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Halo effects on fusion cross section in $^{4,6}He+^{64}Zn$ collision around and below the coulomb barrier

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Abstract. The structure of the halo nuclei is expected to influence the fusion mechanism at energies around and below the Coulomb barrier. Here new data of $^{4}He+^{64}Zn$ at sub-barrier energies are presented which cover the same energy region of previous measurements of $^{6}He+^{64}Zn$. The fusion cross section was measured by using an activation technique where the radioactive evaporation residues produced in the reaction were identified by the X-ray emission which follows their electron capture decay. By comparing the two system, we observe an enhancement on the fusion cross section in the reaction induced by ^{6}He, at energy below the Coulomb barrier. It is shown that this enhancement seems to be due to static properties of halo 2n ^{6}He nucleus.

1. Introduction

In recent years, great effort have been made to investigate the effect of the projectile structure on the fusion reaction mechanism in collisions induced by halo nuclei, at energies around and below the Coulomb barrier. In typical halo nuclei, such as ^{6}He, ^{11}Li, ^{11}Be, ^{19}C or ^{8}B, the outer nucleons are characterized by low binding energy (0.1-1 MeV) and they occupy single-particle states having low angular momentum (*s* or *p*). The corresponding single-particle wave function of these valence nucleons has a long tail, which extends mostly outside the potential well. The structure of halo nuclei is expected to strongly affect the reaction mechanisms, especially at energies near the Coulomb barrier. Direct processes are expected to be favored due to the low binding energies of valence nucleons. Concerning the effects that halo structure could generate on the fusion mechanism one should take into account two different categories: static and dynamic effects. Static effects are due to the long range of the radial wave-functions associated with the valence orbitals. The presence of the diffuse halo affects the shape of projectile-target potential, thus reducing the Coulomb barrier and therefore enhancing the fusion cross section around and below the barrier. Dynamic effects are due to the coupling of the relative motion of projectile and target to their intrinsic excitations or to the other reactions channels. In particular, due to the very low break-up threshold, coupling with the break-up may be important. A lot of theoretical studies have been done in order to understand the role of these dynamic effects on the fusion cross section with halo nuclei. However, until now, contradictory effects on fusion cross section have been predicted by different theoretical models. The role of the break-up process of halo and weakly bound projectile in fusion have been investigated via Coupled Channel

(CC) calculations. In order to properly describe the reaction dynamics, in collisions involving these nuclei, the coupling not only to bound but also to continuum states (break-up states) must be included in CC calculations. Continuum-Discretised Coupled-Channel (CDCC) calculations have been, hence, developed [1,2]. These calculations predict that dynamical effects enhance the sub-barrier total fusion (complete + incomplete) cross-section with respect to the nocoupling case. In addition, due to the break-up, a suppression of the total fusion cross-section is predicted by CDCC calculations at energies above the barrier [2]. However, the calculated cross-sections and hence the amount of sub-barrier enhancement, depend upon the adopted approximations and the phase space in the continuum considered (range of energies, energy bin and partial waves) [3]. Opposite results have been obtained with a different approach [4] based on a time dependent wave-packet formalism which uses a three body model (core, halo and target). According to this model, the cross-section in the neutron halo case is slightly suppressed compared to the non-halo case.

2. Reaction induced by halo nuclei

The experimental investigation on the reaction processes, using radioactive beams, is quite difficult owing to the very low intensity (10^5-10^7pps) of the available halo beams, coupled to the difficulty of measuring fusion cross-sections at low energies for reactions induced by light projectiles. Fusion reactions induced by the 2n halo ^{6}He nucleus in the energy region around the Coulomb barrier are the most studied of any involving light radioactive beams. This is because ^{6}He beams are available in several radioactive beam facilities with good intensities (up to 10^7pps). The only low energy reaction studies involving the 1n halo ^{11}Be, existing in the literature, concerns the system ^{11}Be+^{209}Bi. Also from the experimental point of view different authors did not reach similar conclusion about the enhancement/suppression effect on the fusion cross section due to the projectile halo structure since most of the existing data do not really explore the region below the barrier with reasonable errors. Moreover is not always clearly discussed which is the role played in the observed final result by different static and dynamic effects. However, a remarkable feature of reactions involving halo nuclei is also the very large near and sub-barrier direct reaction cross-sections, dominating fusion by orders of magnitude. Different papers have evidenced that direct reactions completely dominate the total reaction cross-section at these energies [5,6,7,8].

