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Reactions with light exotic nuclei

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Abstract. Experimental cross sections for the ^{6}He+^{120}Sn are analysed. Elastic scattering angular distributions and alpha particle production cross sections have been measured and are compared with the total reaction cross sections.

1 Introduction

Experimental investigations have been performed over the last years of reactions induced by exotic projectiles, such as ^{6}He and others on several targets. Such so-called exotic nuclei have a cluster structure formed by a stable core plus one or two weakly bound neutrons. Due to the low binding energies and low angular momentum of the valence neutrons, in some cases, they form a kind of halo that extends spacially over large distances from the core. Such features make the exotic nuclei very reactive, even in collisions at energies near the Coulomb barrier. Due to their low two-neutron separation energy (0.97 MeV for ^{6}He) they can easily breakup, either in the long range Coulomb field of heavy targets (Coulomb breakup) or in the short range strong interaction (nuclear breakup). In addition, the neutron halo favours neutron transfer reactions from the projectile to the target even below the Coulomb barrier. One important question that arises is what could be the effect of the neutron halo on the fusion cross section. One could imagine that, as the neutron halo is easily deformable, it could in principle help fusion, with the neutrons tunneling the Coulomb barrier of the target and bringing together the alpha core. On the other hand, the neutrons are weakly bound and could easily breakup removing flux from the complete fusion. Both pictures are probably correct and their effect depends on the scattering energy. An enhancement of the fusion at energies below the Coulomb barrier is expected and possibly a small suppression at energies above the barrier. However, measurements of fusion cross section with light exotic projectiles are very difficult. Due to the alpha + 2 neutrons structure of ^{6}He, it is not easy to separate experimentally the fusion-evaporation particles from other direct process, which would give the same reaction products with similar energies. A complete understanding of the reaction mechanism would require coincidence measurements of the charged particles, neutrons and gammas emitted in the reactions, and would be a very challenging task from the experimental point of view. On the other hand, interesting information can be obtained

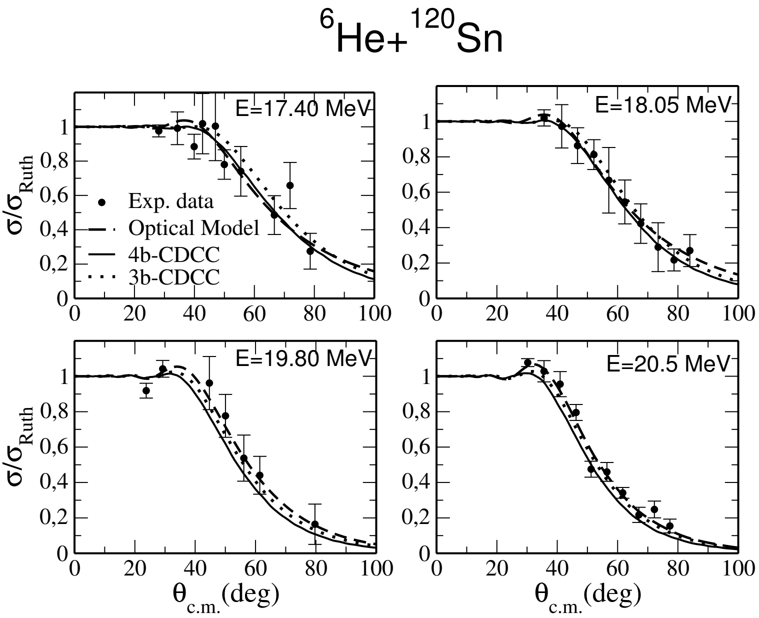

Figure 1. ^{6}He+^{120}Sn elastic scattering angular distributions from ref. [1].

from the elastic scattering and the alpha particle distributions observed in those reactions. The elastic scattering angular distributions provide the total reaction cross sections and the analysis of the energy and angular distributions of the charged particles emitted can provide some information of the process in which they are produced. Here I will present results of the analysis of the total reacion cross section obtained from the analysis of the ^{6}He+^{120}Sn angular distributions [1] compared with the total reaction cross section of the α-production in the same collision.

2 ^{6}He+^{120}Sn elastic scattering

^{6}He+^{120}Sn elastic scattering angular distributions have been measured [1] using the RIBRAS system [2, 3] at four energies slightly above the Coulomb barrier. The angular distributions are shown in Fig. 1 together with optical model, 3-body and 4-body CDCC calculations considering the projectile breakup (see [1] for details).

