

## Spin distributions—another approach for experimentally probing the fusion barrier distribution

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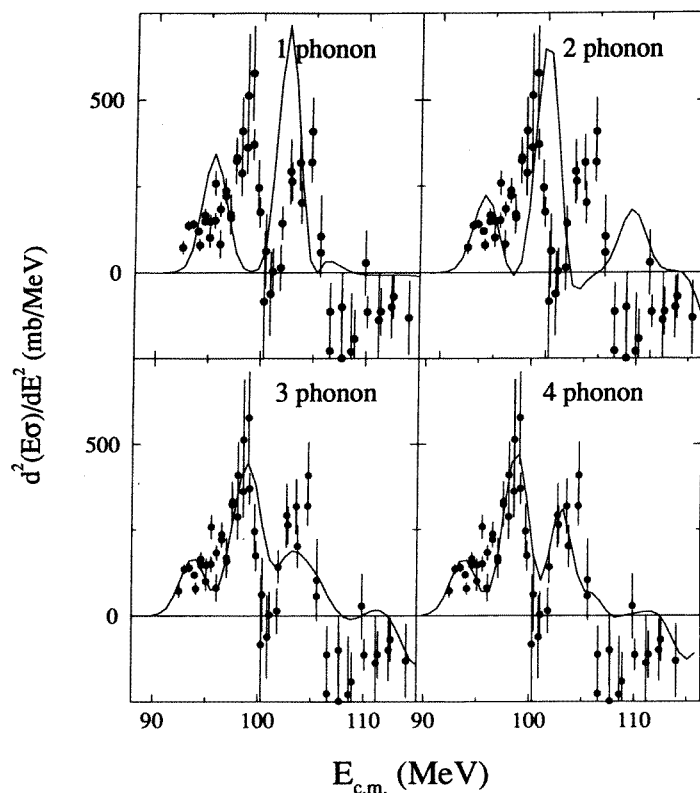
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**Abstract.** The investigation of subbarrier fusion is undergoing a revival following the suggestion of a way to extract an experimental representation of the barrier distribution from the second derivative,  $d^2(E\sigma_{\text{fus}})/dE^2$ . By performing precise measurements of fusion excitation functions one is able to extract the strength and height of the barriers, providing important information on the coupling mechanism. As an alternative approach, it has recently been proposed that the first derivative of the compound nucleus (CN) spin distribution is equivalent to  $d^2(E\sigma_{\text{fus}})/(dE^2)$ . Multiplicity distributions for the reactions  $^{64}\text{Ni}+^{100}\text{Mo}$  and  $^{32}\text{S}+^{110}\text{Pd}$  have been measured making use of the Argonne/Notre Dame-BGO-array and GASP, respectively. In particular, the influence of fission on the high spin tail of the spin distribution and the consequences for the experimental representation of the distribution of barriers is discussed for  $^{64}\text{Ni}+^{100}\text{Mo}$ .

### 1. Introduction

The investigation of subbarrier fusion has attracted renewed interest, following the partial success of the coupled channel approach in reproducing fusion cross sections. The experimental representation of the barrier distribution from the second derivative of the fusion cross section times energy,  $d^2(E\sigma)/dE^2$  [1], has demonstrated the richness of information that may be obtained by precise measurements of the fusion excitation function. Excellent results have been obtained from investigations of the fusion of the spherical nucleus  $^{16}\text{O}$  with the deformed  $^{154}\text{Sm}$  target by Leigh *et al* [2]. The measured barrier distribution was reproduced using deformation parameters  $\beta_2$  and  $\beta_4$  which are consistent with the values obtained from Coulomb excitation experiments.

Using the same approach, the influence of double phonon coupling on subbarrier fusion for  $^{58}\text{Ni}+^{60}\text{Ni}$  has recently been shown [3] (figure 1). The identification of these complex surface vibrations as the only relevant effects, and the negligible influence of other channels, in particular the elastic 2n-transfer, have been substantiated by the comparison with the older  $^{58}\text{Ni}+^{58}\text{Ni}$  data [4] which also show a characteristic double-peaked structure. This system has been investigated in order to look for the effects of transfer but instead, a signature of multiphonon coupling was found. Thus, the next logical step was to look for a clear case



