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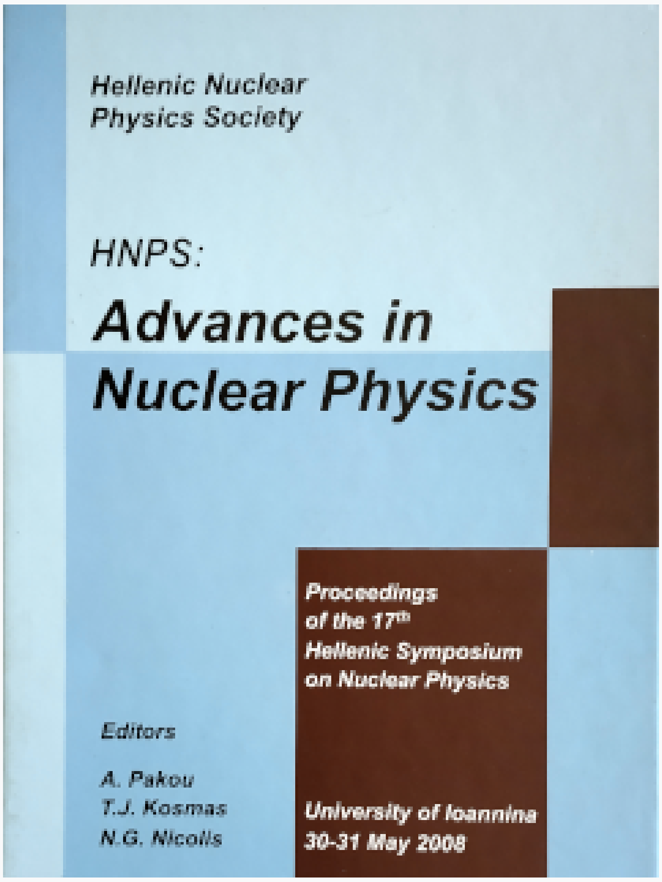

Strong transfer channels for reactions with weakly bound projectiles at near and sub-barrier energies and implications to fusion

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Strong transfer channels for reactions with weakly bound projectiles at near and sub-barrier energies and implications to fusion

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Abstract

Angular distributions of exclusive α-γ and proton-γ measurements of the systems ^{6,7}Li+^{28}Si are performed at near-barrier energies. Transfer channels are identified and quantified at 4 energies namely 8, 9, 13 and 15 MeV for ^{6}Li and at one energy of 13 MeV for ^{7}Li. The energy evolution of total transfer to total reaction cross sections is formed with the aid of CDCC calculation from sub to near-barrier energies. Additionally total reaction cross sections are measured for both systems at sub- and near-barrier energies from 6 to 15 MeV via the γ - spectroscopy technique (measurements in singles). Finally fusion cross sections are estimated in the above angular range. It is found that for weakly bound nuclei at sub- and near barrier energies, the contribution of transfer is strong with serious consequences on fusion. Fusion is found to obey simple BPM theoretical interpretations while it is found stronger for ^{6}Li than for ^{7}Li. Main transfer channels are found to be 1n- and 2n-transfer for the ^{6}Li+^{28}Si and ^{7}Li+^{28}Si systems correspondingly.

