Gamma-ray multiplicity distributions in $^{16}\text{O}+^{152}\text{Sm}$ fusion near and below the Coulomb barrier


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We have studied $\gamma$-ray multiplicity distributions for the system $^{16}\text{O}+^{152}\text{Sm}$ at five beam energies in the range 60–80 MeV, near and below the Coulomb barrier. The data were obtained using a large array of $\gamma$-ray detectors and an efficient evaporation-residue detector system utilizing an electrostatic deflector. The data are in good agreement with predictions of angular momentum distributions calculated using a coupled-channels model incorporating the effects of deformation.

The study of enhanced fusion cross sections near and below the Coulomb barrier has attracted a great deal of interest. Fusion cross sections orders of magnitude larger than those expected from simple barrier-penetration models have been observed in a large number of heavy-ion systems [1,2]. Several different theoretical approaches have been developed in order to understand the behavior of the fusion cross section in this energy region. Modifications to the effective fusion barrier by deformation [3], coupling to inelastic excitations [4], particle transfer [5], zero-point motion [6], and neck formation [7] all have been shown to yield substantial enhancements in sub-barrier fusion cross sections. Typically, these descriptions have proved capable of reproducing the energy dependence for fusion in a wide variety of heavy-ion systems to energies as low as 80% of the nominal Coulomb barrier.

Despite this success, the ability to fit the fusion excitation function does not, in itself, provide the most stringent test of the fusion model. Theories which have different physical input can often yield similar cross sections. The partial-wave distribution is more sensitive to the detailed content of the model than is the cross section, and thus, a determination of the spin distribution provides much tighter constraints on the different theories of sub-barrier fusion enhancement.

Several authors have studied the effects of angular momentum in this energy region. Single moments of the spin distribution, such as the mean angular momentum $\langle L \rangle$ or the root-mean square angular momentum $\langle L^2 \rangle^{1/2}$, have been determined from measurements of the mean $\gamma$-ray multiplicity $\langle M_\gamma \rangle$ [8–10], isomer ratios [11], and fission-fragment [12,13] and $\alpha$-particle [14] anisotropies.

A measurement of complete $\gamma$-ray multiplicity distributions has been performed by Halbert et al., for fusion of $^{64}\text{Ni}+^{100}\text{Mo}$ at near-barrier energies [15]. Halbert et al., using several theoretical models, found that the fusion excitation function and the measured spin distributions could not be reproduced simulta-
neously. In ref. [15], fusion events were tagged by detecting discrete, low-lying transitions using high-resolution γ-ray detectors. That method has some potential drawbacks. For instance, due to the poor efficiency of the Ge detectors, contributions from weak fusion channels could be missed. More importantly, at energies near the Coulomb barrier, backgrounds from competing processes such as Coulomb excitation may also complicate the measurement. Often, these typically low-multiplicity backgrounds must be suppressed experimentally, causing the loss of some fraction of the data [15].

Many of these problems could be avoided by detecting evaporation residues directly with high efficiency, and without regard to channel selection [10]. In the present work, we have combined an evaporation-residue (ER) detector system with a large γ-ray detector array in order to obtain γ-ray multiplicity distribution data for heavy-ion fusion in the near and sub-barrier region. This experimental method has several advantages over some of the approaches described above, such as a much higher efficiency for tagging residues than is obtained by detecting discrete low-lying transitions, and sensitivity to all fusion–evaporation channels regardless of cross section. The direct identification of residues also eliminates the necessity of subtracting background contributions arising from competing reaction processes.

We have applied this method to fusion in the $^{16}\text{O} + ^{152}\text{Sm}$ system. Fusion cross section data for $^{16}\text{O}$ on various Sm isotopes were obtained by Stokstad et al. [16] and DiGregorio et al. [17]. They found strong sub-barrier cross section enhancements for $^{16}\text{O} + ^{152}\text{Sm}$. This system thus provides an excellent opportunity to use spin-distribution information to test and compare different models of sub-barrier fusion enhancement.