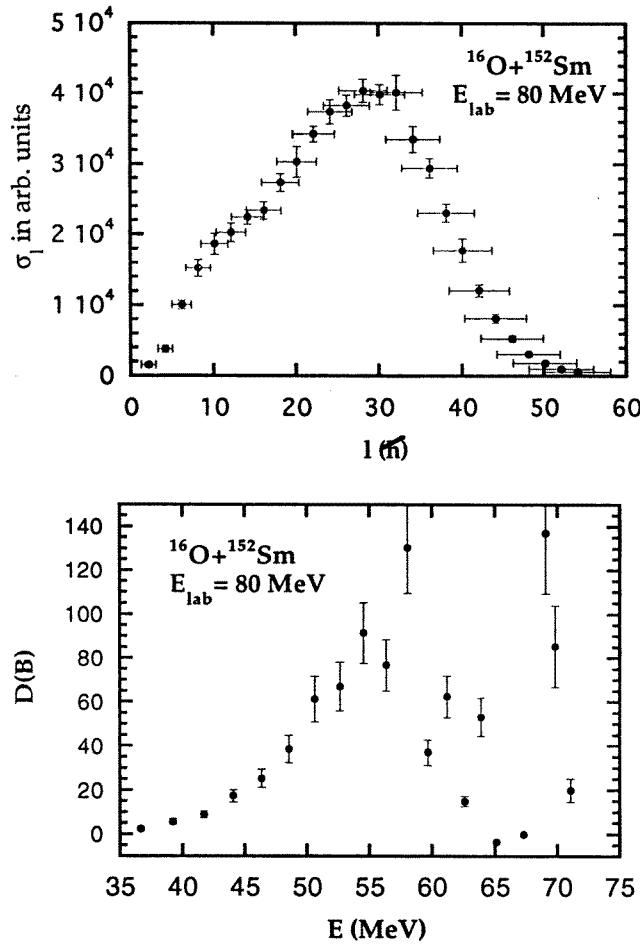
**Figure 1.** The experimental barrier distribution for  $^{58}\text{Ni} + ^{60}\text{Ni}$  compared with coupled-channel calculations in the one-, two-, three- and four-phonon-channel spaces generated by considering up to mutual double excitation. (From [3]).

where effects other than surface vibrations can be excluded.  $^{110}\text{Pd}$  is a vibrational nucleus with a well known two- and three-phonon structure; we therefore decided to study the fusion of  $^{110}\text{Pd}$  with  $(^{32})^{36}\text{S}$ . The barrier distribution obtained from the measured fusion excitation function shows a characteristic structure which can be explained almost completely only by coupling up to the three-phonon states of  $^{110}\text{Pd}$  [5]. This result shows, however, one of the limits of the technique of extracting the barrier distribution from differentiating twice the function  $E \times \sigma_{\text{fus}}$ . In the higher energy range due to the large absolute cross sections and the flat slope the experimental errors become large and the distribution is no longer well defined. This region, however, contains valid information for the understanding of the reaction process.

## 2. Spin distribution as an alternative

As an alternative approach it has been shown recently [6] that the first derivative of the compound nucleus (CN) spin distribution is equivalent to the barrier distribution obtained from the second derivative of  $E \times \sigma_{\text{fus}}$ . On the basis of the assumption

