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Effects of Non-Zero Spin in Sub-Barrier Fusion Involving Odd Mass Nuclei: the Case of ^{36}S+^{50}Ti,^{51}V

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A detailed comparative study of the sub-barrier fusion of the two near-by systems ^{36}S + ^{50}Ti, ^{51}V was performed at the National Laboratories of Legnaro (INFN). We aimed to investigate the possible effect of the non-zero spin of the ground state of the ^{51}V nucleus on the sub-barrier excitation function, and in particular on the shape of the barrier distribution. The comparison of the exctiation functions and barrier distributions highlighted a very similar behavior, down to the level of 20 - 30 μb. Coupled-channels calculations have been performed including the low energy excitations of both projectile and targets and the results are in very good agreement with the data. This indicates that the low-lying levels in ^{51}V can be interpreted in the weak-coupling scheme and that the extra proton in the $f_{7/2}$ shell does not have a significant influence on sub-barrier fusion.

KEYWORDS: sub-barrier fusion, non-zero spin, coupled-channels

1. Introduction

Fusion reactions at energies near and below the Coulomb barrier have been the object of several studies and measurements, showing a variety of behaviors and trends that are not yet clearly understood and are currently under investigations [1–3]. Most of the existing studies have concerned even-even projectile and target nuclei. This is mainly due to the more straightforward data analysis that such systems require. However, when non-zero spin nuclei are involved, interesting effects are expected. The ion-ion potential and consequently the height of the Coulomb barrier would be different for each magnetic substates of the non-zero ground state spin and this would affect the fusion cross section, which would be the average over the fusion cross section estimated for each magnetic substates. This effect should be highlighted at energies below the barrier.

Only few recent studies have been performed on this topics. One concerned the system ^{9}Be+^{144}Sm [4], where the ground state spin of ^{9}Be is $3/2^{+}$. The entrance potentials estimated separately for the two magnetic substates showed a large difference and the Coupled Channels (CC) calculations were able to reproduce the data only by explicitly considering the two magnetic substates (see Fig. 3 and Fig. 4 of [4]).

In this framework, at the National Laboratories of Legnaro (LNL) a detailed comparative study of the two systems ^{36}S + ^{50}Ti, ^{51}V was performed, where no previous data were available. The aim of the measurement was to identify differences in the fusion excitation function of the two near-by systems, that may possibly be attributed to the non-zero spin of the ^{51}V ground state. The nucleus ^{50}Ti, is spherical and rather stiff because of its closed neutron shell. On the other hand, the ^{51}V nucleus has a rather large non-zero spin ($7/2^-$) in its ground state and it is also essentially spherical because of its very small quadrupole moment [5]. Thus, the possible effects of the finite spin of the ground state are isolated, without the onset of deformation, and the two systems can be readily compared to each other before performing detailed CC calculations. A different ion-ion potential and consequently a different barrier, is expected for each magnetic substates. By comparing the two systems, we investigated if the shape of the barrier distribution keeps a trace of those different barriers.

2. Experimental procedure

The ^{36}S beam was provided by the XTU-Tandem accelerator at an average current of 10 pnA. The targets were 50μg/cm^2 in thickness for both ^{51}V and ^{50}TiO$_2$, the later one enriched to 90.3% in mass 50. Since the Coulomb barriers differ of about 2 MeV, the measurements have been performed in the two energy ranges: E_{Lab} = 73 - 100 and 76 - 100 MeV, for ^{50}Ti and ^{51}V, respectively. The carbon backing and the vanadium and titanium layers introduced an average beam energy loss of around 750 - 850 keV, which was taken into account in the analysis.

The experiment was performed by employing the set-up PISOLO based on an electrostatic beam deflector, which is currently in use at LNL for studies of fusion dynamics above and below the Coulomb barrier [6]. The evaporation residues (ER) were identified downstream of the deflector by a double Time - of - Flight (ToF) - ΔE - Energy telescope composed of two micro - channel plate (MCP) time detectors followed by the fast ionization chamber (Fast IC) [7] and by the silicon detector placed in the same gas (CH_4) volume of the Fast IC.

Four silicon detectors placed in the reaction chamber symmetrically around the beam direction have been used to monitor the beam and to normalize the fusion yields to the Rutherford scattering cross section. Two ER angular distributions were measured at the energies of 80 and 90 MeV in the range from -6° to +9°. The total fusion cross section was derived by integrating the two angular distributions, and by simple interpolations or extrapolations for all the other energies where ER measurements were performed only at 2°.