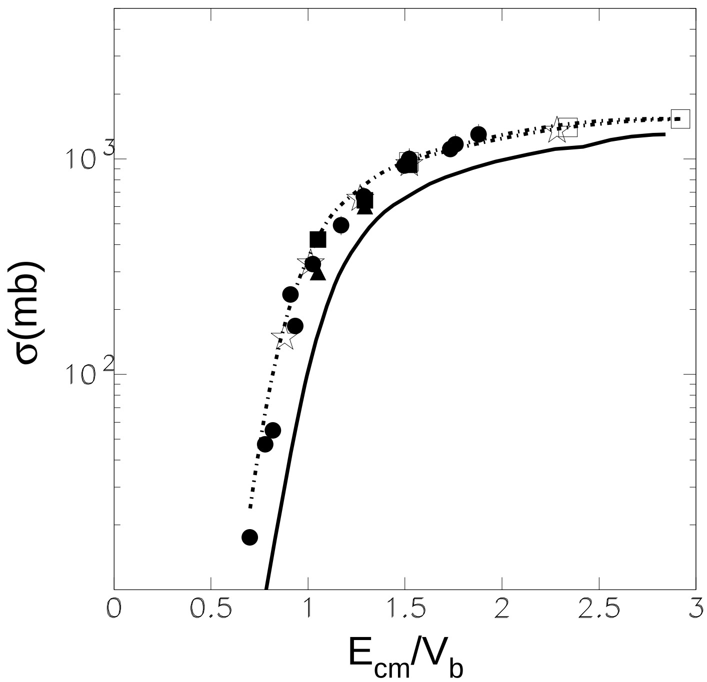

Fig. 1. Total reaction cross sections for ^{6}Li+^{28}Si are compared well with CDCC calculations,designated with the dotted-dashed line. These results are also compared with BPM calculations according to Wong [1]and show a large enhancement.

The study of reaction mechanisms at near barrier energies is a very popular playground, with recent emphasis on research concerning weakly bound nuclei. Approaching the vicinity of the Coulomb barrier, couplings between various channels play a major role in describing fusion. The subject of fusion, while fairly well understood for stable nuclei, has been revisited with the advent of radioactive nuclear beam facilities [2,3]. Studies are now also concentrated on weakly-bound radioactive or stable projectiles with the expectation that the weak nature of these projectiles will greatly affect fusion. Unfortunately, several of these studies take for granted that at sub- and near- barrier energies total reaction cross sections are equal with fusion cross sections. Also other studies for systems which lead to channels obtained both via compound and direct processes are not able to disentangle between them. This has as a result the misinterpretation of the data into a context of enhancements or reductions of the fusion cross sections which really has to be attributed to the total reaction cross sections. To enlight the situation, we present in this work, exclusive measurements on α and p-production for the systems

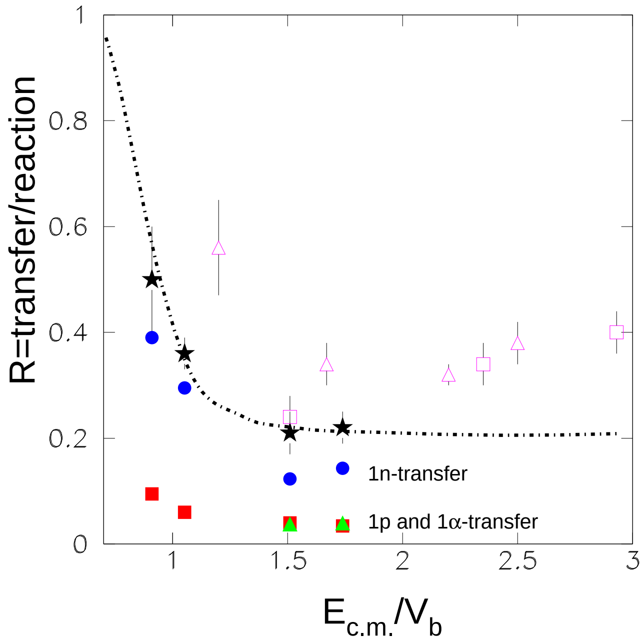

Fig. 2. Ratios of Direct to Total Reaction Cross sections for ^{6}Li+^{28}Si-present measurements designated with the stars-previous measurements [4]-designated with the open squares and previous measurements for ^{9}Be+^{28}Si [4] designated with the open triangles. The decomposition of the present results for each transfer channels is also shown.

^{6,7}Li+^{28}Si at near barrier energies. Particles are tagged by gamma rays deexciting the exit channel nuclei. For the same system exclusive measurements on breakup have already been reported [5], supporting very low cross sections. These system are therefore the most appropriate for probing coupled channel effects connected with transfer at near barrier energies. Thus, the aim of this work is at first to identify and quantify the various transfer channels, estimating simultaneously the direct to total reaction cross section. These ratios will be extrapolated to sub-barrier and well above the barrier energies with the aid of CDCC calculations. A second goal of this study is the determination of total reaction cross sections, with final aim, the estimation of fusion at sub- and near- barrier energies. Total reaction cross sections will be performed at sub-barrier energies for the first time while the measurements will be extended to near barrier energies , where previous measurements exist with various methods. The latter measurements will be used for a systematic description of reaction cross sections but also for testing our method.