$$T_{\ell}(E, \ell) = T_0(E - E_{\text{rot}}(\ell)) \quad (1)$$



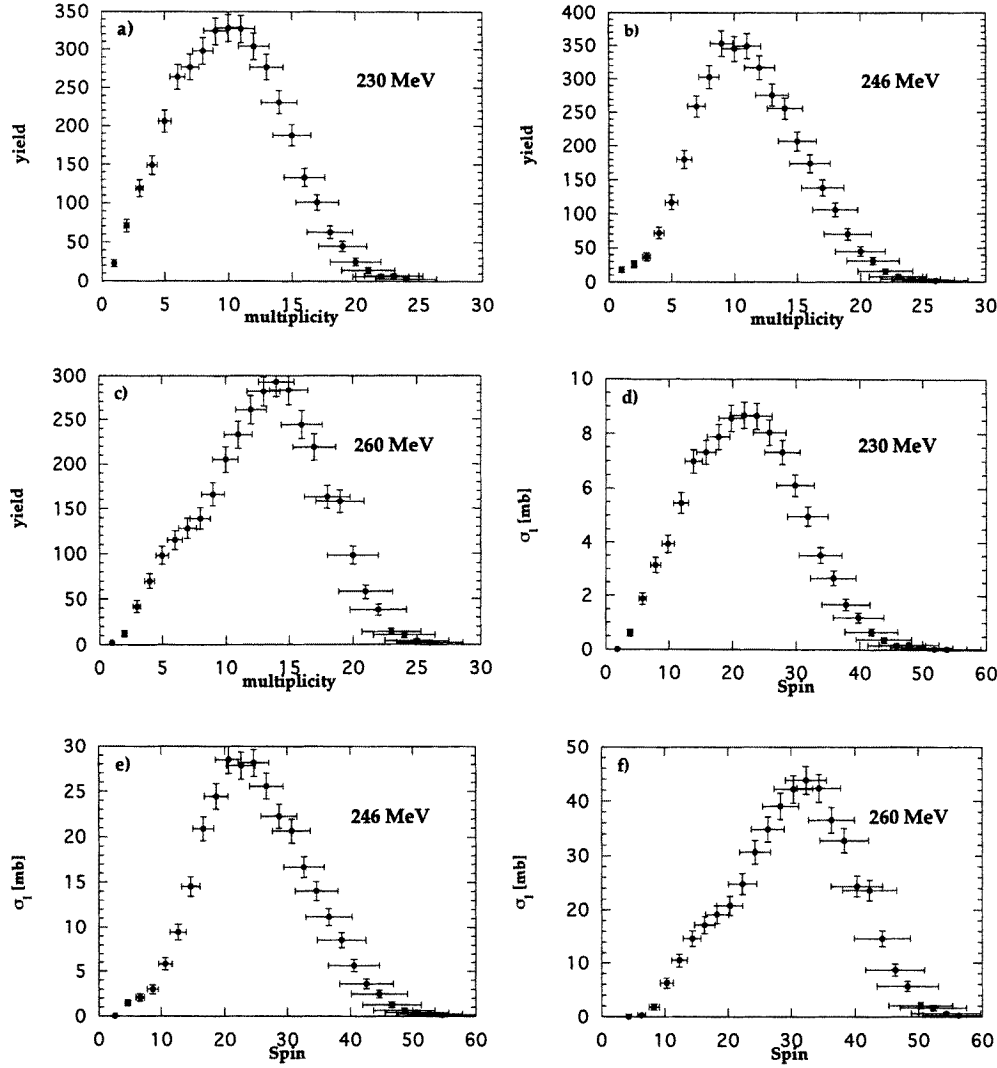
**Figure 2.** Experimental angular momentum distribution for  $^{16}\text{O} + ^{152}\text{Sm}$  at an beam energy of  $E_{\text{lab}} = 80 \text{ MeV}$  [8] (upper panel) and barrier distribution (lower panel) extracted from it. (From [9]).

one can express the partial wave transmission probabilities [7] as

$$T_\ell(E, \ell) = \frac{1}{\pi R_b^2} \left( \frac{d(E\sigma_{\text{fus}})}{dE} \right). \quad (2)$$

The assumption (1) provides a prescription by which the  $\ell$ -dependence of the transmission coefficient (at one energy) can be converted into an *energy*-dependence for the *s*-wave transmission coefficient. With these ingredients one can derive the barrier distribution from a complete angular momentum distribution. In the first step one extracts the *s*-wave transmission function  $T_0(E')$ , using (1), and normalizing by the geometrical cross section for each partial wave  $\ell$

$$T_\ell(E, \ell) = T_0(E' = E - E_{\text{rot}}(\ell), \ell = 0) = \frac{\sigma_\ell(E, \ell)}{(2\ell + 1)\pi\lambda^2}. \quad (3)$$

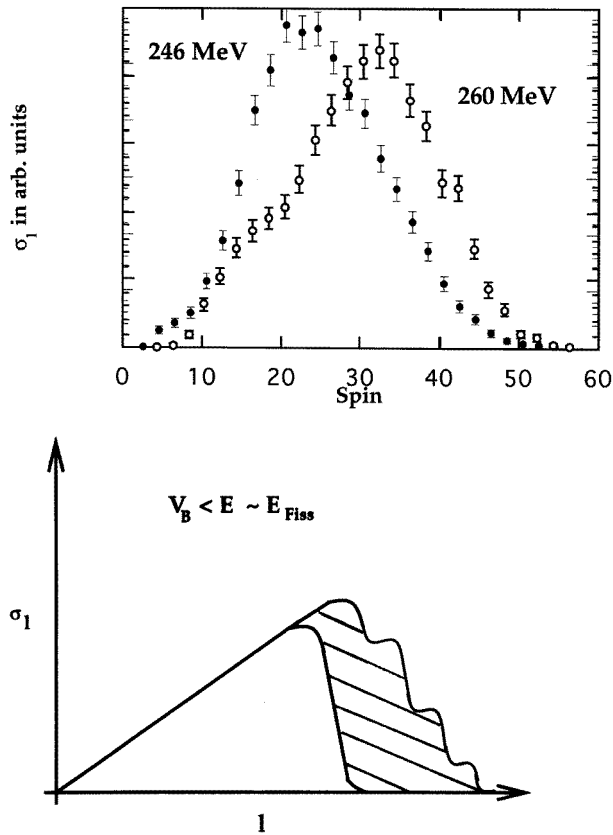


**Figure 3.**  $\gamma$ -multiplicity (a)–(c) and spin distributions (d)–(f) for the reaction  $^{64}\text{Ni} + ^{100}\text{Mo}$  at three energies (see text).