The first measurement of fusion with ^{6}He was performed at the Flerov laboratory in Dubna for the system ^{6}He+^{209}Bi at energies above the barrier [9]. In this experiment, a very large fission cross-section was measured and it was attributed to fusion-fission processes. The same reaction was successively measured at the TwinSol facility at the University of Notre Dame by Kolata and collaborators [10]. The fusion cross-section was extracted using an activation technique by detecting the α particles emitted in the on-line and off-line decay of the evaporation residues. An enhancement of the sub-barrier fusion with respect to a statistical model calculation and to a single barrier penetration calculations [10], but also to fusion induced by ^{4}He onto the same ^{209}Bi target was found. Usually the fusion cross section of the reactions induced by ^{6}He are compared with those obtained using ^{4}He beam on the same target. The ^{4}He represents the ^{6}He core and by comparing the two systems one can observe the effect due to the presence of valence neutrons.

The reaction ^{4,6}He+^{238}U were measured twice at the CRC in Louvain la Neuve by the same group [11,12] . They determined the fusion cross section by the detection of the fission fragments. A large enhancement of fission around and below the barrier in the ^{6}He case respect the ^{4}He ones was observed. The analysis of the light particle, emitted in coincidence with the fission fragments, allowed to conclude that the observed fission enhancement is due to transfer-fission events and no effect on fusion due to the structure of ^{6}He are observed.

The fusion reaction ^{6}He + ^{206}Pb was performed at the ISOL facility DRIBs at the Flerov Laboratory in Dubna [13]. The 2n evaporation channel is compared to the measured 1n evaporation channel of ^{4}He+^{208}Pb. In this paper an enhancement of the sub-barrier fusion cross-section for the ^{6}He induced reaction is observed with respect to the ^{4}He ones. In a model of "sequential fusion" proposed by Zagrabaev [14], the transfer of the two "valence" neutrons in the ^{6}He (with positive Q-value) causes a

gain in the energy of the relative motion of the two nuclei and thus facilitates fusion. Therefore, the enhancement is attributed to the coupling to the transfer channel having positive Q-value. However, the two reactions $^{6}He+^{206}Pb$ and $^{4}He+^{208}Pb$ form the same compound nucleus, but owing to the very different reaction *Q*-value this, for the same $E_{c.m.}$, is formed at a different excitation energy. In particular at the lowest measured beam energy the excitation energy of the compound nucleus ^{212}Po, formed in the reaction with ^{4}He beam, is below the particle threshold, therefore it would be necessary to compare the measured total fusion cross-section for the two reactions $^{4,6}He + ^{208}Pb$ rather than the excitation function for one particular evaporation channel.
Navin et al. [19] measured neutron-transfer and fusion cross-sections for the $^{6}He + ^{63,65}Cu$, at energies around the Coulomb barrier at the SPIRAL ISOL facility at GANIL. They compared this measurement with the ones obtained using same targets and ^{4}He beam. The last measurement was made at the 14UD BARC-TIFR Pelletron Accelerator Mumbai. In the case of ^{6}He beam they performed coincident measurement between γ-rays and light charged particle, too, which allowed to disentangle fusion and neutron transfer mechanisms. In particular they observed ^{66}Cu residue cross-sections much larger than the ones calculated using the statistical model. This result suggested that the dominant production mechanism was other than fusion-evaporation, most probably neutron transfer. Charged particle- γ-ray coincidence events were consistent with this hypothesis.
The only fusion reaction, present in literature, induced by ^{11}Be was performed at RIKEN, Japan, in two successive experiment [15,16]. Also in this case the evaporation residues were identified from their delayed α activity. The cross-section data, for the weakly bound one-neutron halo ^{11}Be, were compared with those for the well bound ^{10}Be nucleus. In addition, the fusion of the stable but weakly bound ^{9}Be nucleus with ^{209}Bi was measured by the same group at the Munich Tandem accelerator [Sig99]. The complete fusion cross-section reported in [16] for the three reaction $^{9,10,11}Be+^{209}Bi$ show no difference within the errors.

