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The ^{12}C(^{12}C,α)^{20}Ne and ^{12}C(^{12}C,p)^{23}Na reactions at the Gamow peak via the Trojan Horse Method

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Abstract

A measurement of the ^{12}C(^{14}N,α^{20}Ne)^{2}H and ^{12}C(^{14}N,p^{23}Na)^{2}H reactions has been performed at a ^{14}N beam energy of 30.0 MeV. The experiment aims to explore the extent to which contributing ^{24}Mg excited states can be populated in the quasi-free reaction off the deuteron in ^{14}N. In particular, the ^{24}Mg excitation region explored in the measurement plays a key role in stellar carbon burning whose cross section is commonly determined by extrapolating high-energy fusion data. From preliminary results, α and proton channels are clearly identified. In particular, ground and first excited states of ^{20}Ne and ^{23}Na play a major role.

1 Introduction

After more than four decades, carbon burning stands out as one of the most interesting subjects to study because of several reasons. ^{12}C $+^{12}$C is the sys-

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tem with more evidence for quasimolecular structure, derived mainly from excitation function measurements for many of the possible reaction channels [1–7]. The vast amount of data accumulated in this respect still awaits a sound and comprehensive theoretical model capable of explaining all the observed details.
Starting from intermediate mass stars (8-10 $M_\odot$) and up with more than 10 $M_\odot$, star evolution and nucleosynthesis is strongly influenced by the carbon fusion process [8]. Superbursts from accreting neutron stars are also important phenomena that have been related to carbon burning, for which accurate reaction rates are needed to constrain superburst models with neutron and strange stars [9]. The temperatures at which carbon burns range from 0.8 to 1.2 GK, corresponding to center-of-mass energies from 1 to 3 MeV. The Coulomb barrier height for the ^{12}C + ^{12}C system is around 6.3 MeV, much higher than the energies of interest. In that region, the cross section falls rapidly below one nanobarn. This is the reason why the measurement of the cross section at astrophysical energies remains a difficult task. The excitation energy of the compound nucleus ^{24}Mg is high enough to decay by particle emission. Alpha, proton and neutron are the dominant evaporation channels, leading respectively to ^{20}Ne, ^{23}Na and ^{23}Mg, which can also be produced in excited bound states. Below a center of mass energy E_{cm} of 2.5 MeV there is not enough energy to feed ^{23}Mg even in its ground state and α and p channel are the only relevant ones at low energies. Considerable efforts have been devoted to measure the ^{12}C + ^{12}C cross section at astrophysical energies, involving both, charged particle [11–13] and gamma ray spectroscopy [14–19]. Nevertheless, it has only been previously measured down to E_{cm} = 2.5 MeV, still at the beginning of the region of astrophysical interest. However, below E_{cm} = 3.0 MeV the reported cross sections disagree and are rather uncertain, because at these energies the presence of ^{1}H and ^{2}H contamination in the C targets hampered the measurement of the ^{12}C+^{12}C process both in particle and gamma ray studies. In a more recent study [20], the astrophysical S(E) factor exhibits new resonances at $E_{cm} \leq$ 3.0 MeV, in particular, a strong resonance at E_{cm} = 2.14 MeV, which lies at the high-energy tail of the Gamow peak. This resonance, if confirmed, would increase the present nonresonant reaction rate of the alpha channel by a factor of 5 near T = 0.8 GK. On the other hand, it has been proposed that a sub-barrier fusion hindrance effect might drastically reduce the reaction rate at astrophysical energies. As known, measurements at lower energies are extremely difficult. Moreover, in the present case the extrapolation procedure from current data to the ultra-low energies is complicated by the presence of possible resonant structures even in the low-energy part of the excitation

function. Thus, further measurements extending down to at least 1 MeV would be extremely important. In this paper, we are going to discuss the indirect study of the ^{12}C(^{12}C,α)^{20}Ne and ^{12}C(^{12}C,p)^{23}Na reactions via the Trojan Horse Method (THM) [21–23] applied to the ^{12}C(^{14}N,α^{20}Ne)^{2}H and ^{12}C(^{14}N,p^{23}Na)^{2}H three-body processes in the quasi-free (QF) kinematics regime, where ^{2}H from the ^{14}N TH nucleus is spectator to the ^{12}C + ^{12}C two-body processes. There is a number of works providing evidence of direct ^{12}C transfer in the ^{12}C(^{14}N,d)^{24}Mg* reaction at 30 MeV of beam energy and up [24, 25].