The derivative of this function gives according to (2) the barrier distribution

$$D(B) = \frac{1}{\pi R_b^2} \frac{d^2(E\sigma_{\text{fus}})}{dE^2} = \frac{dT_0(E')}{dE'}. \quad (4)$$

Thus the partial wave distribution  $\sigma_\ell$  at one energy  $E$  provides us with a transmission function and a barrier distribution spanning a range from  $E$  to  $E - E_{\text{rot}}(\ell_{\text{max}})$ . For instance, in the system  $^{16}\text{O} + ^{152}\text{Sm}$  at an energy above the barrier and a maximum angular momentum around  $50\hbar$ , one covers an energy range of 30–40 MeV which includes the entire barrier region. Wuosmaa *et al* [8] measured for this system a set of spin distributions at various energies, in the range of the Coulomb barrier. The spin distribution measured at an energy above the Coulomb barrier and the barrier distribution extracted from those data using (3)



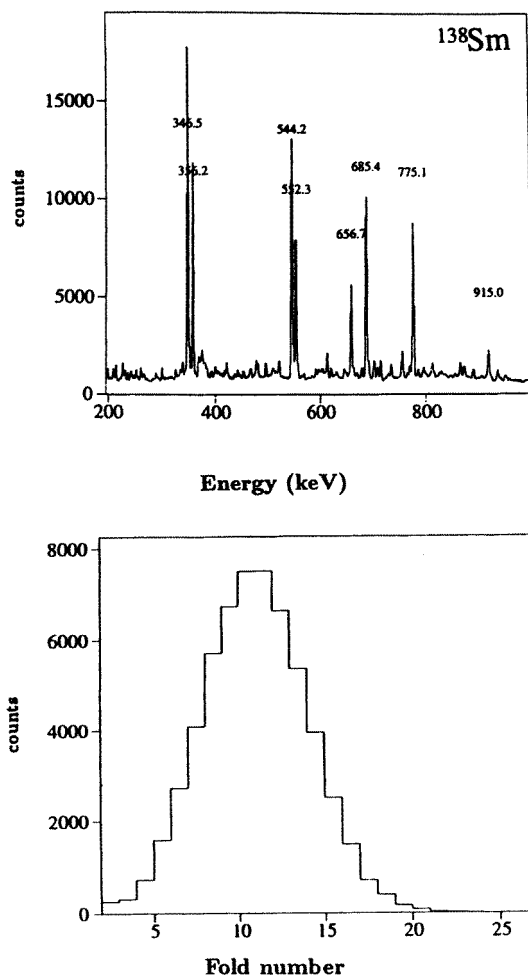
**Figure 4.** Comparison of the spin distributions at the two higher energies (figures 3(e) and (f)). The shaded area in the bottom figure illustrates the truncation of the distribution by fission.

and (4) are shown in figure 2. One notes that the barrier distribution is consistent with what is expected for a deformed nucleus as, for example, in [2].

### 3. The experiment

In a recent experiment  $\gamma$ -multiplicities have been measured for the systems  $^{32}\text{S} + ^{110}\text{Pd}$  and  $^{16}\text{O} + ^{152}\text{Sm}$  at the Ge-array GASP of the Laboratori Nazionali di Legnaro, Italy, in order to extract experimental barrier distributions from the derived spin distributions. The results should: (1) prove the validity of the method and (2) complete the information of the coupling mechanism obtained from the previously measured fusion excitation function. The data are currently being analysed. A second experiment on which we shall concentrate in this paper has been performed with a slightly different apparatus for the reaction  $^{64}\text{Ni} + ^{100}\text{Mo}$ . Here, the Argonne/Notre Dame BGO-array at the Argonne National Laboratory ATLAS-facility has been used in conjunction with a combination of an electrostatic deflector and a Si-strip detector array.