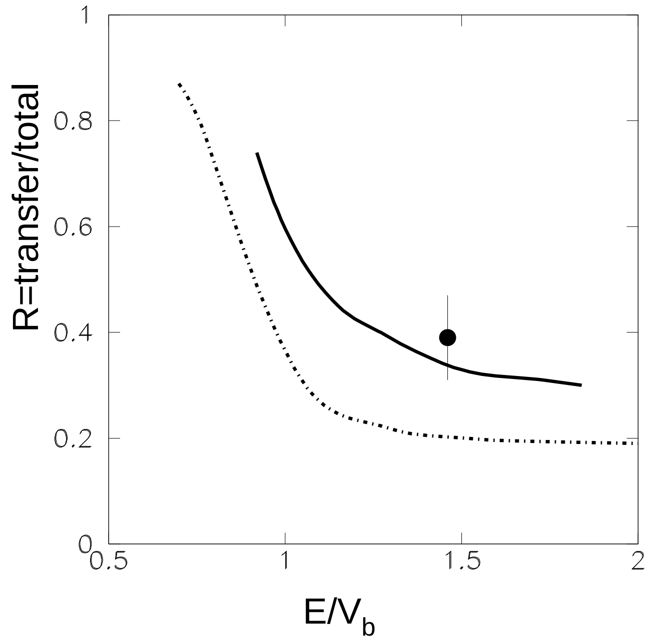

Fig. 3. Ratios of Direct to Total Reaction Cross sections for ^{7}Li+^{28}Si (the solid line represents CDCC+BMP calculations and the solid circle one datum at 13 MeV) are compared with theoretical estimations for ^{6}Li+^{28}Si, dotted-dashed line, as appears in Figure 2.

Beams of ^{6,7}Li$^{3+,2+}$ were delivered by the TN11/25 HVEC 5.5 MV Tandem accelerator of the National Research Center of Greece-DEMOKRITOS at several bombarding energies from 6 to 16 MeV. Beam currents were of the order of 30 nA. The beam impinged on a 400 μg/cm^2 thick self supporting natural silicon target in a target frame fixed parallel to the face of the detector. Two types of measurements were performed: angular distributions in a particle-γ coincidence mode to deduce transfer and singles measurements to deduce total reaction cross sections. Angular distributions were measured with two telescopes (ΔE=10μm, E=2000μm) set 12.7 cm from the target, rotated in a D-shape chamber, in the angular range θ_{lab}=20^0 to 70^0. Gamma rays were observed by a 50% efficient Ge detector, fixed at 90^0 with respect to the beam direction, 3.1 cm from the target. A coincidence requirement between particles and gammas allowed the clear identification of each channel and subsequently via evaporation calculations the determination of the transfer contribution for each channel. These calculations were tested in this work against reaction channels which were formed purely via compound processes, while were also validated before [6,7] via inclusive angular distribution measurements at more

