Study of the ^{12,13}C+^{64}Zn reactions dynamic at energy above the Coulomb barrier.

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Abstract

We propose to measure in coincidence alpha particles coming from the breakup of ^{12}C triggered by neutron transfer in the ^{13}C+^{64}Zn reaction at the incident energy of 42 MeV ($E_{c.m.} = 35.4$ MeV), above the Coulomb barrier ($V_C \sim 26$ MeV), beside the elastic scattering and inelastic excitation of projectile and target. The obtained results will shed some light on the understanding of the reaction dynamic induced by ^{13}C and characteristics of the triple alpha structure of ^{12}C, in particular the Hoyle state. Additionally, the results will be compared with experimental data using the same ^{64}Zn target, such as, ^{4,6}He ^{6,7}Li, ^{9,10,11}Be and ^{8}B.

Introduction

In medium-sized stars like our Sun, when the Hydrogen (H) fuses into Helium (He), their outer layers expand and their core contracts. During this internal contraction, the ^{4}He nuclei (alpha particles), each with two protons and two neutrons, experience a force that allows them to fuse, forming an atomic nucleus of four protons and four neutrons, the ^{8}Be. In a time of 10^{-16} s before the unstable ^{8}Be nucleus dissociates into two alpha particles, a third alpha particle can collide with ^{8}Be, fusing and forming an excited ^{12}C nucleus: the Hoyle state. The Hoyle state in the ^{12}C excited nucleus is the origin for carbon formation, in the stellar environment, and a key element for the existence of organic life. The existence of this state was initially theorized by the Fred Hoyle, in 1954 [1] and finally confirmed experimentally a few years later by Cook et al. [2].

The ^{12}C, in the ground state, has a lower energy, as it is not formed through the fusion of a nucleus of ^{4}He and a nucleus of ^{8}Be. To reach the stable configuration, a resonance must be present as an intermediate step. Therefore, the Hoyle state is a ^{12}C resonance formed by ^{4}He and ^{8}Be nuclei and an exotic ^{12}C state, with approximately 7.65 MeV, of extra energy, that takes place inside the stars. Therefore, the Hoyle state of the ^{12}C, in addition to playing a central role in nucleosynthesis and the existence of organic life, has a cluster structure, which is linked to the nature of the strong interaction and the abundance of ^{12}C itself. Thus, understanding the nature of the ^{12}C has the potential to unravel fundamental problems of nuclear forces, structure and reactions.

Motivation

The ^{13}C nucleus is a stable isotope of carbon, it has an excited state $1/2^+$ at 3.09 MeV and $3/2^-$ at 3.68 MeV and the neutron binding energy is 4.95 MeV, while ^{12}C has an excitated state 2^+ at 4.44 MeV and the excited state 0^+ at 7.65 MeV (the Hoyle state).

In 2018, exploratory measurements of ^{13}C impinging on ^{197}Au targets, at energies around the Coulomb barrier, were carried out at the TANDAR-CNEA laboratory. Results show a surprisingly high production of alpha particles, much higher than the one observed for ^{12}C.

Recently, in April 2023, the authors have measured the reactions ^{12,13}C on ^{120}Sn at the incident energy of 47 MeV at the Open Laboratory of Nuclear Physics (LAFN) - University of São Paulo (Brazil). Using an upgrade of the detection system STAR (Silicon Telescopes Array for low statistical Reactions), called STAR2, consisting of two 50x50 mm^2 silicon telescopes, each composed by a 20 μm thick SSSSD detector (vertical strips) as a ΔE followed by 300 μm thick SSSSD (horizontal strips) as a E_{res} detector, alpha particles coming from the reaction ^{13}C+^{120}Sn were measured in coincidence. As well as in exploratory measurements at the TANDAR, preliminary results show a high production of alpha particles, much higher than the one observed for ^{12}C. What reaction process produces this amount of alpha particles? The most reasonable explanation is that the presence of an extra neutron in ^{13}C nucleus favours, at certain energies, the transfer of 1 neutron to the target nucleus, followed by the fragmentation of residual ^{12}C, in different fragments, such as: $\alpha+$ ^{8}Be; $\alpha+\alpha+\alpha$. Both the production of ^{8}Be and the excitation of the residual ^{12}C could lead to the fragmentation of ^{12}C into 3 alpha particles. Both processes can compete, opening a wide research field.

