Comparison of vibrational versus rotational couplings of ^{32}S in barrier distribution of ^{32}S + ^{90}Zr reaction

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Introduction

During heavy-ion induced fusion process, the nuclear intrinsic degrees of freedom, such as inelastic excitations, neutron transfers, and static or dynamical deformations, are coupled to the relative motion of the interacting nuclei and significantly affect the fusion dynamics [1, 2]. The coupling of intrinsic degrees of freedom of the fusing nuclei gives rise to a distribution of fusion barriers instead of a single barrier [1, 2]. These barrier distributions provide a fingerprint of nuclear structure effects of the colliding nuclei. It has also been established that a representation of fusion-barrier distribution can be extracted from quasi-elastic (QEL) scattering, measured at backward angles [3]. Recently, quadrupole and hexadecapole deformations of ^{24}Mg have been determined very precisely using quasi-elastic scattering measurements for ^{24}Mg +^{90}Zr reaction [4].

There are ambiguities for the ground state structure in the light mass region of the 2s-1d shell. Particularly, the inelastic scattering (electron, proton, neutron, α) data for ^{32}S could be explained equally well by considering it as a spherical or deformed nucleus [5]. However, the rotational-model analyses of the inelastic scattering to the low-lying collective states cannot distinguish between prolate or oblate shapes of ^{32}S; nevertheless, the majority of data slightly favor a prolate shape for this nucleus. Available measurements indicate a negative sign for the hexadecapole deformation, with a large uncertainty about its magnitude. On the other hand the ratio of $E(4^+)/E(2^+)$ for ^{32}S is close to 2 which is in favor of vibration like character. At the same time there exist some theoretical conjunctures in favor of deformed ground state of ^{32}S.

In this scenario, it is an interesting task to investigate the structure of ^{32}S through quasi-elastic (QEL) scattering. QEL excitation function and barrier distribution for ^{32}S +^{90}Zr have been reported earlier, where data could be explained quite well considering vibrational couplings of ^{32}S [6]. In that work no attempts were made to explain the data considering the rotational structure of ^{32}S. In the present work we have reanalyzed the same data in the frame work of coupled channel calculations using the code CCFULL. The quasi-elastic excitation function data were digitized from Fig.1 of Ref.[6] and 1% statistical uncertainty was assigned at each energy point. Barrier distribution was derived with a point difference formula from the QEL excitation function as shown in the Fig. 1.

Coupled Channels Calculations

Coupled channels (CC) calculations were carried out for the ^{32}S + ^{90}Zr reaction using a modified version of CCFULL code [7] for quasi-elastic scattering. Wood-Saxon type optical model potentials were used for both the real as well as imaginary parts. The optical model parameters (OMPs) for the real potential were grossly estimated from the Broglia-Winther potentials, and those were further refined so that the uncoupled calculation could reproduce the experimental data as best as possible. The OMPs for the real potential used were as follows: the depth of the potential, V_r=160.0 MeV, the radius parameter, R_r=1.1 fm, and the diffuseness parameter, a_r=0.67 fm. For the imaginary part of optical potential, the potential was set to be well confined inside the Coulomb barrier in order to simulate a compound nucleus formation. The imaginary potential parameters used in the CC calculations were as follows: the depth of the potential, V_I=30 MeV, the radius parameter, R_I=1.0 fm, and the diffuseness parameter, a_I=0.1 fm. It is to be noted here that results are not sensitive to the imaginary potential parameters as long as the potential is well confined inside the Coulomb barrier. The radius parameters for the projectile (r_{0P}) and target (r_{0T}) were used to be 1.2 and 1.06 fm, respectively, in the coupled channels Hamiltonian. The Coulomb radius was used to be 1.1

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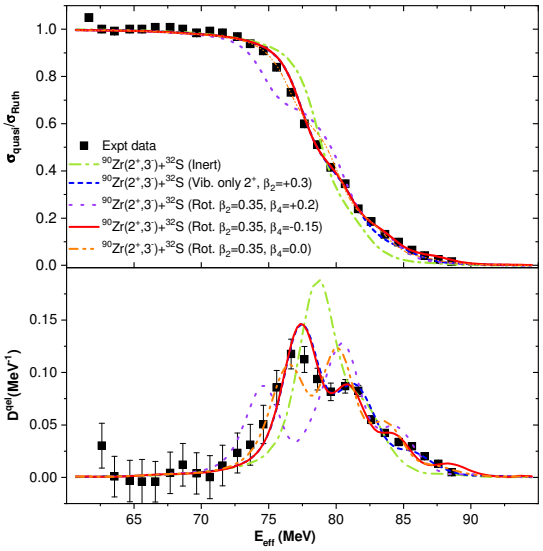

FIG. 1: Quasi-elastic excitation function (top panel) and derived barrier distribution (bottom panel) taken from Ref. [6]. Different lines represent the coupled channels calculations using the code CCFULL with vibrational couplings of ^{90}Zr (2^+ and 3^- states).

fm. For the channel couplings to the collective excited states in the ^{90}Zr nucleus, we take into account the vibrational quadrupole (2^+) state at 2.19 MeV and the octupole (3^-) state at 2.75 MeV. The β_2 and β_3 values used for the 2^+ and 3^- states of ^{90}Zr were 0.089 and 0.211, respectively [4].

Results and Discussion

It is noticed from Fig. 1 that only target coupling (vibrational of ^{90}Zr) cannot explain the data. In the earlier analysis by Yang *et al.* [6], they used CCDEF code and considered both 2^+ and 3^- states. In the present work, for the vibrational coupling of ^{32}S only 2^+ state at 2.23 MeV with β_2=0.35 was used which explained the data as good as the earlier work. The large excitation energy 3^- states (5.006 MeV) will have negligibly small effect on the results. Good agreement of data with vibrational coupling as such cannot rule out the possibility of rotational coupling as it was also observed in inelastic scattering data. CC calculations were carried out for rotational coupling of ^{32}S considering first three states; 0^+, 2^+, 4^+. Calculations were carried out with several values of hexadecapole deformation, β_4 while the β_2 was fixed at 0.35. Experimental excitation energy of the 4^+ (4.46 MeV) was used. Data shows very good sensitivity with sign as well as magnitude of β_4 as demonstrated in the Fig. 1. It is seen that rotational coupling with β_2=0.35 and β_4=-0.15 explains the data to the same as extent as reproduced by the vibrational couplings alone.

It is to be noted here that earlier also in cases of ^{28}Si +^{92}Zr and ^{28}Si +^{154}Sm reactions, barrier distribution derived from QEL excitation function were reproduced equally well by considering ^{28}Si spherical or deformed nucleus while it is well established that ^{28}Si has an oblate deformed ground state [8]. It was concluded that in those cases where excitation energy of 2^+ is large and β_2 and β_4 have opposite sign [8], rotational coupling yields similar results as of vibrational coupling. In case of ^{28}Si, β_2 and β_4 are -.407 and +.10 with excitation energy of the 2^+ state to be 1.77 MeV, satisfying the above condition. β_2 and β_4 for ^{32}S as determined in the present work are +.35 and -.15, having opposite sign, and even larger excitation energy of 2^+ state (2.23 MeV) than the ^{28}Si making it a similar candidate as the ^{28}Si.

In conclusion, similar to the inelastic scarring data, it is not possible to determine unambiguously the ground state structure of ^{32}S through quasi-elastic scattering data. Detailed calculations that led to this conclusion and a comparison with ^{24}Mg for which QEL scattering data stands out quite clearly that it has a prolate deformed ground state while it also has opposite signs of β_2 and β_4, will be presented.

References

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