Vol. 42 (2011) ACTA PHYSICA POLONICA B No 3–4

RADIATIVE CAPTURE IN THE ^{12}C+^{16}O SYSTEM: STRUCTURAL VERSUS STATISTICAL ASPECTS OF THE DECAY*

S. Courtin[a], A. Goasduff[a], F. Haas[a], D. Lebhertz[b]
D.G. Jenkins[c], P.A. Marley[c], D.A. Hutcheon[d], C.A. Davis[d]
C. Ruiz[d]

[a]IPHC, CNRS-IN2P3, Université de Strasbourg
67037 Strasbourg Cedex 2, France
[b]GANIL CEA-CNRS-IN2P3, BP 55027, 14076 Caen Cedex 5, France
[c]Department of Physics, University of York, York YO10 5DD, UK
[d]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Colombia, V6T 2A3, Canada

(Received February 7, 2011)

This paper discusses how the radiative capture process can shed light on the origin of the resonances observed in light heavy-ion collisions. The impact of resonant features on the fusion cross-sections is described from energies around the Coulomb barrier down to the Gamow energy in systems like ^{12}C+^{12}C and ^{12}C+^{16}O.

DOI:10.5506/APhysPolB.42.757
PACS numbers: P21.60Gx, 25.70.Ef, 25.70.Gh, 27.30.+t

1. Introduction

Resonances are well established phenomena in specific light heavy-ion reactions such as ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O from the Coulomb barrier (CB) to some 5 MeV per nucleon. At CB, resonances have usually narrow widths and can be interpreted in terms of long lived states in the compound nucleus. At higher energies and shorter reaction times, widths become larger and resonant effects evolve towards refractive effects such as nuclear rainbows. The occurrence of resonances at CB can be explained in terms of the phase space the system has access to decay. The smaller the number of open channels (NOC), the better the chances to observe resonant effects in the collision. Calculations of the NOC per unit of incident flux have been performed by Abe and Haas [1] For 1 mb of incident flux, at CB, NOC = 9 for

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", August 30–September 5, 2010, Zakopane, Poland.

^{12}C+^{12}C, NOC = 350 for ^{12}C+^{16}O and NOC = 600 for ^{16}O+^{16}O. These numbers are in very good agreement with the amplitudes of the resonances measured in the collisions of these systems at CB. These systems have rather limited NOC and thus are the best cases to observe resonant features. We will discuss ^{12}C+^{12}C and ^{12}C+^{16}O systems in this paper. The ^{16}O+^{16}O system shows less pronounced resonances. It is in fact difficult to study experimentally since oxide based targets can lead to contamination of the spectra.

The study of light heavy-ion resonances has drawn a renewed interest with the recent measurement of a very low energy resonance in the ^{12}C+^{12}C system. This resonance has been measured in the p and α channels at $E_{\rm CM} =$ 2.14 MeV at the Dynamitron Tandem Laboratory in Bochum [2], close to the Gamow energy $E_{\rm Gamow} = 1.5$ ($\pm$ 0.3) MeV at $T = 5 \times 10^8$ K [3]. The understanding of the resonances is extremely important from CB down to these energies since they have important consequences on the capture cross-sections and on the carbon burning rate in stars. Below CB, the fusion cross-section drops exponentially and it is common to extrapolate the behaviour of the S factor down to astrophysical energies but doing so can be hazardous in systems with low NOC for which resonances can occur.

2. Spectroscopy of molecular states at CB

Resonances observed in ^{12}C+^{12}C and ^{12}C+^{16}O at CB are usually discussed in terms of molecular configurations in the compound nuclei ^{24}Mg(^{12}C$-^{12}$C) and ^{28}Si(^{12}C$-^{16}$O) but no definitive evidence has been found yet. Cluster calculations are scarce at very low energies. Nevertheless, Suzuki and Hecht have predicted sub Coulomb ^{12}C+^{12}C resonances based on ^{12}C$-^{12}$C, $\alpha-^{20}$Ne and ^{8}Be$-^{16}$O configurations [4]. After this reference, Fig. 1 shows the molecular spectroscopic factor from 27 MeV down to 16 MeV excitation energy in ^{28}Si. A lot of resonances are predicted around CB ($E^* = 20$ MeV) and below. Note the large 0^+ molecular spectroscopic factor around $E^* = 17$ MeV, in the Gamow window given in Section 1. Our experimental programme aims at doing the spectroscopy of molecular states in systems where NOC is small from CB first, down to lower energies. We have populated ^{28}Si, via the ^{12}C+^{16}O collision around CB on 2 resonances ($E_{\rm CM} = 8.5$ and 9 MeV) and measured the subsequent γ decay. This decay should show specific features of a very deformed system if the resonance is of molecular ^{12}C$-^{16}$O origin. Such heavy-ion radiative capture experiment has a low cross-section (*i.e.* typically 40–100 nb/sr) and requires high efficiency γ-ray detection as well as a state-of-the-art 0° spectrometer with a large incident beam rejection. The ^{12}C(^{16}O,γ)^{28}Si experiment has been performed at the TRIUMF ISAC facility using the Dragon 0° spectrometer to detect the ^{28}Si recoils and the 30 BGO array to record the coincident γ decay.

