STUDY OF SUB-BARRIER FUSION OF ^{36}S+^{50}Ti,^{51}V SYSTEMS*

G. Colucci[a], G. Montagnoli[a], A.M. Stefanini[b], K. Hagino[c,d,e]
A. Caciolli[a], P. Čolović[f], L. Corradi[b], E. Fioretto[b]
F. Galtarossa[b], A. Goasduff[a], J. Gręebosz[g], M. Mazzocco[a]
D. Montanari[h], C. Parascandolo[i], F. Scarlassara[a]
M. Siciliano[j], E. Strano[a], S. Szilner[f], N. Vukman[f]

[a]Department of Physics and Astronomy, Padova University and INFN-Padova 35131 Padova, Italy
[b]INFN, Legnaro National Laboratories, 35020 Legnaro (Padova), Italy
[c]Department of Physics, Tohoku University, Sendai 980-8578, Japan
[d]Research Center for Electron Photon Science, Tohoku University 1-2-1 Mikamine, Sendai 982-0826, Japan
[e]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[f]Ruđer Bošković Institute, 10002 Zagreb, Croatia
[g]Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland
[h]IPHC, CNRS-IN2P3, Université de Strasbourg 67037 Strasbourg Cedex 2, France
[i]Department of Physics, Napoli University and INFN-Napoli, 80126 Napoli, Italy
[j]IRFU/DPhN, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

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A detailed comparative study of the sub-barrier fusion of the two nearby systems ^{36}S+^{50}Ti,^{51}V was performed at the National Laboratories of Legnaro (INFN). The experiment aimed to evidence possible effects of the non-zero spin of the ground state of the ^{51}V nucleus on the sub-barrier excitation function and on the shape of the barrier distribution. The comparison of both excitation functions and barrier distributions showed 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 the two 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.

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1. Introduction

Fusion reactions near and below the Coulomb barrier have proved to be essential in the study of the close connection between the fusion dynamics and the low-lying collective structure of the colliding nuclei [1–3]. Most of the existing studies have concerned even–even projectile and target nuclei, mainly because of the simpler theoretical treatment that such systems require. However, interesting effects are expected when odd nuclei are involved. The non-zero ground-state spin implies that the ion–ion potential and, consequently, the height of the Coulomb barrier is different for each magnetic substate. This would affect the fusion cross section which is the average over those substates. This effect should be particularly evident below the barrier, since the shape of the barrier distribution should keep memory of the various barriers associated with the m-substates.

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 measurement aimed to identify differences in the fusion excitation function of the two cases that may possibly be attributed to the non-zero spin of the ^{51}V ground state.

The projectile ^{36}S has an $N = 20$ closed shell. Its structure is rigid and well-known, so that its effect on fusion cross sections can be safely calculated. The ^{50}Ti nucleus is spherical and rather stiff because of its closed neutron shell. On the other hand, the ^{51}V has a rather large non-zero spin $(7/2^-)$ in its ground state and it is also essentially spherical because its measured quadrupole moment is very small [4]. Thus, since the nuclei can be treated as spherical, possible effects of the finite spin of the ground state are isolated, without the onset of deformation. Furthermore, coupling to the one proton pick-up channel in ^{36}S+^{51}V is not expected to have a significant effect on sub-barrier fusion. The above-mentioned features allow to directly compare the two cases before performing detailed CC calculations. A different ion–ion potential and, consequently, a different barrier, is expected for each of the four 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 XTU-Tandem accelerator of LNL provided the ^{36}S beam at an average current of 10 pnA and in the energy range of 73–100 MeV. The targets were 50 μg/cm^2 in thickness for both ^{51}V and ^{50}TiO$_2$, the later one enriched to 90.3% in mass 50. 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, which is currently in use at LNL for studies of fusion dynamics above and below the Coulomb barrier [5]. The set-up is based on an electrostatic beam deflector which allows to measure the fusion cross sections by direct detection of the evaporation residues (ER) at small angles with respect to the beam. The ER were identified downstream of the deflector by a double Time-of-Flight (ToF) ΔE–E telescope composed of two micro-channel plate (MCP) time detectors followed by the fast ionization chamber (Fast IC) [6] and by the silicon detector placed in the same gas (CH_4) volume. Four collimated silicon detectors were placed symmetrically around the beam direction in order to check the beam position and focusing, and to normalize the fusion yields to the Rutherford scattering cross section.

