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COUPLED CHANNEL CALCULATIONS FOR THE $^{32}S+^{100,102,104}Ru$ REACTIONS.

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ABSTRACT

Sub-barrier fusion enhancements below and around the coulomb barrier are one of the most studied phenomena and have been extensively performed to probe the collective significance of both nuclear structure and dynamical process effects. A large enhancement in the sub-barrier heavy ion fusion cross-sections compared to the prognostications of the One- Dimensional Barrier Penetration Model. In the present study, coupled- channel calculations were performed for the $^{32}S+^{100,102,104}Ru$ systems using the CCFULL code[3,4]. Special attention was given to assessing the part of hexadecapole (β_4) deformations of both the projectile and target nuclei along with neutron transfer channels for $^{32}S+^{104}Ru$ system. These advanced- order deformation parameters impact the shape of the interaction potential and hence affect the fusion probability, particularly in the sub-barrier region using semi-empirical coupled channel calculations in NRV code [5,6]. Experimental fusion cross-section data for these systems were carried out by Pengo et al. [20], serving as a standard to validate the theoretical results.

INTRODUCTION

Fusion cross-sections near and below the Coulomb barrier are known to be significantly affected by the natural degrees of freedom of the interacting nuclei [1,8]. These degrees of freedom include low-lying surface vibrations and static deformation effects in nuclear shapes. Similar couplings of collaborative excitations modify the classical conception of a single, sharp fusion barrier into a distribution of implicit barriers [2,11-18]. As a result, fusion can do more readily at sub-barrier energies, leading to a conspicuous enhancement in the fusion cross-section compared to a simple one- dimensional barrier penetration model. To regard for these complex effects, coupled- channels (CC) calculations have come an essential theoretical tool in heavy- ion fusion studies. These calculations incorporate the coupling between the relative stir of the colliding nuclei and their internal excitations, thereby furnishing a more realistic description of the fusion process [7,8]. One of the extensively used computational codes for performing similar analyses is CCFULL code [3,4], which allows for the addition of multiple coupling schemes, including vibrational and rotational states, as well as advanced- order deformation parameters similar as the hexadecapole(β4) deformation. In some reactions, low- lying inelastic excitations are sufficient to reproduce the experimental data. But in certain reactions, it's necessary to include both inelastic excitations and transfer channels [10,11,12]. For that, a relative study, fusion excitation functions of $^{32}S+^{100,102,104}Ru$ systems were taken by Pengö et al. [20]. While the $^{32}S+^{100,102}Ru$ systems has smaller transfer channels, and the $^{32}S+^{104}Ru$ system has an order of 2n to 6n multi-nucleon positive Q- value transfer channels. To quantitatively analyze the effects of nuclear structure couplings on fusion dynamics, coupled- channel (CC) calculations have been employed. These models incorporate the coupling of relative stir to internal degrees of freedom, including inelastic excitations and nucleon transfer channels, thereby offering a more realistic representation of the fusion process.

In the present study, coupled- channel calculations were performed for the $^{32}S+^{100,102,104}$ Ru systems using the CCFULL code. Special attention was given to assessing the part of hexadecapole (β_4) deformations of both the projectile and target nuclei. These advanced- order deformation parameters influence the shape of the interaction potential and hence affect the fusion probability, particularly in the sub-barrier regime. Experimental fusion cross-section data for these systems were attained from Pengö et al. [20], serving to validate the theoretical results.

Theoretical Calculations

In the present work, the fusion excitation functions for the $^{32}S+^{100,102,104}Ru$ systems is shown in Figure 1, where the energy axis is presented in the centre-of-mass ($E_{c.m.}$) frame. The experimental data were plotted as black circles, squares, and triangles. It is important to note that the statistical error bars are smaller than the data point symbols, indicating high precision in most of the measured values. Quantitatively, the statistical uncertainties remain around 1% for the higher and intermediate energy ranges. However, as expected, these uncertainties increase for the lower energy data points, reaching up to approximately 20% due to the reduced fusion cross sections and limited event statistics in the sub-barrier region.