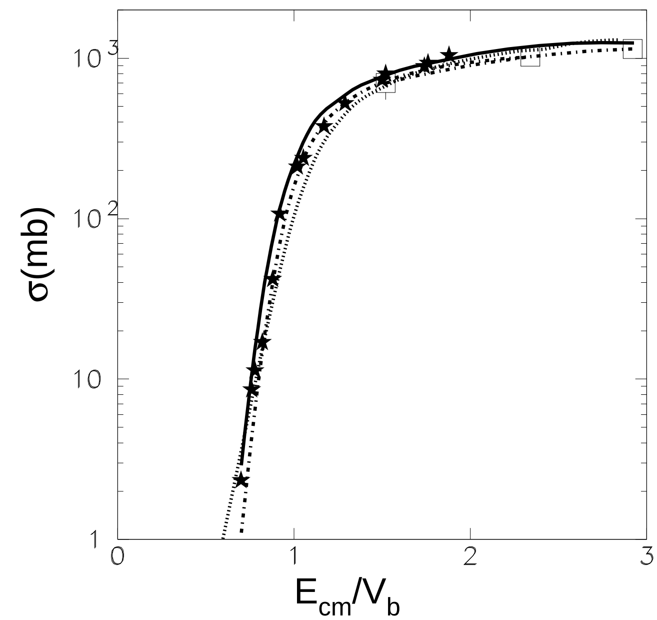

Fig. 4. Fusion Cross Sections for ^{6}Li+^{28}Si, estimated in this work are designated with the stars and are compared with previous measurements [4] and various BPM calculstions.

backward angles. Singles gamma measurements were performed in the same setup, with the Ge detector at 90^0, using the elastically scattered lithium observed in the telescopes for normalisation purposes. The efficiency of the Ge detector was determined via a ^{152}Eu source of known activity. Summing effects were estimated by placing a ^{152}Eu and ^{22}Na source at various distances from the detector.

For each exit channel, in both singles and coincidence measurements, cross sections were obtained by summing up gammas from all ground state transitions. In the latter case, gammas were tagged with alpha and/or proton particles. These ground state transitions include gammas de-exciting the first and the higher excited states up to 3 and 6 MeV, depending on channel and beam energy. Losses due to direct feeding of the ground state are estimated to be of the order of 2% according to compound calculations.

Total reaction cross sections were obtained by summing the cross sections of all the observed exit channels and the missing channels, the latter estimated via CASCADE calculations [8]. Missing channels do not exceed 20% to 30% of the measured cross section from lower to higher energies. The results of total reaction cross sections for ^{6}Li are shown in Figure 1 together with predictions

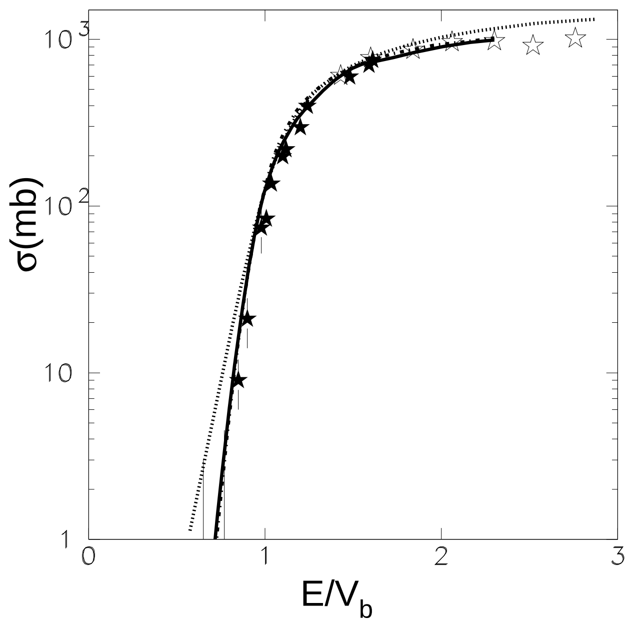

Fig. 5. Fusion Cross Sections for ^{7}Li+^{28}Si, estimated in this work are designated with the stars and are compared with previous measurements [9] and various BPM calculstions.