Figure 1 (top panels) shows the times of flight as a function of the residual energy for the ^{36}S+^{50}Ti (left panel) and ^{36}S+^{51}V (right panels) systems. The ER are well-separated from the degraded beam at energies both above (top panels) and below (bottom panels) the Coulomb barrier. The fusion of ^{36}S with the carbon and the oxygen of the target is also well-distinguished, with the exception of the case of ^{36}S+^{51}V at 100 MeV (Fig. 1, top right panel) because of the metallic target and the shorter acquisition time.

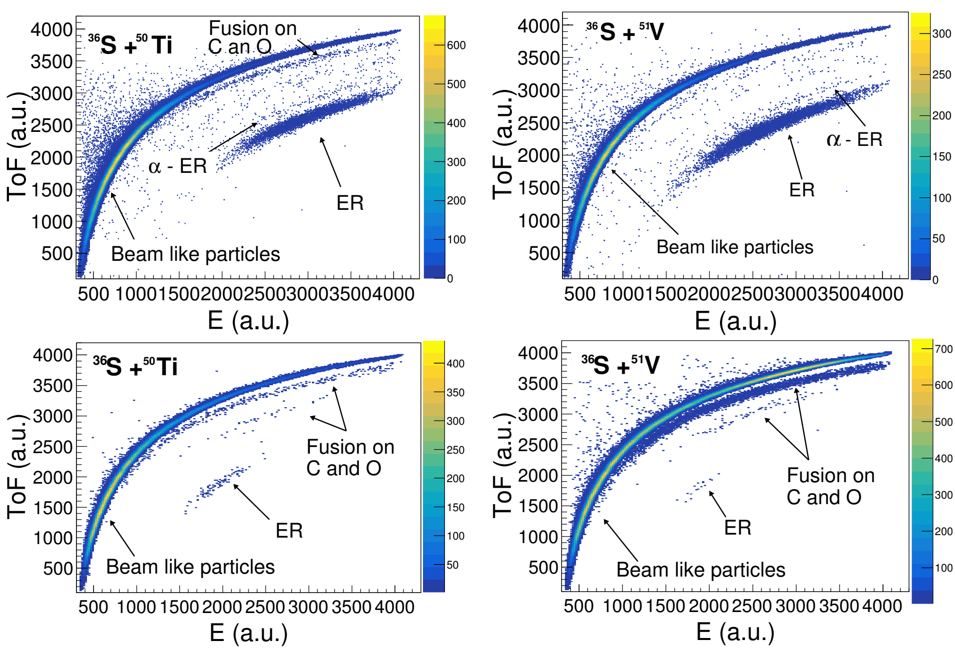

Fig. 1. Time of flight TOF_3 *versus* residual energy of the ^{36}S+^{50}Ti (on the left) and ^{36}S+^{51}V (on the right) systems. The measurements were performed at the incident energies of 100 MeV (at the top) and 78 MeV (at the bottom).

Following fusion, a fraction of the compound nuclei evaporates alpha particles resulting in ER lighter than the ones formed by nucleon evaporation. This fraction is well-separated from the majority of ER and obviously was included in the total yield of the ER. The alpha emission decreases with decreasing energy and becomes negligible at energies below the Coulomb barrier (see Fig. 1, bottom panels).

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 functions and barrier distributions

The cross sections vary by five orders of magnitude and were measured down to 20 and 30 μb for ^{36}S+^{50}Ti and ^{36}S+^{51}V, respectively. In Fig. 2 (left panel), the excitation functions of the two systems are compared. The reported errors are only statistical uncertainties, that is, 1–2% above and near the barrier, increasing to 20–30% at sub-barrier energies. The comparison shows a very similar behaviour of the two systems. In order to observe possible small differences, a comparison of the experimental barrier distributions was therefore performed.

The barrier distributions were obtained using the three-point difference formula [7], by employing energy intervals of $\sim$ 1.5 MeV. The comparison of the two barrier distributions is shown in Fig. 2 (right panel). Also in this case, the two shapes are similar and show a well-defined peak at lower energies.