2 The Trojan Horse Method

The Trojan Horse Method (THM) [21–23] is a powerful indirect technique to determine the astrophysical factor for rearrangement reactions. It has already been applied several times to reactions of relevance for astrophysics ([26–35] and references therein). The purpose of the THM is to determine the cross section for the binary reaction (2 particles → 2 particles) $A+x \rightarrow C+c$, from the measured cross section for the TH reaction 2 particles → 3 particles $A+a \rightarrow C+c+s$ in the quasifree (QF) kinematics regime, where the "Trojan Horse" (TH) particle, $a = (x\,s)$, has a strong $(s\,x)$ cluster structure. The reaction $A+a \rightarrow C+c+s$ can proceed through different reaction mechanisms. The TH reaction mechanism, gives the dominant contribution to the cross section in a restricted region of the three-body phase space where the relative momentum of the fragments x and s, p_{sx}, fulfill the QF conditions. For a $x-s$ relative motion in s-wave, p_{sx} is zero in the QF conditions or small compared to the bound state $(s\,x)$ wave number as given below. Since the transferred particle x in the TH reaction $A+a \rightarrow C+c+s$ is virtual, its energy and momentum are not related by the on-energy-shell (OES) equation $E_x = k_x^2/(2\,m_x)$. The energy for the $A+a$ relative motion is chosen to be above the Coulomb barrier in such a way that the two body interaction can be considered as taking place inside the nuclear field, without experiencing either Coulomb suppression or electron screening effects. The $A+a$ relative motion is compensated for by the $x-s$ binding energy, determining the so called "quasi-free two-body energy" given by

$$E_{QF} = E_{Aa} - B_{x-s} \qquad (1)$$

where E_{Aa} represents the beam energy in the center-of-mass system and $B_{x\,s}$ is the binding energy for the $x-s$ system. In Eq.1, E$_{QF}$ is not changed varying the projectile energy. What is done is to keep the beam energy at a fixed value and to vary the relative momentum p_{sx} from its QF value to an upper limit given by $\kappa_{xs} = \sqrt{2\,\mu_{xs}\,B_{xs}}$ that represents the on-energy-shell (OES) $a = (x\,s)$ bound state wave number [36]. This upper limit is usually few tens of MeV/c. This little variation is linked to the $x - s$ inter-cluster motion inside a and it is taken on the p_s variable, the momentum of the spectator particle (in the laboratory system $\vec{p}_{xs} = \vec{p}_x = -\vec{p}_s$) and/or on its emission angle, both measured or easily reconstructed. This brings to the following formula:

$$E_{QF} = \frac{m_x}{m_x + m_A}\,E_A - \frac{p_s^2}{2\,\mu_{sB}} + \frac{\vec{p}_s \cdot \vec{p}_A}{m_x + m_A} - B_{x\,s}. \tag{2}$$

with μ_{sB} reduced mass of the $s - B$ system ($B = A + x = C + c$). Thus, the TH cross section can be used to determine the energy dependence of the astrophysical factor, $S(E)$, of the binary process, $A + x \rightarrow C + c$, down to zero relative kinetic energy of particles A and x without distortion due to electron screening [37]. The absolute value of $S(E)$ is obtained normalizing to direct measurements at higher energies. At low energies where electron screening becomes important, comparison of the THM astrophysical factor to the direct result provides a determination of the screening potential. The THM has been applied successfully to many direct and resonant processes, usually involving light particles as spectators, such as d, ^{3}He, ^{6}Li. Here, we address the first application of the THM to heavy ion reactions, using ^{14}N as spectator.

3 The experiment

The ^{12}C(^{14}N,α^{20}Ne)^{2}H and ^{12}C(^{14}N,p^{23}Na)^{2}H reactions were investigated at the Laboratori Nazionali del Sud - INFN, by using a ^{14}N beam at 30 MeV accelerated by the SMP TANDEM and delivered onto a 100 μg/cm^2 C target. Special care was taken in beam collimation in order to produce a beam spot on the target smaller than 1.5 mm. The experimental setups consisted of four telescopes (38 μm silicon detector as ΔE- and 1000 μm position sensitive detector (PSD) as E-detector) placed on both sides with respect to the beam direction in symmetric configuration (two on each side), covering angles from 7° to 30° and from 47° to 68°. We have detected the ejectile of the two-body reactions (either α or p) in coincidence with the spectator d particle. The heavy counterparts in the two-body reactions have quite low energy and, if detected, this would imply a high detection threshold. In order to fulfill the QF requirement for the spectator d particle to be essentially part of the beam, this particle was detected at forward angles. The trigger for the event acquisition was given by the coincidences between one of the two most forward telescopes and any one of the two telescopes on the opposite side with respect to the beam direction. The angular regions covered by the detectors were optimized for measuring the break-up process of interest in QF kinematics, and the investigated range of deuteron momentum values was feasible to check the existence of the QF mechanism.