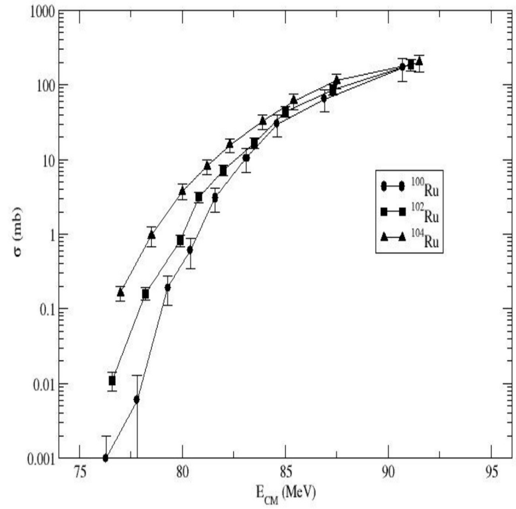

Figure 1: Experimental data for $^{32}S+^{100,102,104}Ru$

This comparison highlights the critical role of inelastic and transfer couplings in these reactions, revealing remarkably structural behavior across the entire energy range. In the present study, higher order of couplings was performed for the ^{32}S + $^{100,102,104}Ru$ systems using the CCFULL code. Further calculations have been performed as shown in figure 2.

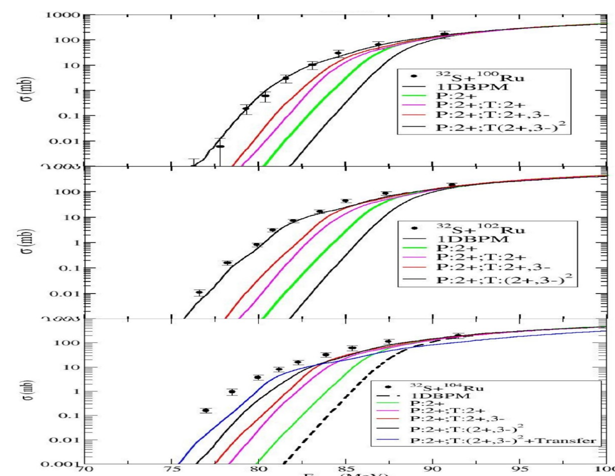

Figure 2: Inclusion of 2+,3- states with two phonon coupling of the target and the inclusion of 2+ state of projectile showing more enhancement for $^{32}S+^{100,102}Ru$ systems, but could not fit for $^{32}S+^{104}Ru$ system even after inclusion of transfer channels.

Initial analyses incorporating standard Akyuz-Winther potential parameters. Minimum impact observed for 2+ state of the projectile at below and above the coulomb barrier. Posterior consideration of the projectile's 2+ state and target states of 2+ and 3- led to data underestimation below the barrier and concordance over, challenging farther advances. The objectification of single phonon excitation for the projectile's 2 $^{+}$ state and two phonon couplings of the target nuclei's 2+ and

3- states produced satisfactory results for the $^{32}S+^{100,102}Ru$ systems but not for $^{32}S+^{104}Ru$ system. Including neutron transfer channels in addition to inelastic couplings failed to amend the disagreement observed in $^{32}S+^{104}Ru$. A thorough examination revealed the inclusion of neutron transfer channels, suggesting that structural rearrangements do n't significantly modify the barrier distribution or tunnelling probabilities in this case. Amend coupled channel calculations, varying levels of quadrupole and hexadecapole deformation of the target nuclei were considered, performing in enhanced agreement with experimental data for the $^{32}S+^{104}Ru$ system [21].

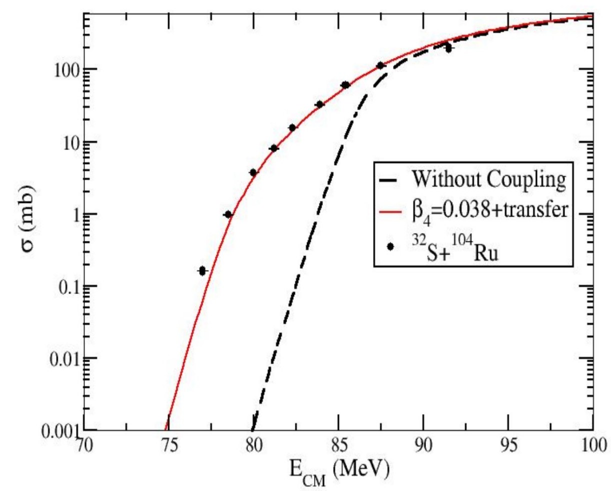

Figure 3: Inclusion of hexadecapole deformation with transfer shows good agreement to the experimental data $^{32}S+^{104}Ru$ system.

