Indirect study of the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the Trojan Horse Method applied to the $^{12}C(^{14}N,\alpha)^{20}Ne)^2H$ and $^{12}C(^{14}N,p)^{23}Na)^2H$ three-body reactions


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1. Introduction

This proposal aims at measuring the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the Trojan Horse Method (THM) applied to the $^{12}C(^{14}N,\alpha)^{20}Ne$ and $^{12}C(^{14}N,p)^{23}Na$ (H) three-body processes in the quasi-free (QF) kinematics regime, where $^2H$ from the $^{14}N$ TH nucleus is spectator. The astrophysical relevance of the $^{12}C+^{12}C$ fusion processes is described in a dedicated paragraph. This work is part of an experimental campaign involving several institutions and laboratories where the $^{12}C+^{12}C$ fusion processes are being studied using other TH nuclei, such as $^{16}O$ and $^{13}C$. In particular, a first run of the $^{16}O+^{12}C$ experiment has been performed at the Horia Hulubei Tandem Laboratory in Bucarest (Romania) where the requested beam time was fully allocated and another proposal with the $^{16}O$ TH nucleus is being submitted at the PAC Committee of the Instituto de Física, Universidade de São Paulo (Brasil). In this context the Catania group has a key role, being the leading expert on the THM. The THM is an indirect approach to determine the cross section of nuclear reactions at low-energy which very often are not accessible in direct experiments. The main advantage of this technique is that the THM delivers the so called bare nucleus astrophysical S(E) factor, free of Coulomb suppression and electron screening effect in the entrance channel. Both effects hamper the extraction of the low-energy cross section in direct experiments. By now, this method has been successfully applied to many reactions of astrophysical interest [1-9]. Joining the results of the THM experimental works on the $^{12}C+^{12}C$ interaction performed with different TH nuclei, will also provide a test of the pole invariance, namely of the independence of the $^{12}C+^{12}C$ two-body reaction amplitude on the chosen TH nucleus [9].

2. Astrophysical motivation

The $^{12}C+^{12}C$ fusion channel in the low energy region is of great interest in astrophysics [10] because of its critical role in studying a wide range of stellar burning scenarios in carbon-rich environments. Indeed, this reaction is important to understand the carbon-burning nucleosynthesis occurring in stars of more than 10 solar masses during their later evolutionary stages [11]; in intermediate mass stars (8-10 solar masses) which may lead to a detonation wave and a supernova explosion under electron degeneracy [12]; in binary systems, where a massive carbon-oxygen white dwarf overcomes the Chandrasekhar mass limit by accreting material from its companion star. This is another scenario where the electron degeneracy may detonate explosive carbon burning [13]; in superbursts from accreting neutron stars [14].

The carbon burning temperature ranges from 0.8 to 1.2 GK, corresponding to center-of-mass energies $E_{cm}$ from 1 to 2 MeV. A detailed knowledge of the carbon fusion processes is needed at those energies in order to shed light on all these scenarios and to put constraints on the models. Considerable efforts have been devoted to measure the $^{12}C+^{12}C$ cross section at astrophysical energies, involving both charged particle and gamma ray spectroscopy [15-17]. 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 $^1H$ and $^2H$ contamination in the C targets hampered the measurement of the $^{12}C+^{12}C$ process both in particle and gamma ray studies [15-17]. In a more recent study [18], the astrophysical S(E) factor exhibits new resonances at $E_{cm} < 3.0$ 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 increases 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 proposal we are going to discuss the indirect study of the $^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the Trojan Horse Method.
(THM) [9-17] 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 [19,20].

3. Experimental procedure

We plan to investigate a $^{12}$C + $^{12}$C relative energy region from 3.5 MeV down to 0.5 MeV, in order to span the Gamow peak together with an extended part at the higher energies where direct data already exist. In this way we can perform a validity test of the THM in the overlap region and check if $^{14}$N is a good TH nucleus.