4 Data analysis and preliminary results

Energy calibration of each PSD was performed by means of a standard eight-peak α source and data from elastic scattering of ^{14}N on ^{1,2}H at beam energies of about 13, 22 and 30 MeV. with an overall energy resolution of about 1.5%. Angular calibration was achieved by using grids with equally spaced slits placed in front of each PSD during preliminary runs of the experiment, with an angular resolution of about 0.3°. Several steps are involved in the data analysis before the two-body cross section of astrophysical relevance can be extracted. First, it is necessary to identify the events due to the three-body reactions of interest and select those experiencing the QF mechanism. Channel selection begins with the separation of the d and p/α locus in the ΔE-E 2D plot by means of graphical cuts. Selected events were then used to reconstruct the experimental Q-values.

If one considers a two-dimensional spectrum with a kinematical variable, such as the energy or the angle of any one of the involved particles as a function of the Q-value, coincidence events of interest should lie on a vertical line that cuts the Q-value axis at the expected value. Typical spectra for the present experiment are reported in Figs.1 (^{12}C(^{14}N,α^{20}Ne)^{2}H) and 2 ^{12}C(^{14}N,p^{23}Na)^{2}H where the deuteron detection angle is shown as a function of the Q-value. Two dominant sharp vertical lines show up in each figure, crossing the Q-value axis at about -5.7 and -7.3 MeV in Fig.1, corresponding to the ground and first excited state of ^{20}Ne, and at about -8 and -8.4 MeV in Fig.2, referring to the ground and first excited state of ^{22}Na. The spectra makes us confident of the quality of the calibration and of the possibility to identify the channels of interest. Events within these vertical region will be selected for further analysis.

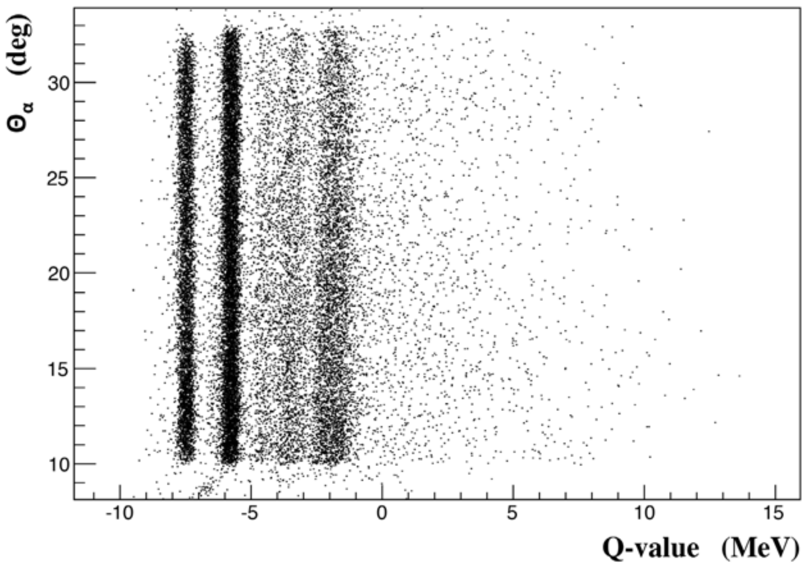

Figure 1: Two-dimensional spectrum showing the deuteron detection angle vs the Q-value. The sharp vertical regions at about -5.7 and -7.3 MeV of the Q-value, corresponds to the ground and first excited state of ^{20}Ne.

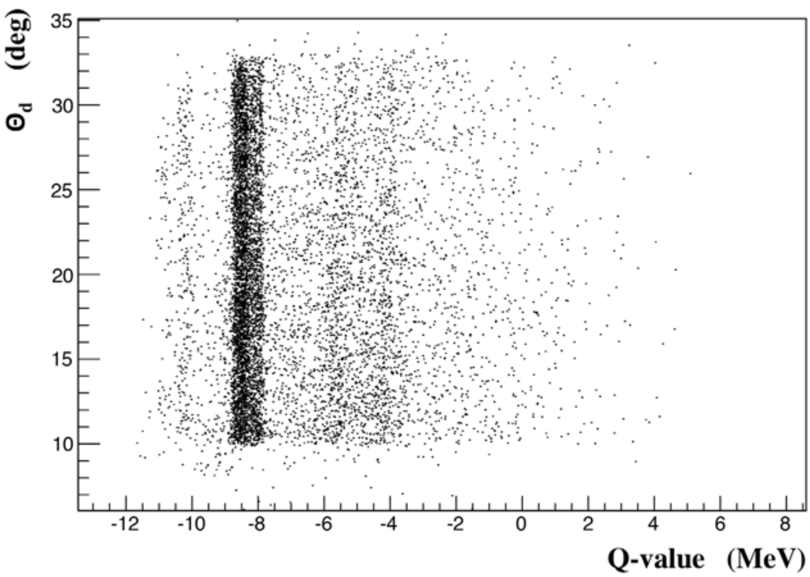

Figure 2: Two-dimensional spectrum showing the deuteron detection angle vs the Q-value. The sharp vertical regions at about -8 and -8.4 MeV of the Q-value, corresponds to the ground and first excited state of ^{22}Na.

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