generated by Continuum-Discretized Coupled-Channels calculations (CDCC) and are found to be in good agreement. Details of the calculation can be found in [11,12]. Finally in the same Figure, we present BPM calculations according to Wong [1]. It is obvious that the total reaction cross section is greatly enhanced against this prediction by almost a factor of ∼80 % for E/V$_b$=0.8 to ∼20% beyond E/V$_b$=2. To identify and quantify this enhancement which exist also for ^{7}Li, we use the angular distribution measurements. From these measurements and following the technique described in [10,6] we disentagle the direct, which in the present case equals transfer, from the compound contribution. Ratios of total transfer to total reaction are presented in Figure 2, for ^{6}Li at 4 energies. It is obvious the increasing energy trend towards lower energies. The same trend is followed by ^{9}Be+^{28}Si measured previously [4], but where the direct part is stronger as it was expected for such a weakly bound nucleus as ^{9}Be. Previous results are also shown for the same system [4] which show very good compatibility inn the overlaping energy region. At higher energies the results are much higher than our theoretical predictions. This deviation from our results, may be attributed to contaminated channels (these measurements are inclusive) or and to the inclusion of breakup which at higher energies may become substantial. Results for ^{7}Li are presentd in Figure 3, one experimental datum at 13 MeV and theoretical predictions according to

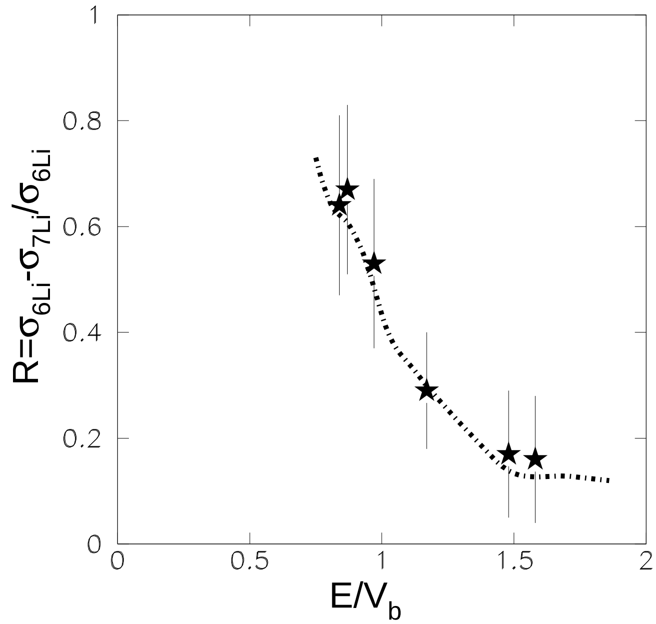

Fig. 6. Comparison of fusion cross sections for the systems ^{6}Li+^{28}Si and ^{7}Li+^{28}Si

our CDCC calcualtions. In the same Figure the theoretical prediction for ^{6}Li is also shown. It is apparent that the contribution of transfer to total reaction cross section for ^{7}Li is much stronger than for ^{6}Li. According to our angular distribution measurements transfer channels contributing in the ^{6}Li+^{28}Si reaction are primarily 1n-transfer and in a lesser extend 1p-transfer and 1α-transfer while for the ^{7}Li+^{28}Si reaction is 2n-transfer and in a lesser extend 1p-transfer. Taking into account the above ratios and the total reaction cross section measurements, we can estimate fusion cross sections which are presented in figures 4 and 5 together with various BPM calculations. The results are well represented by such theoretical approaches. Finally in Figure 6 we compare the cross sections for both systems and we conclude that fusion for ^{7}Li is weaker than that for ^{6}Li ecpecially for sub-barrier energies.

Summarising, we have obtained both experimentally and theoretically total reaction cross sections for ^{6}Li+^{28}Si at sub- and near barrier energies, namely at E_{lab}= 6 to 16 MeV. It was shown that these results are greatly enhanced against BPM calculations. We have quantify this enhancement which is proved to be due to a strong 1n-transfer and 2n-transfer channels for ^{6}li and ^{7}Li correspondingly. The energy evolution of the enhancement, that is the ratio of direct to total reaction cross section was also obtained via exclusive particle -γ angular distribution measurements and the aid of CDCC calculations. Fusion cross sections were estimated during this procedure and were found to be very well described by BPM calculations especially when effective potentials are validated via elastic scattering measurements.

The main conclusion of this work is that, for weakly bound projectiles where compound and direct mechanisms lead to the same residual nuclei, fusion is not equal to total reaction cross section at sub and near-barrier energies. The reaction channels responsible for this "disagreement" are strong transfer channels which persist down to sub-barrier energies.

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