3. Results

3.1 Excitation function and barrier distributions

The cross sections vary by five orders of magnitude in the measured energy range, reaching minimum values of 20 and 30 μb for the ^{36}S+^{50}Ti and ^{36}S+^{51}V systems, respectively. The excitation functions of the two systems are compared in Fig. 1 (left panel), where the cross sections are shown in a reduced energy scale taking into account that the two reactions have different Coulomb barriers. The reported error bars correspond only to the statistical uncertainty, that is, 1 - 2% at high energies and 20 - 30% at sub-barrier energies. The comparison highlights a very similar behaviour of the two systems. Thus, in order to put in evidence possible small differences, a comparison of the barrier distributions was performed.

Extracting barrier distribution from the experimental data has proved to be an excellent method to evidence structure effects in the fusion processes, especially at energies around and below the

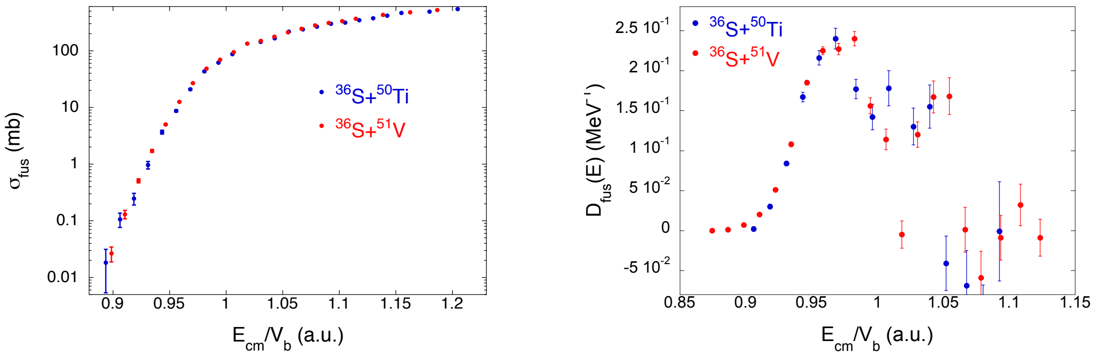

Fig. 1. Comparison of the excitation functions (on the left) and barrier distributions (on the right) for the two fusion reactions. The energy scale is normalized to the height of the two Coulomb barriers.

Coulomb barrier. The barrier distributions $D_{fus}(E)$ of the two systems were obtained using the three-point difference formula [8], with energy intervals of ∼1.5 MeV in order to make visible the structures at energies above and below the barrier. The two barrier distributions are compared by using a reduced energy scale in Fig. 1 (right panel). The shapes of the two distributions are extremely similar.

It appears that to correctly understand the experimental results, a theoretical interpretation is necessary. In this perspective a coupled-channels analysis was performed.

3.1.1 Coupled-Channels calculations

The experimental data of the two fusion reactions have been compared to the theoretical calculations based on the coupled-channels model. For both systems the CC calculations were performed by means of the CCFULL code [14]. The ion-ion potential was of Woods-Saxon shape for both systems ($V_0 = 85.3$ MeV, $r_0 =$ 1.16 fm and $a = 0.66$ fm for $^{36}S + ^{50}Ti$, and $V_0 = 85.3$ MeV, $r_0 = 1.17$ fm and

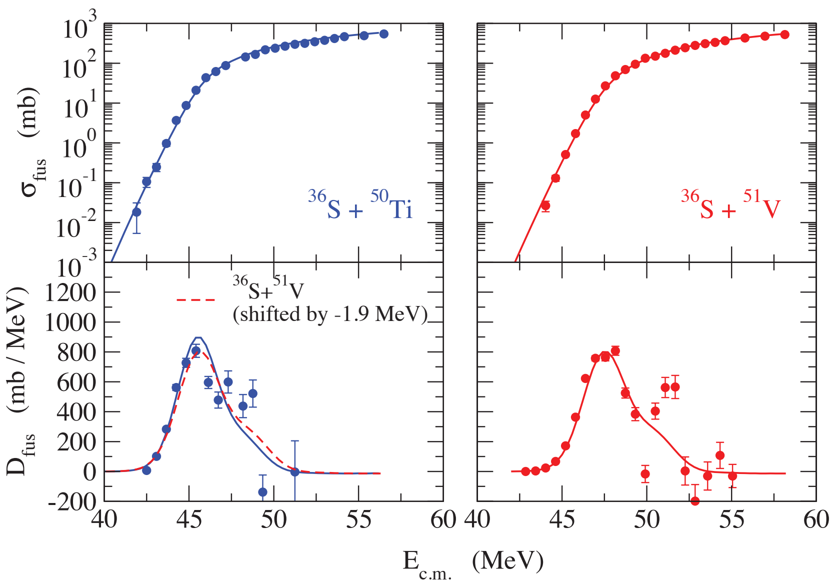

Fig. 2. Excitation functions (up) and fusion barrier distributions (bottom) of ^{36}S+^{50}Ti (on the left) and ^{36}S+^{51}V (on the right), compared with the CC calculations described in the text.