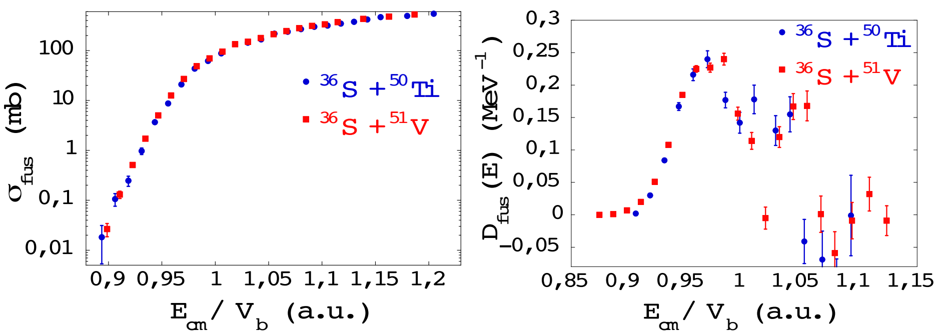

Fig. 2. Comparison of the excitation functions (on the left) and barrier distributions (on the right) for the two fusion reactions. The energy scale is normalized to the height of the two Coulomb barriers.

Since no differences are observed between the two systems by the only comparison of the experimental data, a theoretical interpretation is necessary.

3.2. Coupled-channels calculations

The theoretical calculations are based on the coupled-channels model and performed by means of the CCFULL code [8]. In the case of the ^{36}S+^{50}Ti system, the CC calculations included the one-phonon excitation of both the lowest quadrupole and octupole vibration states (at 1.554 MeV and 4.410 MeV, respectively) of ^{50}Ti and the first 2^+ state at 3.29 MeV in ^{36}S. In the case of ^{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. A modified version of CCFULL was therefore employed in order to include the 2^+ excitation in ^{36}S as well as the couplings to the $5/2^-$, $3/2^-$, $11/2^-$, $9/2^-$, and $3/2^-$ excited states in ^{51}V (for more details, see [9]).

Despite the CC calculations are slightly inconsistent with the barrier distribution structure observed at energies above the main peak, as shown in Fig. 3 (bottom panels), they reproduce very well the excitation functions of both systems (see Fig. 3 upper panels). This can be interpreted under the weak-coupling approximation, where the low-energy levels of ^{51}V result from the scheme $^{51}\mathrm{V}(I) = ^{50}\mathrm{Ti}(2^+) \otimes p(1f_{7/2})$ [10] and the extra proton in the $f_{7/2}$ shell does not significantly influence sub-barrier fusion.

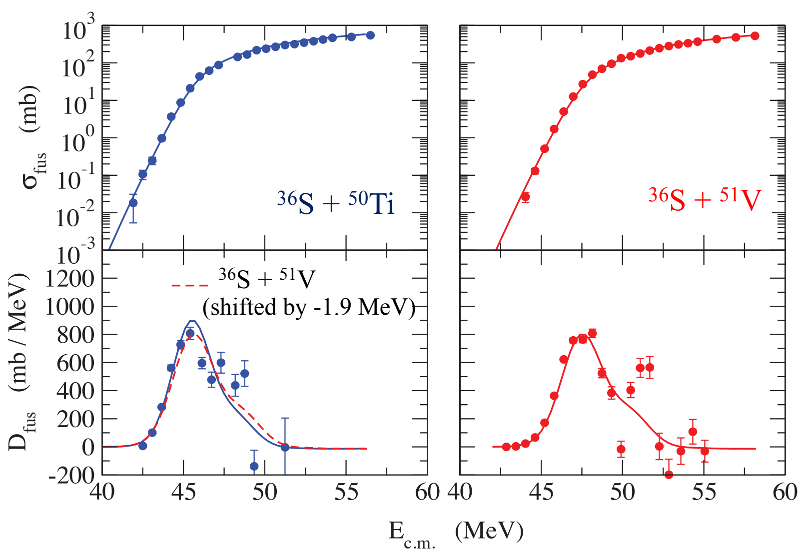

Fig. 3. Excitation functions (top) and fusion barrier distributions (bottom) of ^{36}S+^{50}Ti (on the left) and ^{36}S+^{51}V (on the right), compared with the CC calculations.

4. Summary

The fusion cross sections of the two systems ^{36}S+^{50}Ti,^{51}V show a very similar behaviour down to 20–30 μb. The two extracted barrier distributions have a similar shape. A CC analysis was performed in order to highlight differences between the two cases attributable to the non-zero spin ground state of ^{51}V. The CC analysis included the low-energy excitations of the ^{36}S and ^{50}Ti,^{51}V nuclei and the results are in very good agreement with the experimental excitation functions of both systems. This may be explained in the weak-coupling scheme where the relatively stiff ^{50}Ti (close to the doubly magic ^{48}Ca) is not significantly influenced by the additional proton to form ^{51}V.

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