To this aim we need a 30 MeV $^{14}$N beam with a spot size on target of about 1 mm and intensities of 1-2 pnA, impinging onto a 100 $\mu$g/cm$^2$ isotopically enriched $^{12}$C target. We choose appropriate kinematic conditions where the $^{12}$C+d binding energy (10.27 MeV) inside $^{14}$N compensates for the $^{14}$N+$^{12}$C relative motion. Thus, the $^{12}$C+$^{12}$C interaction takes place at $E_{QF} = (30 m_{^{12}C} \cdot m_{^{12}C} + m_{^{14}N}) \cdot 10.27$ MeV= 2.6 MeV. A cutoff in the deuteron momentum distribution of 60 MeV/c (due to the Fermi motion of the d particle inside $^{14}$N), fixes the requested 0.5 to 3.5 MeV range of $^{12}$C-$^{12}$C relative energies around $E_{QF}$. Since the $^{12}$C projectile is virtual (initially it is in the bound state of $^{14}$N), the Gamow factor does not appear in the $^{12}$C+$^{12}$C entrance channel of the binary processes, allowing to extract their cross sections down to the relevant energies without experiencing either the Coulomb suppression or the screening effects. Following theoretical approaches based on the Impulse Approximation (IA), the experimental three-body cross section is factorized in terms of the two-body cross section of interest, of the d momentum distribution inside $^{14}$N which is well known, and a kinematic factor [6-8]. Thus the relevant two-body cross section can be easily extracted.

If energy and angle of any two of the three outgoing particles are measured in coincidence, three body kinematic relations will allow us to completely identify the reaction channel. In particular we detect 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, their energy reconstruction would be affected by additional uncertainties such as that coming from energy straggling on target. In order to fulfill the QF requirement for the spectator d particle to be essentially part of the beam (to retain its initial momentum inside $^{14}$N), this particle has to be detected at forward angles. Its energy ranges from 2 to 8 MeV. The particle identification will be supplied by a silicon telescope, consisting of 20 $\mu$m silicon detector as $\Delta E$- and a 1000 $\mu$m Position Sensitive Detector (PSD) as E-stage. It will cover angles from 10° to 25°.

The other coincident particle (either α or p), whose energy ranges from 8 to 16 MeV (for the α) or from 4 to 8 MeV (for the proton), will be detected and identified close to the so called QF angles by means of two telescopes, each consisting of 20 $\mu$m silicon detector as $\Delta E$- and a 500 $\mu$m Position Sensitive Detector (PSD) as E-stage. They will cover angles from 10° to 60°, which include also a dead region between them of about 5° to 10°, due to their holders.

The selected angular regions correspond to a quite wide angular range for the two-body center of mass angle $\theta_{c.m.}$, which is shown in Figure 1 correlated to the $^{12}$C-$^{12}$C relative energy $E_{c.m.}$, as results from a Monte Carlo calculation.

4. Beam time request

A typical three-body cross section for reactions involving $^{14}$N break-up is, in the worst case, of the order of about 1 mbarn/sr$^2$ MeV and we can also empirically estimate a QF channel contribution.
Figure 1. Example of $^{12}\text{C}-^{12}\text{C}$ relative energy ($E_{\text{c.m.}}$) vs. two-body center of mass angle ($\theta_{\text{c.m.}}$) two-dimensional plot, resulting from a Monte Carlo calculation. The projected events correspond to a cutoff in momentum distribution for the spectator d particle of 60 MeV/c.

to this cross-section of as little as 10%. A $^{14}\text{N}$ beam intensity of 1-3 pnA impinging on a 100 $\mu$g/cm$^2$ C target would therefore yield about 0.1 cps for the selected phase space. In order to get a statistical error smaller than 5% for 10 keV bins, about 40000 events/MeV are required to get good statistics in the overall 0.5 - 3.5 MeV energy range. Therefore we require 42 BTU of beam time for the measurement itself (beam energy = 30MeV).

Including also 6 BTU of beam time for detector settings and calibration procedure, we ask for a total beam time of 48 BTU.

References