Targets consisting of 150 μg/cm² of $^{152}\text{Sm}$ evaporated onto thin $^{12}\text{C}$ backings were bombarded at laboratory energies of 80, 70, 65, 62.5 and 60 MeV, with ≈4 nA $^{16}\text{O}$ beams from the Argonne National Laboratory ATLAS accelerator system. The γ-ray multiplicity data were obtained using 42 elements of the Argonne–Notre Dame BGO γ-ray facility, augmented with an ER detector system. The BGO elements covered ≈70% of the total $4\pi$ γ-ray solid angle, and were also surrounded by eight Compton-suppressed Ge detectors. The ER detector consisted of an electrostatic deflector followed by a forward time-of-flight array consisting of 25 400 mm² silicon detectors. The heavy-ion detectors were close packed in a two-layer structure contained within a 17.8 cm × 17.8 cm square. Monte Carlo simulations of the response of the system using ER angular distributions obtained from statistical-model calculations, and including the effects of charge distribution and multiple scattering, gave an efficiency of approximately 20% for ER detection. Comparison of the measured relative fusion yields to those reported in ref. [16] shows that the deflector system is equally efficient for all neutron evaporation channels. The chief source of background in the ER array consisted of beam particles scattered from the plates of the deflector. The timing of the silicon detectors with respect to the beam, combined with the measured energy, served to separate residues from such scattered particles.

Fig. 1 contains the experimental γ-ray fold and multiplicity data for $^{18}\text{O} + ^{152}\text{Sm}$ at the five beam
energies studied. The histograms in fig. 1 represent the raw measured $\gamma$-ray fold distributions, which reflect the number of elements of the BGO array that fired for each event. Even at a laboratory energy of 60 MeV, where the fusion cross section is only 1.06 mb [16], good statistics were obtained from the $\gamma$-ray multiplicity array with a relatively short run time of two hours.

The data were corrected for the instrumental response of the BGO array using an iterative Monte Carlo procedure [18,19]. The resulting unfolded $\gamma$-ray multiplicity distributions appear as the data points in fig. 1. The resolution of the BGO array and of the unfolding procedure constitute the dominant contributions to the uncertainties in the data points in fig. 1, and are reflected in the horizontal error bars. The vertical error bars represent both counting statistics and the statistical nature of the unfolding process, and are generally smaller than the plotting symbols. These data are sufficient to yield individual moments $\langle M^0 \rangle$ of the multiplicity distribution up to $N=9$ at $E_{\text{lab}}=80$ MeV, and up to $N=3$ at $E_{\text{lab}}=60$ MeV, with uncertainties of $ \pm 20\%$.

In order to compare the data with model predictions for the spin distribution, information about the statistical decay of the compound nucleus must be used to either transform the experimental $\gamma$-ray multiplicities into angular momenta, or to generate a model multiplicity distribution based upon the theoretical partial cross section. The transformation of multiplicities into spin has commonly been used in the literature, mainly because it permits direct comparison between the theoretical spin distribution and the results derived from data. Generating a theoretical multiplicity distribution, however, permits a comparison between purely theoretical and purely experimental quantities that does not depend upon a model-dependent transformation of the measured multiplicities. Both treatments contain the same information, and carry the same implicit assumptions about the structure and decay of the compound nucleus. In some cases of disagreement experiment and theory, part of the discrepancy has been attributed to the transformation between $M_\gamma$ and $\langle L \rangle$. In order to study this question in greater detail, we have performed both analyses of the $\gamma$-ray multiplicity data from $^{16}O+^{152}\text{Sm}$.

In the first of these analyses, the theoretical partial cross sections were used as input to a statistical model of the decay of the compound nucleus. The statistical calculation then generated an $M_\gamma$ distribution for comparison with the data. For these calculations we used the code PACE2S [20]. The level density parameter for the statistical calculation was chosen to be $a=A/8.5$ MeV$^{-1}$, and the yrast line obtained from the rotating liquid drop model. We find that for a given input spin distribution, small changes in the parameters of the PACE2S calculation have little effect on the resulting calculated $\gamma$-ray multiplicity distributions.

The fusion excitation function measured by Stokstad et al. [16] appears in fig. 2a. The solid curve

![Fig. 2. (a) Fusion cross section for $^{16}O+^{152}\text{Sm}$, data points from Stokstad et al. [16]. The curves are described in the text. (b) Mean $\langle M_\gamma \rangle$ and (c) width $\Gamma(M_\gamma)$ obtained from experimental and theoretical $\gamma$-ray multiplicity distributions. (d) and (e) Moments $\langle L \rangle$ (d) and $\langle L^2 \rangle$ (e) of experimental and theoretical spin distributions. The solid (dashed) curves in (b)-(e) represent the predictions of the coupled-channels (energy-dependent barrier-penetration) calculations.](image-url)
represents a calculation of the fusion cross section using a coupled-channels formalism and parameters given in ref. [6], with the quadrupole deformation of the target treated in the frozen approximation [21]. The dotted curve represents a calculation which neglects channel coupling and deformation. This second calculation, quite similar to a simple one-dimensional barrier-penetration model, clearly underestimates the cross section by orders of magnitude at energies below the Coulomb barrier ($E_{\text{lab}} \approx 65$ MeV).