The  $^{64}\text{Ni} + ^{100}\text{Mo}$  reaction has been the subject of several previous experiments and the fusion cross sections around the barrier are known along with the average angular momenta [10, 11]. The most recent investigation [10] claimed evidence for the



**Figure 5.**  $\gamma$ -ray spectrum and fold distribution in coincidence with characteristic  $\gamma$ -rays of the 4n-channel of the reaction  $^{32}\text{S} + ^{110}\text{Pd}$ .

importance of the one-plus-two phonon coupling, which should, on the other hand lead to a characteristic ‘experimental barrier distribution’ similar to that obtained from experimental fusion excitation functions for  $^{32}\text{S} + ^{110}\text{Pd}$  and  $^{58}\text{Ni} + ^{60}\text{Ni}$ .

The Argonne BGO-array and GASP each have an efficiency of about 70%. The lower granularity of 50 detectors as compared with GASPs 80 BGO-crystals is still sufficient as the maximum multiplicities are around 25 (see figure 3).

The main difference between the two setups is the way the evaporation-residue (ER) trigger was defined. Whereas in the GASP measurements characteristic  $\gamma$ -lines have been used for the ER-multiplicity coincidences, with the ANL BGO-array the ER were detected directly in an array of four seven-strip Si-detectors with a total active area of  $(8 \times 12) \text{ cm}^2$ . The array was located at a distance of  $\approx 1 \text{ m}$  from the target behind the electrostatic deflector. The latter has the advantage of integrating over the whole ER-distribution. Therefore, discontinuities due to the summing of different ER-channels in the spin distribution, as in principle is possible in the GASP measurement, are avoided. On the other hand, some

assumptions about the effects of particle evaporation must be made in the transformation from measured  $\gamma$ -ray multiplicity to spin (see discussion in section 4).

#### 4. Preliminary results for $^{64}\text{Ni} + ^{100}\text{Mo}$ and interpretation

We measured  $\gamma$ -multiplicities for  $^{64}\text{Ni} + ^{100}\text{Mo}$  in coincidence with evaporation residues (ER) at three energies— $E_{\text{lab}} = 230, 246$  and  $260$  MeV; i.e. at the barrier, at the point where fission becomes important and at an intermediate energy.

At all three energies we obtained  $\approx 3700$  counts for the total multiplicity spectrum. This rather low statistics was basically due to a background of scattered beam through the deflector which forced us to use a relatively low beam current. Nevertheless some conclusions can be drawn from the obtained multiplicity data which are shown in figures 3(a)–(c). Preliminary spin distributions have been computed using a simple relation of the type

$$\ell = \Delta I_{\gamma ns}(M_{\gamma} - M_{\gamma s}) + \text{constant} \quad (5)$$

where  $M_{\gamma}$  denotes the measured  $\gamma$ -multiplicity,  $\Delta I_{\gamma ns} = 2$  is the spin taken away by the yrast-transitions and the constant contains the spin removed by statistical  $\gamma$ -rays ( $M_{\gamma s}$ ), the particle evaporation and the groundstate spin of the ER, using average values. This procedure is not correct for the lower spin region of the distribution, because the various evaporation channels are not equally distributed over the whole spin range. Therefore, the absolute spin-values should be taken with care. The shape of the higher end of the distribution, however, should not be affected. There we expect to observe the influence of the barrier distribution. For a large range of barriers a long tail should appear which at higher energies will be cut by fission. In figure 4 a superposition of the spin distributions for the two highest energies is shown. One notes clearly a change in shape as illustrated by the diagram in the same figure. The spin distribution taken at the lower energy has a relatively long tail of  $> 22\hbar$ , whereas the other one falls to zero over only  $\approx 12\hbar$ . The statistical errors, however, do not allow the extraction of the representation of barrier distributions in a way to provide a detailed analysis of the coupling mechanism.

#### 5. Conclusion and outlook

In conclusion, we have observed a long tail in the high spin region of the measured multiplicity (spin) distribution at energies at and slightly above the nominal Coulomb barrier. This suggests the presence of a rather broad distribution of barriers as expected for a coupling scheme including several phonon states. At higher energies where fission sets in, this tail is truncated and not determined any longer by the potential landscape of fusion but is governed by the energetic properties of the fission process. Better statistics are desirable in order to execute any detailed coupled channels analysis on the basis of the experimental representation of barriers. Much higher statistics have been accumulated for the reactions measured at GASP as can be seen for the 4n-channel of  $^{32}\text{S} + ^{110}\text{Pd}$  in figure 5. The much more complex data analysis is presently ongoing.

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