Fusion of the ^{6}Li+^{120}Sn and ^{7}Li+^{119}Sn and the role of neutron transfer and breakup processes

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Fusion of the ^{6}Li+^{120}Sn and ^{7}Li+^{119}Sn and the role of neutron transfer and breakup processes

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Abstract. Excitation functions have been measured for the fusion of the weakly bound nuclei ^{6}Li and ^7Li respectively with ^{120}Sn and ^{119}Sn at energies around the Coulomb barrier by using an activation technique. With such a study we aim to investigate the role played by direct processes as neutron transfer and breakup on fusion. At energies above the barrier, the complete fusion cross section are lower than those predicted by fusion models. This suppression is independent of beam energy and is in agreement with the values reported in literature for heavier systems. At energies below the barrier, no significant enhancement due to the positive Q-value for one and two neutron transfer for the ^{7}Li+^{119}Sn system is observed as compared with the ^{6}Li+^{120}Sn.

1. Introduction

The fusion process at energies close to the Coulomb barrier has been object of extensive experimental and theoretical studies in the last decades. The sensitivity of the fusion process to internal degree of freedom of the colliding nuclei, such as rotation and vibration, has been well recognized [1]. At energies below the Coulomb barrier, the coupling of the relative motion to these degrees of freedom leads to an enhancement of the fusion cross-section, relative to the one expected from the one-dimension barrier penetration model (1D-BPM). It has been shown [2, 3] that the effect of channel coupling is to replace the single fusion barrier by a distribution of barriers of different heights, some of which are lower than the height of the single barrier. Moreover, the importance of neutron transfer in increasing the sub-barrier fusion probabilities was also established, but quantitative understanding of the coupling strengths remained elusive due to the need to rely on complex theoretical calculations. The importance of neutron transfer on nuclear fusion originates from the fact that neutrons are insensitive to the Coulomb field and their transfer might start at larger separations than other particles. Therefore, it is possible that a flow of neutrons between target and projectile has already started [4], before fusion takes place, influencing the subsequent fusion reaction which occurs inside the barrier. Thus, it is expected that, if a system exhibits neutron-transfer reactions with positive Q-values, the sub-barrier fusion cross-section will increase [4]. The idea that neutron transfer process would lead to an enhancement of the fusion cross-section is supported by a semi-classical model [5], according to which an intermediate neutron transfer with positive Q-value may lead to a gain in relative kinetic energy of the colliding nuclei and, thus, to an enhancement of the barrier penetrability and therefore of the fusion cross-section. Most of the experiments performed to study the effects of neutron transfer on the fusion cross-section compared systems with positive Q-value for neutron transfer with their isotopic counterparts with no positive Q-value. By comparing similar systems one could expect that it is easier to isolate the effects of transfer couplings with respect to inelastic channels (which are always present). Experimentally, the study of ^{28}Si+^{94}Zr [6] ^{32}S+^{96}Zr,^{100}Mo,^{110}Pd [7, 8, 9] and ^{40}Ca+^{48}Ca,^{96}Zr,^{124,132}Sn [10, 11, 12, 13, 14] fusion reactions has shown an enhancement in the sub-barrier fusion cross section of these systems with respect to their reference systems. This enhancement has been related to the presence of positive Q-value neutron transfer channels.

In recent works concerning the study of fusion reaction of Sn+Ni and Te+Ni [15], ^{16,17}O+^{76,74}Ge [16] and ^{60}Ni+^{100}Mo [17], similar sub barrier fusion cross sections have been measured even if the studied systems present very different Q-values for multi-neutron transfer. A possible solution of this controversy has been proposed by studying these fusion reactions using the quantum diffusion approach [18]. According to this theory, in systems like the ^{40}Ca+^{96}Zr, the change of the magnitude of the fusion cross section, occurs since the neutron transfer produce a change in the deformation of the interacting nuclei, before the fusion. In particular, the variation of the nuclei′s shapes generates a lowering of the Coulomb barrier and consequently an enhancement of the fusion cross section. Instead, in systems like as example the ^{60}Ni+^{100}Mo, the neutron transfer do not modify significantly the deformation of the colliding nuclei and so it weakly influences the fusion cross section. With these calculation the authors were able to well reproduce existing the data. New measurements, particularly on the simple cases of one-neutron ($1n$) and two-neutron ($2n$) transfer with positive Q-values are needed for improving the understanding of this issue.