The energy dependence of the mean, $\langle M_r \rangle$, and the RMS width, $\Gamma(M_r)$, of the multiplicity distributions from the present work appears in figs. 2b and 2c. The solid curve represents the theoretical values obtained with input spin distributions given by the same coupled-channels calculation yielding the solid curve in fig. 2a. It has also been suggested that, in analogy to the treatment of threshold anomalies in elastic scattering, sub-barrier fusion enhancements could be described with the use of an energy dependent potential [22]. For comparison, the dashed curves in figs. 2b and 2c show the theoretical results obtained using partial cross sections generated from such a calculation, based upon a Woods–Saxon potential, with the depth of the potential adjusted at each energy to reproduce the measured or interpolated fusion cross section.

The experimental values of $\langle M_r \rangle$ and those calculated starting with spin distributions obtained from the coupled-channels prescription agree well in the energy range studied. The widths of the experimental distributions are also in good agreement with the coupled-channels prediction, with the exception of the $80$ MeV point, where it should be noted that the fusion cross section has not been measured. The values obtained from the energy-dependent barrier-penetration calculation, in particular in the near-barrier region at $E_{\text{lab}}=65$ and 70 MeV where channel couplings have their strongest effect, are in poor agreement with experiment. This result is in agreement with the suggestions of Dasso et al. [23], who have pointed out the inability of such a procedure to reproduce the fusion spin distribution.

In our alternative analysis, we adopt the multiplicity to spin transformation described by Halbert et al., given by

$$L(M_r) = (M_r - \langle M_{\gamma S} \rangle) \Delta L_{\gamma NS} + \langle M_{\gamma S} \rangle \Delta L_{\gamma S} + \langle M_n \rangle \Delta L_n + \langle M_\alpha \rangle \Delta L_\alpha \ldots \quad (1)$$

In eq. (1), $M_r - \langle M_{\gamma S} \rangle$, $\langle M_{\gamma S} \rangle$, $\langle M_n \rangle$, and $\langle M_\alpha \rangle$ are the average multiplicities of non-statistical and statistical $\gamma$-ray transitions, evaporated neutrons, and $\alpha$ particles, respectively, and $\Delta L_{\gamma NS}$, $\Delta L_{\gamma S}$, $\Delta L_n$, and $\Delta L_\alpha$ represent the average amount of angular momentum carried off by each type of transition. To estimate the values of these quantities, we have again used the code PACE2S. In contrast to our first analysis, the results obtained from the statistical decay calculations now represent only average values taken over many cascades. The different quantities used in eq. (1) can, in principle, have both angular-momentum and excitation-energy dependence, and this information, while taken into account in the first analysis, is lost in the second. Since the residual nuclei in this system are all good rotors, we have used $\Delta L_{\gamma NS} = 2$. As indicated from the statistical calculations, and verified by Ge spectra [24], the amount of charged-particle emission from this system is small, and was therefore neglected.

The dependence of the statistical-model results on the different input parameters was again investigated. We find that values of the quantities used in eq. (1) are quite insensitive to changes in the level density parameter $a$ from $\frac{1}{4}A$ to $\frac{1}{10}A$ MeV$^{-1}$. Of course, the statistical code also requires a partial-wave distribution for the initial compound nucleus. We performed these calculations using partial cross sections obtained from both the coupled-channels and energy-dependent barrier-penetration calculations, with the other parameters held fixed. Little difference was found between the two sets of results. The main discrepancies occurred near the Coulomb barrier, where two partial-wave distributions differ most strongly, causing the resulting experimental $\langle L \rangle$ and $\langle L^2 \rangle$ to vary by no more than 8% at those energies.

In our alternative analysis, the predictions of the coupled-channels calculation. As before, especially in the near-barrier region, the energy-dependent barrier-penetration calculation agrees
poorly with the measured $\langle L \rangle$ and $\langle L^2 \rangle$.