$a = 0.66$ fm for ^{36}S + ^{51}V). For the ^{36}S+^{50}Ti, the CC calculations included the collective vibrational excitations of both the target and the projectile nuclei. In particular, the one-phonon excitation of both the lowest quadrupole vibrational state 2^+ at 1.554 MeV of ^{50}Ti and the first 2^+ state at 3.29 MeV in ^{36}S, were considered.

In the case of the ^{36}S+^{51}V, the four magnetic substates m = 1/2, 3/2, 5/2 and 7/2 of the $7/2^-$ ground state of ^{51}V produce different Coulomb barriers that have to be treated individually in the CC calculations. For this purpose, a modified version of CCFULL was employed, which is able to include the 2^+ excitation in ^{36}S as well as the couplings to the $5/2^-$, $3/2^-$, $11/2^-$, $9/2^-$, and $3/2^-$ states in ^{51}V. In particular, eight transitions among those states in ^{51}V are known experimentally and have been considered in the calculations (for more details see [10, 11]).

Despite that the calculated barrier distributions are slightly inconsistent with the structure observed at energies above the main peak for both systems, as shown in Fig. 2 (bottom panels), the CC calculations reproduce very well the two similar excitation functions (see Fig. 2 upper panels). This indicates that the extra proton in the $f_{7/2}$ shell does not significantly influence sub-barrier fusion. Thus the weak-coupling approximation, where the low-energy levels of ^{51}V result from the scheme ^{51}V(I) = ^{50}Ti $(2^+) \otimes (1\ f_{7/2})$ [12], works well in the present case.

In Fig. 2 (bottom left panel), it is possibile to observe a small difference between the two CC barrier distributions around 49-50 MeV. However, good data in that energy region would not be easily measured. Even by extracting the barrier distribution from quasi-elastic scattering [13, 14] would hardly allow to confirm or disprove the small difference above the barrier predicted by CC calculations.

4. Summary

The fusion cross sections of the two systems ^{36}S+^{50}Ti,^{51}V have been measured from above the barrier down to 20 - 30 μb. The comparison of the two excitation functions and barrier distributions showed a very similar behaviour. A CC analysis was performed in order to highlight differences between the two systems attributable to the non-zero spin ground state of ^{51}V. The calculations included the low energy excitations of the ^{36}S beam and of the ^{50}Ti, ^{51}V targets. In particular, the CCFULL code has been modified so to enable the treatment of the odd spin states. The theoretical predictions are in very good agreement with the experimental excitation functions of both systems at energies above and below the Coulomb barrier. This may be explained in the weak-coupling scheme where the relatively stiff ^{50}Ti (close to the double magic ^{48}Ca) is not significantly influenced by the additional proton to form ^{51}V.

References

[1] B.B. Back, H. Esbensen, C.L. Jiang, and K.E. Rehm, Rev. Mod. Phys. **86**, 317 (2014)
[2] Kouichi Hagino and Noboru Takigawa, Prog. Theor. Phys. **128**, 1061 (2012)
[3] G. Montagnoli and A. M. Stefanini EPJA **53**, 169 (2017)
[4] H. Esbensen, Phys. Rev. C **81**, (2010)
[5] P. Unkel, P. Buch, J. Dembczynski, W. Ertmer and U. Johann Z., Phys. D **11**, 259 (1989)
[6] G. Montagnoli et al., Phys. Rev. C **97**, (2018)
[7] G. Colucci et al, Acta Phys. B **50**, 573 (2019)
[8] M. Dasgupta, D. J. Hinde, N. Rowley and A. M. Stefanini, Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998)
[9] K. Hagino, N. Rowley and A.T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999)
[10] G. Colucci, PhD Thesis, (2018)
[11] G. Colucci et al., Eur. Phys. J. A **55**, 111 (2019)
[12] F. Ballester, E. Casal, J.B.A. England and J.B.A. England, Nucl. Phys. A **513**, (1990)
[13] H. Timmers et al., Nucl. Phys. A **584**, 190 (1995)
[14] K. Hagino and N. Rowley, Phys. Rev. C **69**, 054610 (2004)