2.1. $^{6}He+^{64}Zn$ experiment
In [6,18] we had performed the $^{6}He+^{64}Zn$ reaction at the Centre of Research of Cyclotron in LLN to measure elastic scattering, direct reaction and fusion cross section at energies around the Coulomb barrier. The same quantities were also measured using a ^{4}He beam. To measure the fusion cross-section we used an activation technique based on the off-line measurement of the atomic X-ray emission following the electron capture decay of the evaporation residues produced in the reaction. This technique will be discussed, in details, in the next paragraph. Stacks of four ^{64}Zn targets, each followed by a ^{93}Nb catcher, were irradiated with ^{6}He beam in order to measure different points in the fusion excitation function with a single ^{6}He energy. The fusion cross-section could be obtained by summing up the cross-sections of all evaporation channels. The same nuclei can be produced by fusion-evaporation and by other reaction processes. For these reason we had performed a comparison of the measured cross-section for the different channels with a statistical model calculation, performed with the CASCADE code. This comparison showed a good agreement except for the ^{65}Zn residue, were a large enhancement with respect to the calculation was observed. The excess in the yield measured for this channel was attributed to one and two neutron transfer reactions. Therefore, in order to obtain the fusion excitation function we have subtracted the contribution due to the transfer by replacing the measured value for ^{65}Zn with the one calculated using the statistical model calculations. The results are shown in figure 1. No evident effects were observed for $^{6}He+^{64}Zn$ fusion with respect to $^{4}He+^{64}Zn$ within the measured energy range. However the ^{6}He data extended lower energies than the ^{4}He ones. Therefore, new data with ^{4}He beam are needed in order to investigate the role of valence neutrons at energies below to the Coulomb barrier.

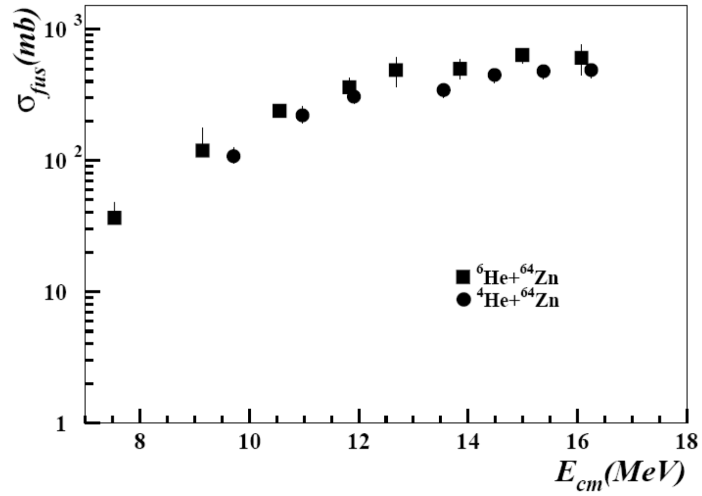

Figura 1. $^4He+^{64}Zn$ (circles) and $^6He+^{64}Zn$ (squares) fusion cross-sections [6]

3. New $^4He+^{64}Zn$ experiment

3.1 Experimental technique

The new $^4He+^{64}Zn$ experiment was performed at Ruder Boskovic Institute (Zagreb) with an average ^4He beam current of about 10^{11} pps. The reaction was measured at E_{lab}=8.1 MeV, 9.2 MeV and 10.1 MeV. As in our previous measurement [6,18] the fusion excitation function was performed using the activation technique. The direct detection of evaporated residues (E.R.), produced in the collision of a low energy light projectile onto a medium mass target is not always possible since the largest fraction of E.R. will not come out from the target owing to the their low kinetic energy. However by choosing a suitable target, as in our case, almost all the produced radioactive residues decay by electron capture (E.C). It is possible to obtain E.R. unstable against E.C. decay and "detect" the E.R. by looking at X-ray emitted in their decay. This technique consists of two steps. The first is the target activation. During this time the Zn target (540μg/cm^2) is first irradiated with the ^4He beam. The fusion-evaporation reactions take place within the target and the largest fraction of E.R. produced will not come out from it. The small fraction of residues emerging from the target is stopped in the ^{93}Nb catcher (1000μg/cm^2), placed behind the target. In figure 2 a schematic view of experimental set-up is shown.

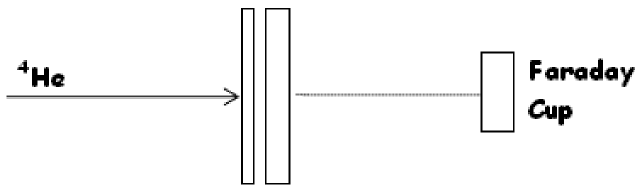

Figura 2. Experimental set-up for the fusion measurement. The faraday cup was used to measure the beam current.