A more detailed comparison between the experimentally deduced spin distributions and those obtained from theory appears in fig. 3. The data are normalized to the measured fusion cross section, except at $E_{\text{lab}} = 80$ MeV, where they are normalized to the extrapolated fusion excitation function. The solid and dashed lines represent the same calculations as in figs. 2b–2e. In the near-barrier region, the data clearly favor the predictions of the coupled-channels model over those of the energy-dependent barrier-penetration calculations. At the lowest energy, the shapes of the two theoretical distributions are nearly identical, as seen from the moments $\langle L \rangle$ and $\langle L^2 \rangle$ plotted in fig. 2. The apparent difference between the two curves at $E_{\text{lab}} = 60$ MeV arises because the coupled-channels calculation slightly underestimates the fusion cross section. At $E_{\text{lab}} = 80$ MeV, the discrepancy between theory and experiment is not yet understood. Well above the Coulomb barrier, however, other reaction mechanisms not contained within the coupled-channels calculations, such as neutron transfer, deep inelastic scattering, and incomplete fusion could begin to affect the spin distribution. More varied experimental data, as well as more extensive theoretical calculations will be necessary to resolve this question.

The results of the present work indicate that near and below the Coulomb barrier, $\gamma$-ray multiplicity distribution data for $^{16}$O+$^{152}$Sm can be reproduced using a theory which includes the effects of channel coupling and deformation. In earlier studies of similar asymmetric systems, the mean angular momenta deduced from either $\gamma$-ray multiplicity [8–10], or isomer-ratio measurements [11], were also generally in good agreement with theoretical predictions. More significant discrepancies between theory and experiment occur in heavier near-symmetric and symmetric systems, such as $^{64}$Ni+$^{100}$Mo [15] and $^{86}$Se+$^{86}$Se [25]. Although the latter two measurements rely on discrete-line Ge data for tagging evaporation residues, it seems unlikely that discrepancies as large as those reported in ref. [15] could arise solely from this source of error. Indeed, for comparison, at $E_{\text{lab}} = 70$ MeV we have also analyzed $\gamma$-ray multiplicity data obtained by gating on discrete low-lying transitions in $^{164}$Yb and $^{168}$Yb, corresponding to the 4n and 3n evaporation channels, respectively. Using this procedure, we find the values of $\langle M_r \rangle = 9.2 \pm 0.8$, and $\Gamma(M_r) = 6.04 \pm 0.8$, in good agreement with those determined from the ER-BGO coincidence data alone, $\langle M_r \rangle = 8.4 \pm 0.5$, and $\Gamma(M_r) = 6.3 \pm 0.5$. Also, the multiplicity to spin transformation is relatively well understood in the mass 160 region, and probably cannot contribute more than 10~20% to errors in the derived values of $\langle L \rangle$ and $\langle L^2 \rangle$. More tantalizing is the possibility that the coupled-channels description falls short in symmetry and near-symmetric systems. The requirement of enhanced-channel coupling constants in the $^{64}$Ni+$^{100}$Mo system could indicate that other reaction mechanisms are at work. Experiments of the type described in this work studying fusion in more symmetric systems could help answer some of these questions.

In conclusions, we have studied $\gamma$-ray multiplicity distributions for $^{16}$O+$^{152}$Sm fusion at several energies near and below the Coulomb barrier. We find that the combination of an efficient evaporation-residue detector with a large $\gamma$-ray multiplicity array is a pow-

![Fig. 3. Angular-momentum distributions obtained from $\gamma$-ray multiplicity distribution data at the five laboratory energies studied. The solid curves are the results of the coupled-channels plus deformation calculation, and the dashed curves are the adjusted barrier-penetration model. The data have been normalized to the experimental cross section.](image-url)
erful method for obtaining γ-ray multiplicity-distribution data. The technique permits such data to be obtained quickly and without some of the potential biases that affect measurements relying on Ge tagging at low energies. Using two separate analyses, both modeling the γ-ray multiplicity distribution and transforming the measured γ-ray multiplicities into angular momenta, near and below the barrier, the data are in agreement with the predictions of a coupled-channels plus deformation calculation for fusion in this system. These results suggest that the methods used in this work could be applied to more symmetric systems, where significant discrepancies between theory and experiment may exist.

References

[24] A.H. Wuosmaa et al., to be published.