In order to access the alpha structure of the Hoyle state of ^{12}C (7.65 MeV) and to understand the breakup mechanism of reactions induced by ^{13}C, we propose to decrease the Coulomb barrier of the system using a ^{64}Zn target from 37 MeV with ^{120}Sn to 26 MeV with ^{64}Z (in center of mass frame) and a ^{13}C beam at the incident energy of 42 MeV ($E_{c.m.}$ = 35.4 MeV).

Moreover, the experimental data will be useful for a systematic study of reactions induced by different stable, weakly bound and halo nuclei on the same ^{64}Zn target, ^{4,6}He [3, 4, 5], ^{6,7}Li [6, 7], ^{9,10,11}Be [8, 9] and ^{8}B [10].

Experimental setup

The measurements will be performed using the scattering chamber located at the beam line 30B. A self-supporting ^{64}Zn target, 880 μg/cm^2 thick, will be used in the experiment. The ^{12,13}C elastically and inelastically scattered (due to excitation of the projectile and target) and the different alpha fragments will be measured in coincidence by system STAR2, consisting of two 50x50 mm^2 silicon telescopes (ΔE-E), each composed by a 20 μm thick SSSSD detector (vertical strips) as a ΔE followed by 300 μm thick SSSSD (horizontal strips) as a E_{res} detector. An angular range from $\theta_{lab} \sim 97^\circ$ to 163° will be covered, see Fig. 1.

Additionally, four single silicon detectors will be positioned at forward angles in order to measure the elastic scattering and for normalization propose. The ratio of the solid angles will

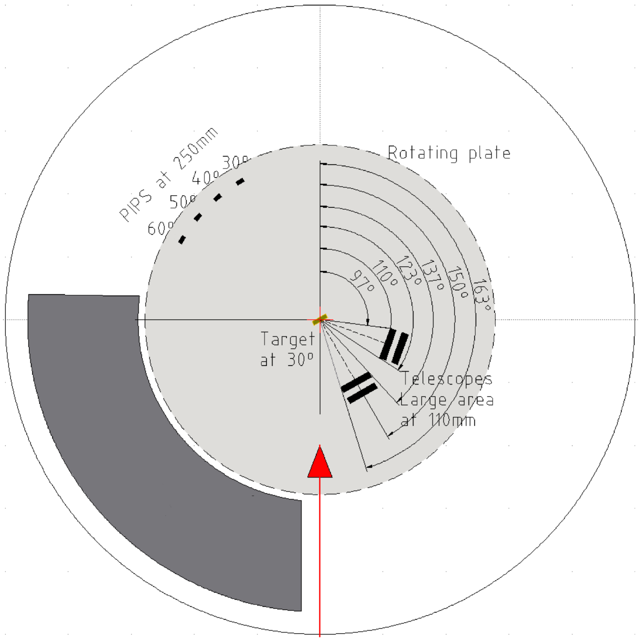

Figure 1: Sketch of the proposed experimental setup.

be determined by the Rutherford scattering of ^{12,13}C on a ^{197}Au target.

Beam time request

Considering the low statistic of alpha coincidence measurements, ^{12,13}C^{5+} ion beams, a terminal voltage of 7.0 MV (i.e. incident ^{12,13}C energy of 42 MeV) and an average intensity at the 30B beam line of 100nA, we ask three days (72h) for the reaction ^{13}C+^{64}Zn and one day for ^{12}C+^{64}Zn (in order to compare with the reaction induced by ^{13}C). For calibrations and solid angle normalization we ask for one more day. Thus, we ask 5 days in total.

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