For further investigate the possible relation between the presence of positive neutron transfer Q-value and the sub-barrier enhancement of fusion cross-section, we measured the fusion cross section of ^{6}Li+^{120}Sn and ^{7}Li+^{119}Sn. These two system are characterized by very similar entrance channels, their fusion leads to same compound nucleus and present different Q-values for $1n$ and $2n$ transfers. They seems well suitable for investigate on the possible role of the neutron transfer on the fusion process, at energies below the Coulomb barrier.

Moreover, our projectiles are weakly bound nuclei, characterised by low-breakup threshold, cluster structure and diffuse matter distribution. Thus, by studying these reactions, at energies above the Coulomb barrier, it is also possible to investigate the role played by breakup on the fusion process. In reactions on heavy targets ($Z > 62$) a reduction of the complete fusion (CF) cross-section has been observed at energies above the barrier, with respect to 1D-BPM calculations or to reactions induced by well bound nuclei [19, 20, 21]. Such a reduction was attributed to the projectile break-up in the strong Coulomb field of the target nucleus. It has been observed that for heavy targets the CF cross-section reduction depends on the break-up threshold of the projectile; it does not seem to depend on the atomic number of the target. On the contrary, fusion reaction on medium and light target does not seem affected by the breakup process, no reduction of the fusion cross section was observed (see as example [22]). In ^{6}Li+^{120}Sn and ^{7}Li+^{119}Sn reactions the discrimination of complete fusion from incomplete fusion is possible since the two processes produce ERs of different charge. Thus, with the study of these systems we aimed also to investigate the relation between the suppression factor and the atomic number of the target in a new mass range.

2. Experimental technique

2.1. Target activation

A fusion reaction induced by a beam of light nuclei on a medium mass target, at energies around the Coulomb barrier, leads to the production of evaporation residues (ER) whose largest fraction does not have enough kinetic energy to leave the target and they cannot be detected directly. In our case, the ER of interest are unstable against electron capture (EC) decay and thus, as in our previous experiments [23, 24, 25], we measured the fusion excitation functions by using an activation technique, based on the measurement of the atomic X-ray emission following the EC decay. The measurement was performed at Laboratori Nazionali del Sud - INFN. Sn targets ($\approx$ 500 μg/cm^2), followed by a ^{93}Nb ($\approx$ 2 mg/cm^2) catchers, were irradiated with Li beams, whose energy was chosen such as to measure the fusion excitation function in a centre of mass energy range from 16 MeV to 24 MeV. The catcher is used to stop the fraction of ER emerging from the target. Possible reactions induced by the beam on the catcher do not represent a problem since the associated X-ray energies are different from the ones corresponding to reactions on the target. To extract the production cross-section it is necessary to measure the number of incident particles on the target. If the ER produced in the reaction have a much longer life time with respect to the irradiation time it is possible to obtain this value simply by integrating the charge accumulated in a Faraday cup, placed downstream the target. In our case the ER of interest have a half-life shorter than, or comparable with, the duration of the activation period. In this case it is necessary to know the beam profile of irradiation. The beam intensity measurement as a function of the time has been performed by detecting the elastically scattered particles from a thin gold foil ($\approx 100\ \mu g/cm^2$) placed before the stack on the beam line, using two $1000 \mu m$ Surface Barrier silicon detectors. These two monitor detectors were symmetrically placed at ±20 with respect to the beam line and at a distance of about 80 cm from the Au foil. Since the elastic scattering at this angle follows the Rutherford law, the beam intensity can be extracted by the well-known cross-section formula. By using two symmetrical monitors it is possible to reduce systematic errors due to mechanical misalignments and small beam position shifts.

