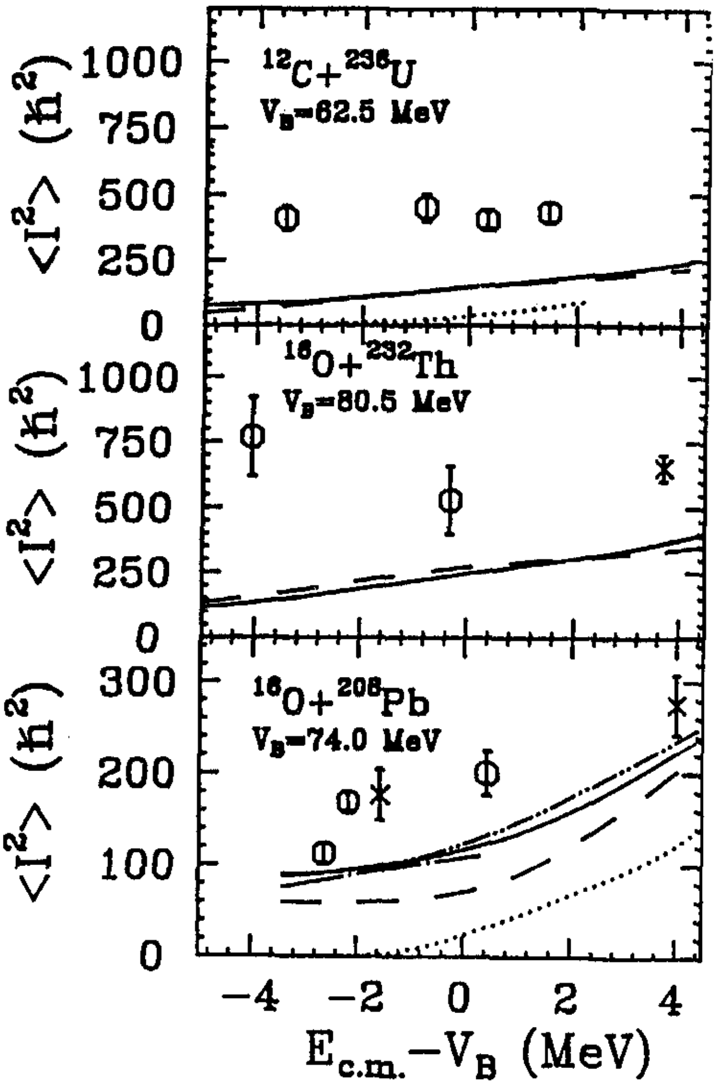

Figure 8: Comparison of $<\ell^2>$ deduced from fission angular distribution, together with theoretical predictions. From ref.[30].

Similar results were also recently found in the system $^{64}Ni +^{100} Mo$ [22]. The results of $< \ell >$ and $< \ell^2 >$ were deduced from M_γ measurements using the Oak Ridge spin spectrometer. In fig.9 we see the experimental results together with different theoretical expectations. The explanation of these results are still a challenge.