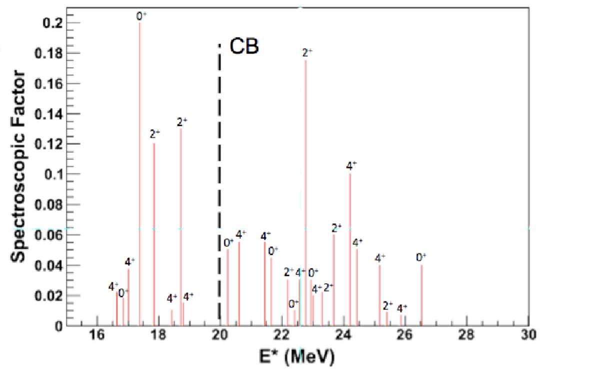

Fig. 1. Molecular spectroscopic factor in the ^{12}C+^{12}C system. Adapted from [4].

Fig. 2 shows the corresponding γ spectrum measured at $E_{\rm CM} = 9$ MeV. The spectrum shows low-lying ^{28}Si transitions (below 8 MeV) and an unexpected large bump around 14 MeV. This corresponds to previously unobserved doorway transitions representing a large part of the radiative capture decay flux. This experiment has thus allowed to measure the complete decay spectrum and the total radiative capture cross-section $\sigma_{\rm RC} = 23.4$ μb, in contrast to a previous study where doorway states could not be measured for experimental limitations and 80% of $\sigma_{\rm RC}$ was missing [5]. The measured transitions to doorway states are good candidates for transitions between molecular states. The BGO array used in this experiment has a high efficiency, even at large γ-ray energies ($\epsilon = 50\%$ at 5 MeV) but a low resolution and this does not allow to identify completely the transitions in the bump at 14 MeV and to draw definitive conclusions on the statistical part and the structural, *i.e.* cluster, part in the decay of the capture resonance.

3. Discussion: further developments

The decay of the ^{12}C(^{16}O,γ)^{28}Si reaction at near barrier energies was found to proceed mainly via doorway transitions. Its consequences to the radiative capture cross-section is thus significant. This reaction has been performed by Harakeh *et al.* at $E^* = 34$ MeV [6] and compared to the ^{3}He+^{25}Mg entrance-channel to evaluate the importance of isospin mixing in the decay. The observed decay has been interpreted in terms of the decay of the GDR built on excited states of ^{28}Si. The authors used a large volume NaI(Tl) crystal to detect high energy γ-rays in an inclusive way. Novel technologies would allow to perform an inclusive experiment with detection of the fragments in a Si detector for example coupled to a state-of-the-art

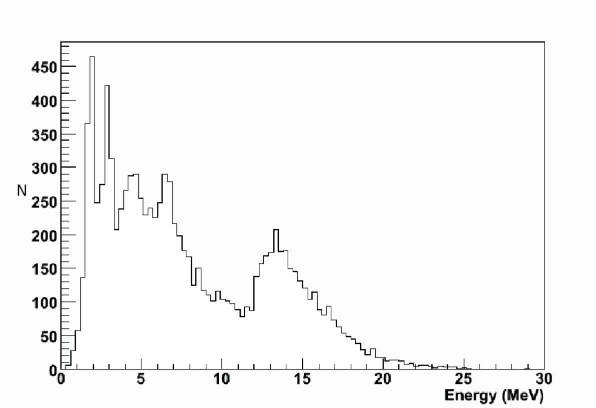

Fig. 2. Experimental $^{12}C(^{16}O,\gamma)^{28}Si$ γ spectrum recorded in the BGO array in coincidence with ^{28}Si recoils in the Dragon DSSSD focal plane detector.

γ array for detection of the coincident γ-rays. This could enable us to study the evolution of the feeding of doorway states to eventual feeding of the GDR.

Concerning the mechanism at lower energies, we have recently performed a $^{12}C(^{16}O,\gamma)^{28}Si$ experiment 15% below the barrier to reduce the NOC and to improve the ratio between radiative capture and fusion evaporation. Data is under analysis. It would, of course, also be interesting to study this reaction using a γ array with good resolution and efficiency over a wide range of energies (1–25 MeV), such as LaBr scintillator based project, at the horizon like the PARIS array associated to a spectrometer or used in a calorimeter mode (see contribution from D. Lebhertz *et al.* to this conference).

REFERENCES

[1] F. Haas, Y. Abe, *Phys. Rev. Lett.* **46**, 1667 (1981).

[2] T. Spillane *et al.*, *Phys. Rev. Lett.* **98**, 122501 (2007).

[3] C. Rolfs, W.S. Rodney, *Cauldrons in the Cosmos*, University of Chicago Press, Chicago 1988.

[4] Y. Suzuki, K.T. Hecht, *Nucl. Phys.* **A388**, 102 (1982).

[5] M.T. Collins *et al.*, *Phys. Rev. Lett.* **49**, 1553 (1982).

[6] M.N. Harakeh *et al.*, *Phys. Lett.* **B176**, 297 (1986).