2.2. Characteristic X-rays measurement

After the irradiation, the characteristic X-rays of the ERs, emitted from different targets (together with own catcher), were measured off-line using Pb shielded large area Si(Li) detectors. Each measurement was repeated in order to measure the activity as a function of time. To determine the fusion cross section it is crucial to know the intrinsic efficiency of the detector. We measured the efficiency of our Si(Li) detectors using some calibrated sources, because in the energy range of interest the efficiency for this kind of detectors is strongly dependent on the energy. In figure 1 some typical X-ray spectra for ^{7}Li+^{119}Sn reactions are shown, in the energy region of interest and for different times after irradiation. It is possible to distinguish the k$_\alpha$ and k$_\beta$ X-rays produced in the decay of Iodine (the only element which can be produced after complete fusion) to Tellurium. In the present experiment, the analysis was performed only on the k$_\alpha$ lines, taking into account that they represent about the 80% of the total X-ray emission. In the spectra it is also possible to distinguish the k$_\alpha$ and k$_\beta$ peaks of Sb, produced by incomplete fusion of tritium with the target, which then decays by E.C. into Sn. Symilar spectra have been observed forv the ^{6}Li+^{120}Sn reaction. Since, the resolution of the X-ray spectra is such that it is not possible to resolve the isotopic shift, from the X-ray lines only different elements can be identified. Each isotopes contributes to the overall activity with its characteristic half-life. This means that contributions of different isotopes can be unfolded by following the activity of the X-ray lines as a function of the time. In figures **??** typical activity curves for the ^{6}Li+^{120}Sn and ^{7}Li+^{119}Sn reactions are plotted. It is possible to observe three different slopes which characterize these curves, which allow to identify in both the curves the ^{124}I and the ^{123}I produced in the 1 neutron and 2 neutron evaporation channel, respectively. The

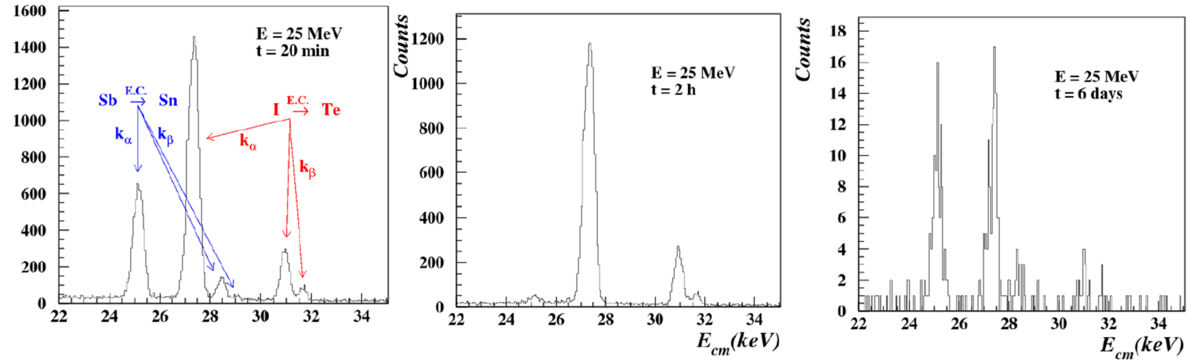

Figure 1. X-ray spectra measured off-line, 20 minutes, 2 hours and 6 days after the end of the irradiation, for the reaction ^{7}Li+^{119}Sn at E$_{LAB}$= 25 MeV.

third component has been identified as ^{123}Te in the case of ^{6}Li+^{120}Sn reaction and ^{121}Te in the case of ^{7}Li+^{119}Sn, produced in the incomplete fusion of α with the target nucleus. In particular these two nuclei are produced from the 1 neutron and 2 neutron evaporation channels; they are metastable and decay by internal conversion thus emitting X-rays. By fitting the activation