The total reaction cross sections obtained from these calculations have been averaged and are shown in Fig. 2 together with a systematics for other stable systems of similar mass.

The total reaction cross sections and energies have been reduced using the expression: $\sigma_{\text{red}} = \sigma_{reac}/(A_p{}^{1/3} + A_t{}^{1/3})^2$ and $E_{\text{red}} = E_{\text{cm}}(A_p{}^{1/3} + A_t{}^{1/3})/Z_pZ_t$, where Z_p (Z_t) and A_p (A_t) are the charge and mass of the projectile (target) [4]. This reduction procedure takes into account trivial effects due the different sizes and different Coulomb barriers of the systems, allowing one to compare cross sections for stable tightly bound, weakly bound and exotic nuclei in the same plot. We clearly see in Fig. 2 that there are 3 classes of cross sections. The tightly bound systems such as the double magic ^{4}He, ^{16}O projectiles present the lowest cross sections. Following, in increasing order of magnitude, the stable but weakly bound isotopes such as ^{6,7}Li and ^{9}Be and finally the exotic ^{6}He which presents

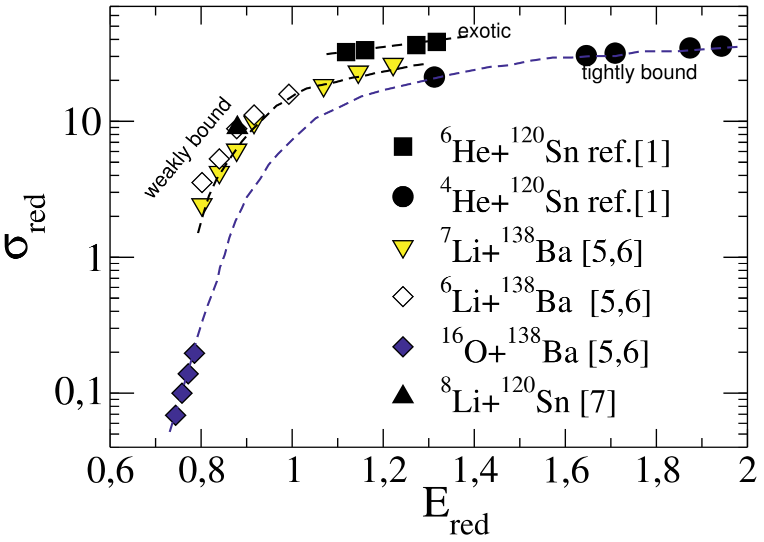

Figure 2. Reduced reaction cross sections from ref. [1].

Table 1. Reduced total reaction cross sections for the ^{6}He+^{120}Sn [1] system obtained from Optical Model and CDCC calculations compared with fusion cross sections. (see text for more details)

E_{lab}(MeV)	σ_{reac}^{OM}(mb)	σ_{reac}^{CDCC}(mb)	σ_{reac}^{av} (mb)	σ^{halo}(mb)	σ_{fus}(mb)	σ_{fus}^{Bass}(mb)
17.40	1451	1491	1471	768	703	618
18.05	1445	1592	1519	763	756	703
19.80	1475	1834	1655	739	916	900
20.50	1579	1916	1748	762	986	1065

the highest reduced cross section. This clear effect can be quantified by the difference:

$$\sigma^{halo} = [\sigma_{\mathrm{red}}^{^6\mathrm{He}+^{120}\mathrm{Sn}} - \sigma_{\mathrm{red}}^{^4\mathrm{He}+^{120}\mathrm{Sn}}] \times (6^{1/3} + 120^{1/3})^2 \tag{1}$$

As ^{4}He is the core of ^{6}He, its reduced cross section should represent reactions occurring with the core, mostly fusion reactions since the core is inert. In fact, direct reactions induced by ^{4}He, such as transfers, are not very likely to occur at low energies due to their very negative Q-values. Thus we suppose that, given the reduction procedure, the total reduced reaction cross sections for the ^{4}He projectile represents mainly complete fusion. As a consequence, the quantity σ_{halo} calculated above should give the cross section for direct reactions, such as projectile breakup and neutron transfer reactions. Then the difference $\sigma_{reac}^{av} - \sigma_{halo} = \sigma_{fus}$ represents the fusion cross section for the ^{6}He. The resulting total reaction cross sections, σ_{halo} and σ_{fus} are shown in Table 1 together with fusion calculations using a simple barrier penetration model [8]. We see that the agreement is good.