Possible reactions induced by the beam on the ^{93}Nb catchers do not represent a problem since the X-ray energies are different to the ones corresponding to reactions on ^{64}Zn. At the end of the irradiation time the activated target and catcher are placed very close to the Si(Li) detector to measure the residues activity. The irradiated target were measured at Laboratori Nazionali del Sud for about twenty days. One of the advantages of this technique is the 100% intrinsic detection efficiency of Si(Li) detector in the energy region of interest (7-11 MeV). Moreover the atomic X-ray in this energy region can be detected with extremely low background .

3.2 Experimental result

Typical X-ray spectra measured off-line for the reaction ^{4}He+^{64}Zn are shown in figure 3, where the two peaks correspond to the K_α and K_β X-ray emission of Zn. The K_β emission represents about 15% of the total k X-rays emission. In the present experiment, the analysis was performed only on the K_α lines.

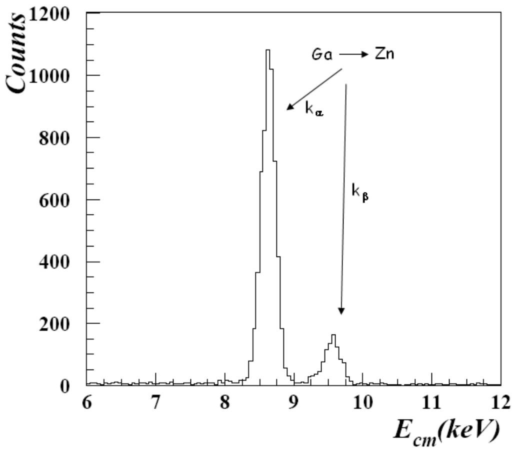

Figure 3. Typical X-ray spectra measured off-line for the reaction ^{4}He+^{64}Zn. It is possible to distinguish two peaks which correspond to the Kα and K_β X-ray emission of Zn

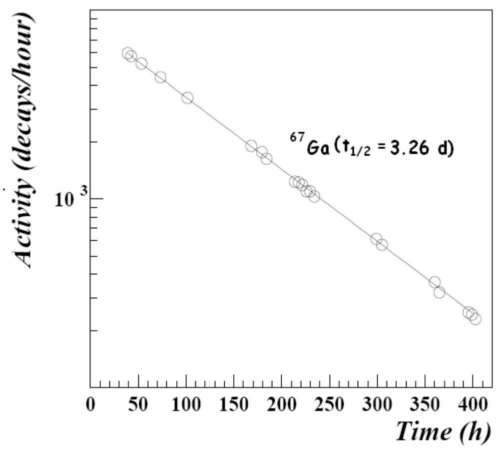

Figure 4. Activity curve for the ^{67}Ga isotope extracted in the activation run.

From the X-ray energies we can only identify different elements but not different isotopes. However it is possible to discriminate the different isotope contributions by following the X-ray activity as a function of time. In the ^{4}He+^{64}Zn reaction we had estimated with statistical model calculations that the only residues produced could be ^{67}Ge and ^{67}Ga. However, the ^{67}Ge is a shortlived nucleus ($t_{1/2}$= 18 minutes) and it decays by E.C. 100% into ^{67}Ga. For this reason after one day we expect to observe only the ^{67}Ga contribution. In figure 4 the activity curve for the Ga isotope is shown. As one can see from the slope of the activity curve only the contribution of ^{67}Ga isotope is present, as expected.
Therefore, the total fusion cross section corresponds to the longer lived ^{67}Ga ($T_{1/2}$=3.26 d) cross section extracted by using the following formula:

$$\sigma = \frac{A_{0exp}}{N_i N_t \lambda_0 K_\alpha \varepsilon_T} \tag{1}$$

A_{0exp} is the experimentally measured activity at the end of the irradiation as obtained from the fit of the activity curve (figure 4). This term is then corrected for the known K_α fluorescence probability and for the detector efficiency (ε_T); λ_0 is the deacy constant; N_t is the number of target atoms per cm^2

and N_i is the integrated beam current (i.e. the number of incident particles). This was determined by using a faraday cup. A correction for the X-ray absorption by ^{64}Zn and ^{93}Nb foils has also been made. In figure 5 both the preliminary data of ^{4}He+^{64}Zn (open circles) and the previous data of ^{4,6}He+^{64}Zn [6] are shown. By observing in particular the points around 9.5 MeV, we notice that the new data are in good agreement with the previous ones.