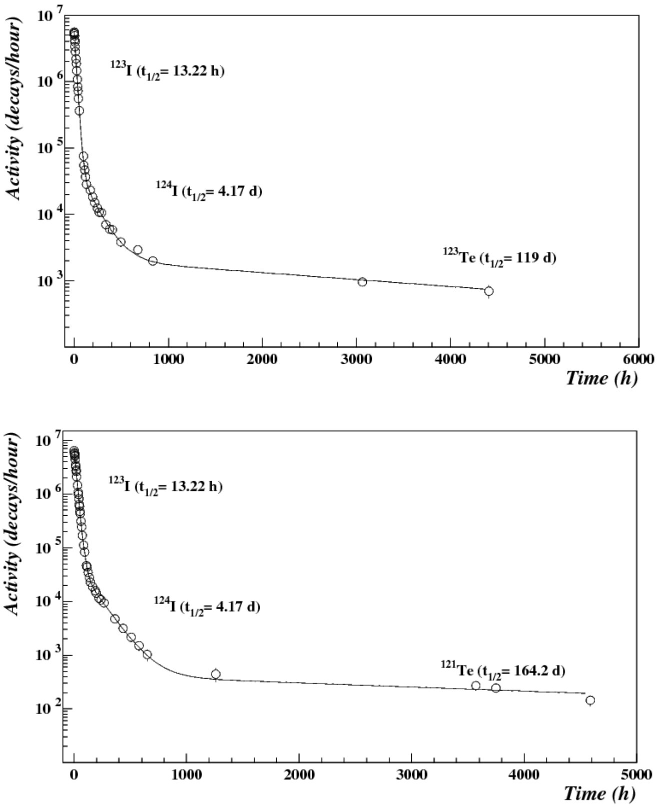

Figure 2. Activity curves for the Iodine isotopes for the ^{6}Li+^{120}Sn (top) and ^{7}Li+^{119}Sn (bottom) at E$_{LAB}$=25MeV. See details in the text.

curves for each ER one obtains A_{0exp}, which is its activity at the end of the irradiation time. Of course, the experimental activity is only a fraction of the real activity of the residue. The values that we have obtained have to be corrected for the detector efficiency and also for the fluorescence probability, k_α, since the electron capture decay is in competition with other decay modes.

In figure 3 the experimental relative yields for the produced residues is shown and compared with the prediction of the statistical model code CASCADE. A good agreement between the experimental data and the calculation predictions has been obtained.