This lack of impact suggests that, for this system, the structural rearrangements associated with transferring neutrons do not appreciably modify the barrier distribution or tunnelling probabilities. Consequently, our emphasis remained on refining the vibrational couplings, since they alone were sufficient to reproduce and, in the case of ^{104}Ru, to recover the experimental sub-barrier fusion yields. To check the influence of quadrupole and hexadecapole deformation of the systematic target nuclei in the fusion of $^{32}S+^{104}Ru$ reactions, were performed the coupled channel calculations with different coupling schemes. For the same system, semi-empirical coupled-channel calculations use the NRV code [4]. However, in the NRV code, either rotational or vibrational channel coupling must be considered simultaneously for both target and projectile in a reaction along with all positive Q-value neutron transfer channels. But in the CCFULL code, rotational or vibrational channel coupling can be considered independently for the fusing partners.

In the present Coupled Channel calculations, the rotational coupling has been considered for both projectile and target nuclei as shown in Fig.3. The predicted fusion excitation function for the ^{32}S + ^{104}Ru system dramatically, bringing the theory into much better agreement with the experimental fusion yields across the sub-barrier region. This finding makes clear that, for ^{104}Ru, it is not sufficient to consider only quadrupole vibrations even at the two-phonon level, but that octupole collectively also plays a decisive role in shaping the barrier distribution and enhancing sub-barrier tunnelling.

Finally, across all three reactions, we also included rotational couplings for both projectile and target nuclei, as depicted. Incorporating the rotational degrees of freedom ensures that any permanent or dynamically deformed shapes of the colliding nuclei are properly embedded in the CC framework. Because nuclear rotations mix with vibrational modes to produce a broad distribution of barrier heights, taking them into account is essential for accurately modelling fusion near the Coulomb barrier.

In sum, our coupled-channel calculations demonstrate that for ^{100,102}Ru, double-phonon quadrupole excitations of the target and a single-phonon quadrupole excitation of the projectile were sufficient to capture the observed enhancement of sub-barrier fusion. In the case of ^{104}Ru, however, it is the combined effect of both quadrupole and octupole collective modes (in addition to rotational couplings) that ultimately reproduces the experimental fusion excitation function.

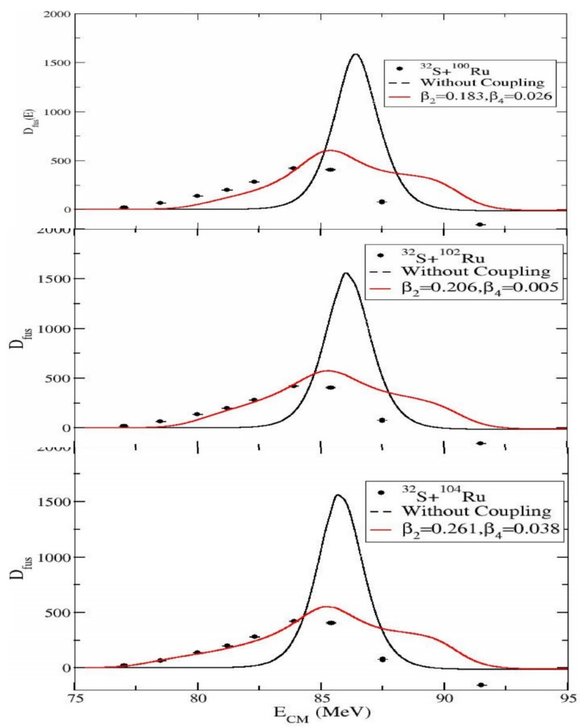

Figure 4: Barrier distributions of the ^{32}S+^{100,102,104}Ru systems

Notably, these calculations produced a good fit to the experimentally extracted barrier distributions for the ^{32}S +^{100,102,104}Ru systems, thereby reinforcing the validity of the coupling schemes employed as shown in Fig 4.

Summary

This study aims to enhance our understanding of how nuclear structure affects heavy-ion fusion reactions, with particular emphasis on the influence of collective excitations. A key focus was placed on how such excitations, especially vibrational and rotational modes, modify the fusion barrier, thereby altering the probability of nuclear fusion, particularly at sub-barrier energies.

The coupled channel calculations, including the 2+ excitation in the projectile and the 2+,3- excitation up to two-phonon states give satisfactory results for $^{32}S+^{100,102}Ru$ systems in Figure 2. NRV calculations of the fusion excitation functions and barrier distributions of the $^{32}S+^{104}Ru$ system were found to be sensitive to the hexadecapole deformation parameter along with transfer channels in Figure 3.

Figure 4 illustrates this effect by comparing barrier distributions calculated with and without the Inclusion of these vibrational couplings. The results clearly show that the inclusion of collective degrees of freedom leads to a broader and more structured barrier distribution, which better reproduces the experimentally observed fusion excitation functions. This confirms the essential role of nuclear structure effects, particularly low-lying collective excitations, in enhancing sub-barrier fusion.

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