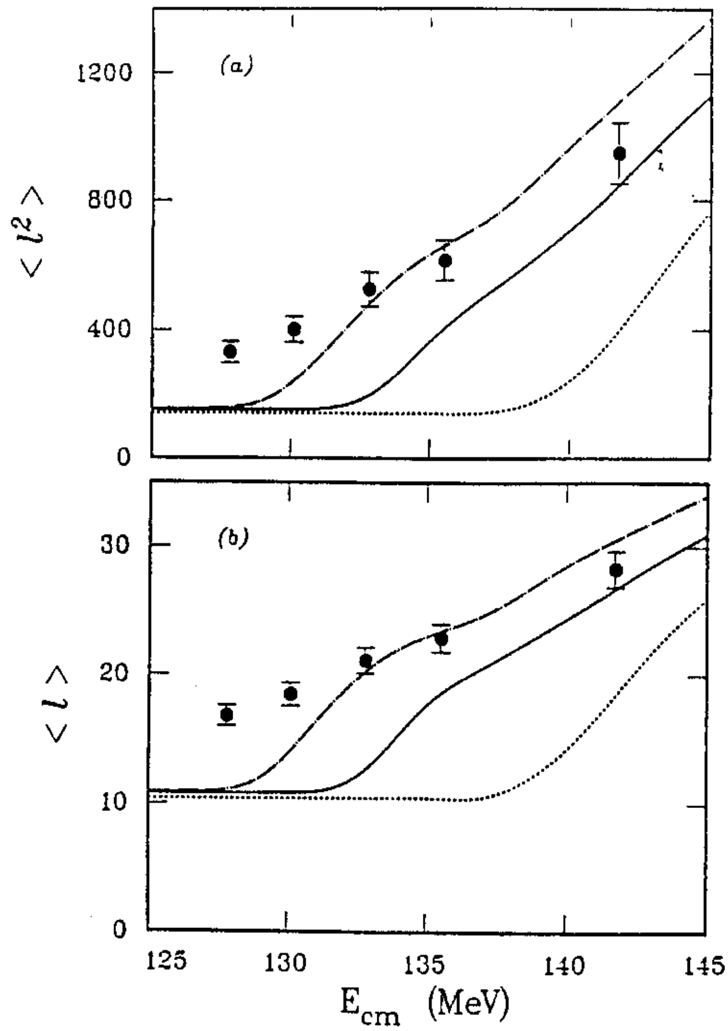

Figure 9: Results of $< \ell >$ and $< \ell^2 >$ for the system $^{64}Ni +^{100} Mo$. The dotted lines single barrier penetration calculation. The full curves are coupled-channel calculations with established coupling parameters. The dot-dash curve are the result of increasing the coupling parameters by 50%. From ref.[22].

For those systems where the α-decay channel is important, it is possible to extract $< \ell^2 >$ from the angular distribution of the evaporated particles. A group from Munich [36] has exploited this sensitivity by measuring the angular distribution of the evaporation residues.

When evaporation residues and fission compete, fractionation between these channels depends, among other things, on the *s.d.* . Measurements of σ_{fiss} and σ_{er} could yield information on the *s.d.* . Lesko et al. [37, 38] have exploited this possibility in the case of $^{A'}Ni +^{A} Sn$. Uncertainties associated with the statistical model necessary to obtain the fractionation between those channels may impose a serious limitation on this technique. Here again the use of a "calibration" reaction would be valuable.

V- Conclusions.

We have seen how experimental information on the spin distribution pose more stringent test on fusion model. Large enhancements of the fusion cross sections, and broadenings of the spin distribution arise from the interplay between the reaction dynamics and nuclear structure degree of freedom The general picture that emerge from the recent studies is that most theories, even when they succeed in reproducing fusion excitation function, they tend to underestimate the broadening of the *s.d.* From a recent systematic [21], it appears that there may be some correlation between the degree of discrepancy between theories and experiments at subbarrier energies, and the product $Z_1.Z_2$. This in turn, may be related to the nuclear matter overlap at the barriers. The assumption of using the reduced mass as the inertia parameter may need to be the subject of further studies. Investigation of this problem in rather light nuclei and above the barrier, using the adiabatic time-dependent Hartree-Fock (ATDHF) approach[39, 40], indicates that the parameter that describes the inertia of these systems shows appreciable deviation from the reduced mass at separations close to the top of the barrier. Perhaps extending this type of studies to heavier systems and to subbarrier energies may help to clarify this point. Recently we have begun an experimental program to investigate this issue experimentally. We are currently studying the fusion cross section and the *s.d.* for a number of systems with different entrance-channel mass asymmetries that lead to the same CN, ^{170}Hf.

Another question that may be interesting to analyse is whether the effect of saturation at subbarrier energies still holds for more symmetric systems than the one studied so far. One may also wonder if the current models will succeed in reproducing the experimental data in these cases.

The connection between the measured quantities and the different moments of the spin distribution is another issue that should be studied critically. We feel that the use of a "calibration reaction" for checking this point can be very valuable.

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