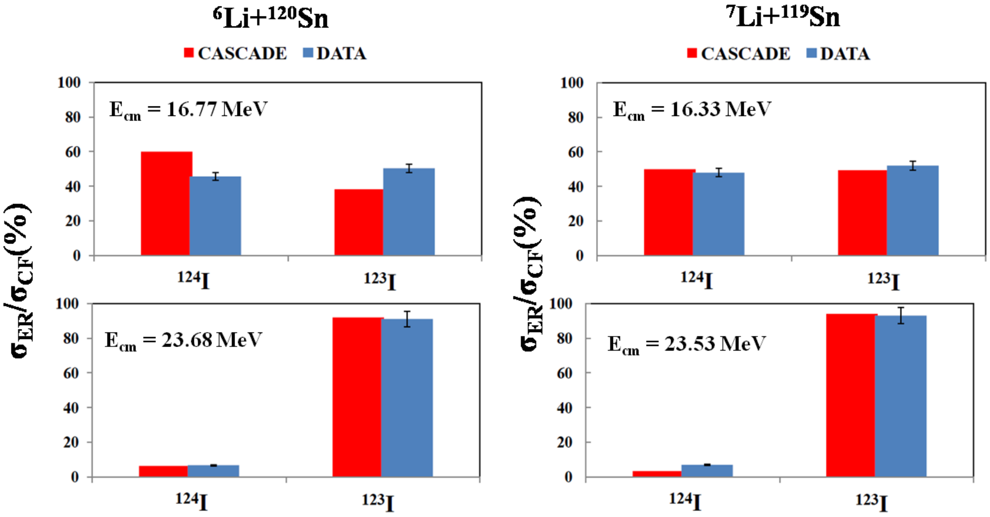

Figure 3. ER production relative yields for the ^{6}Li+^{120}Sn (left) and ^{7}Li+^{119}Sn (right) reactions compared with the prediction of the statistical model CASCADE, at two different energies.

3. Results and conclusions

The complete fusion cross-section has been extracted by summing the contributions of ^{123}I and ^{124}I. In figure 4 the reduced fusion excitation functions for the two studied reactions are reported and compared. The data have been reduced by dividing the fusion cross-section by the square of the barrier radius (R_B^2) and subtracting from the center-of-mass energy the height of the Coulomb barrier V_b. The two fusion excitation functions are different at energies above the barrier. According to previous studies [19, 20, 21] this difference could depend on the different breakup probability of the two projectiles. For both the systems, the suppression factor, obtained by comparing the fusion excitation functions with respect to the the 1D-BPM prediction, is in a agreement with the values reported in literature for heavier systems. It seems that this difference disappears at energies below the barrier, thus sub-barrier fusion enhancement in the ^{7}Li induced collisions imputable to larger n-transfer Q-value cannot be deduced from these data.

In conclusion, by measuring the fusion cross section induced by the weakly bound ^{6}Li and ^{7}Li projectiles on different Sn isotopes, we looked for effects on fusion cross section which can be attributed to the breakup and neutron transfer channels. For both the reaction, the above barrier suppression factors are in agreement with the ones previously measured for heavier targets, confirming further that there is no relation between the CF fusion suppression and the target atomic number. Concerning the possible influence of the positive neutron transfer Q-value on the fusion excitation function at energies below the barrier, no difference imputable to

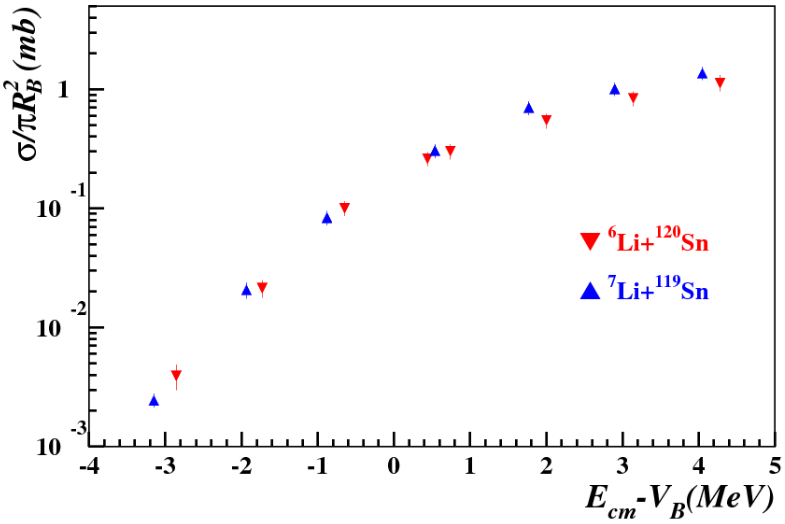

Figure 4. ^{6}Li+^{120}Sn (red reversed triangles) and ^{7}Li+^{119}Sn (blue triangles) fusion excitation function reduced as $\sigma/\pi R_B^2$ vs $E_{cm} - V_B$

the different n-transfer Q-values can be deduced from the present data. To further investigate the possible relation between the n-transfer Q-values with the fusion excitation function, we are going to extend the measure at lower energies. In addition a CDCC calculation not including the contribution of the transfer could helpful to extract this effect.

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