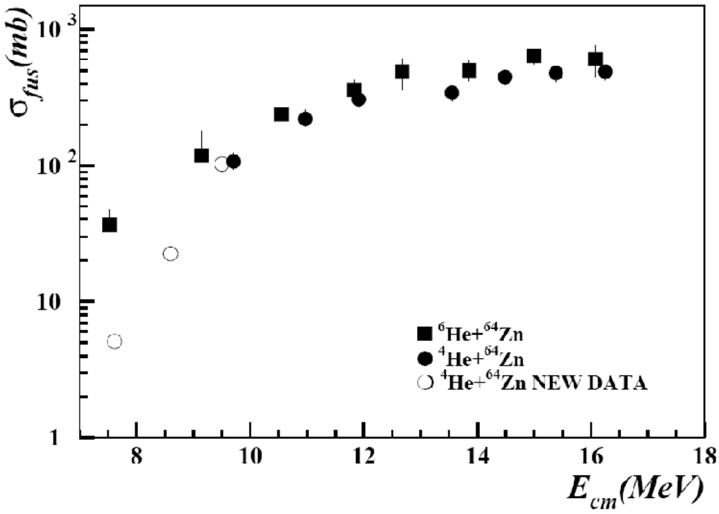

Figura 5. ^{6}He+^{64}Zn (squares) and ^{4}He+^{64}Zn (circles) fusion excitation function. The ^{6}He and ^{4}He at upper energies (closed circles) are the data of the previous experiment [6]. With the open circles are plotted the new preliminary ^{4}He data.

Concerning the comparison of the two fusion excitation function an enhancement of the fusion excitation functions at the energies below the Coulomb barrier in the case of ^{6}He with respect the ^{4}He one is observed. The enhancement is attributed to the halo structure of ^{6}He, however this comparison includes both the static and the dynamic effect, which are respectively due to the size of the system and the coupling to other channels, such as break-up.

4. Conclusion

In the last years different experiments have been performed to study the fusion mechanisms in collisions induced by halo nuclei. Performing a comparison of $\sigma_{fus}(E_{cm})$ between halo and corresponding well bound isotopes a clear systematic behavior for all systems is not yet observed.
Concerning our data the comparison of the ^{4,6}He+^{64}Zn we previously measured has been extended to lower energies by using an activation technique. It has been observed an enhancement of the ^{6}He+^{64}Zn fusion cross section with respect to ^{4}He+^{64}Zn at energies around and below the Coulomb barrier.
In general we underline that most of the existing data do not really explore the region below the barrier with reasonable errors and it is not always clearly discussed which is the role played by static and dynamic effects in the fusion mechanism. Therefore we believe that new fusion cross-section measurements at sub-barrier region are needed.

5. References

[1] Hagino K et al. 2002 *Phys. Rev.* **C61** 037602
[2] Diaz-Torres A, Thompson J J 2002 *Phys. Rev. C* **65** 024606.
[3] Canto L F et al. 2006 *Phys. Rep.* **424**, 1.

[4] Ito M, et al. 2006 *Phys. Lett. B* **37**, 53
[5] Aguilera E F et al. 2001 *Phys. Rev. C* **63**, 061603(R).
[6] Di Pietro A et al. 2004 *Phys. Rev. C* **69** 044613.
[7] Bychowski J P et al. *2004 Phys. Rev. Lett*. **596** 26.
[8] De Young P Aet al., 2005 *Phys. Rev. C* **71** 051601(R).
[9] Fomichev A S et al. 1995 *Z. Phys. A* **351** 129.
[10] Kolata J Jet al. 1998 *Phys.Rev.Lett.* **81** 4580.
[11] Trotta M et al. 2000 *Phys. Rev. Lett.* **84** 2342
[12] Raabe R et al. 2004 Nature **431** 823
[13] Penionzhkevich Y Eet al. 2006 *Phys. Rev. Lett.* **96** 162701.
[14] Zagrebaev V I 2003 *Phys. Rev. C* **67** 061601(R)
[15] Signorini C et al.1998 *Eur. Phys. J. A* **2** 227
[16] Signorini C et al.2004 *Nucl. Phys. A* **735** 329.
[17] Signorini C et al.1999 *Eur. Phys. J. A* **5** 7.
[18] Di Pietro A et al. 2007 *Eur.Phys.J. Special Topics* **150** 15.
[19] Navin A et al., 2004 *Phys. Rev. C* **70** 044601