3 α-particle production in the ^{6}He+^{120}Sn collision

As a next step we try to determine what kind of reactions could be the origin of this excess in the reaction cross section observed for the ^{6}He projectile. In Fig. 3 we present experimental spectra obtained in the present experiment [9].

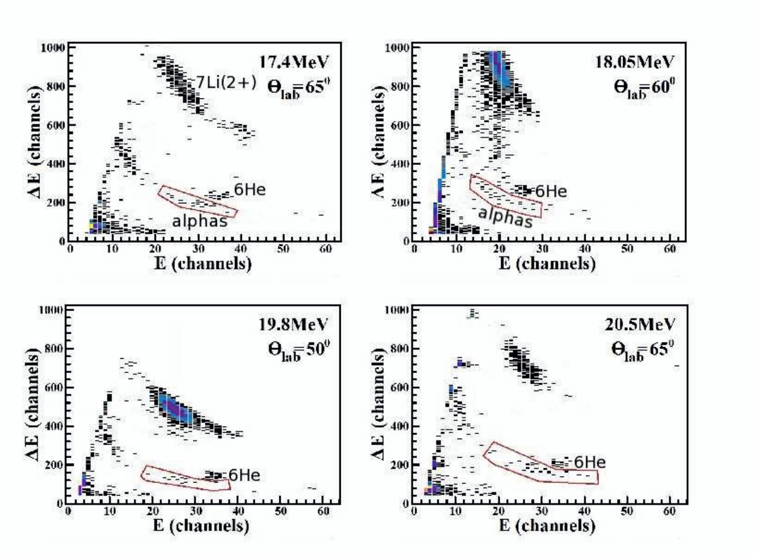

Figure 3. Experimental biparametric spectra for ^{6}He+^{120}Sn from ref. [9]. The contaminant ^{7}Li peak is shown as well as the alpha particles distribution.

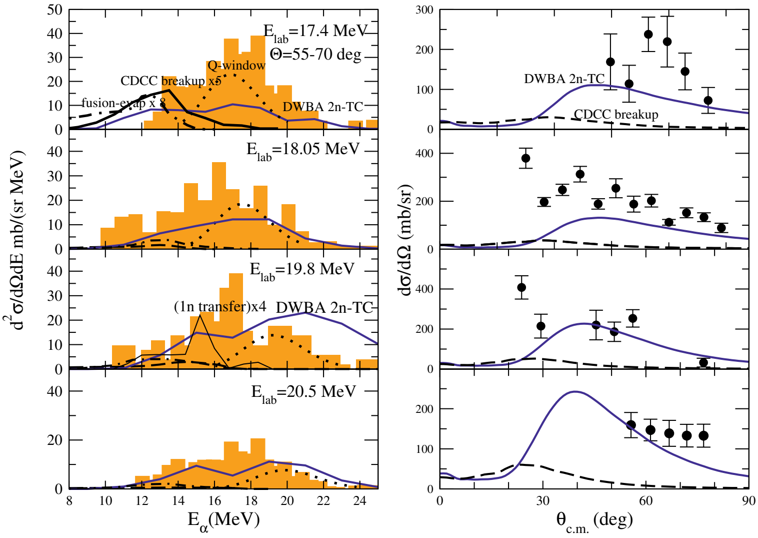

Figure 4. Energy and angular distributions of the alpha particles produced in the ^{6}He+^{120}Sn collision. See ref. [9]

We see that there is a group of counts in the alpha particle line, with energies a little bit lower than the energy of the ^{6}He elastic peak. We analysed these alpha particle yields and in Fig. 4 we present their energy (left) and angular distributions (right). The results are compared with breakup (CDCC) [1], two-neutron transfer to the continuum (DWBA) [9] and fusion-evaporation (PACE) predictions. We see that the two-neutron transfer DWBA calculations better reproduce the experimental energy distributions. Both the projectile breakup and fusion-evaporation calculations predict a lower energy distribution. In addition, the magnitude of the theoretical cross sections for the breakup and fusion are much smaller than the observed. The DWBA transfer to continuum (TC) calculations on the other hand, reproduce quite well the magnitude of the cross sections observed in the energy distributions. The angular distributions are also quite well reproduced, in shape and magnitude, by the TC calculations. The angle integrated TC cross sections give a result of $\approx$ 650 mb, almost constant for the four energies. This result agrees with the values of σ_{halo} in Table 1 indicating that this alpha particle yield could account for the enhancement observed in the total reaction cross section. This is a strong indication that the enhancement observed in the total reaction cross section is probably due to the contributions of direct process such as neutron transfers rather than fusion-evaporation reactions.

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