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Low energy beam induced background studies for a $^{12}C(^{12}C,p)^{23}Na$ reaction cross section measurement

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The cross section of $^{12}C+^{12}C$ fusion reactions determines the conditions of carbon ignition in stars. The presence of structures, which are likely to extend to low energies, makes the extrapolation of data collected at high energy to the stellar energy difficult and potentially inaccurate, so a direct measurement is desirable. Here we report on an extremely improbable two-step background process which prohibits the measurement of the $^{12}C(^{12}C,p)^{23}Na$ carbon fusion reaction at low energies in the presence of deuterium contamination. It appears that with a modified setup and selected targets reliable measurements down to E_{cm}=2.0 MeV are possible.

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[1] Speaker

1. Introduction

The nuclear reactions commonly referred to as carbon burning, $^{12}C(^{12}C,\alpha)^{20}Ne$ Q= 4.62 MeV and $^{12}C(^{12}C,p)^{23}Na$ Q=2.24 MeV, have been studied extensively [1-8] at energies above E_{cm}=2.5 MeV either by γ-ray or particle spectroscopy. Recent target preparation advances [8] allowed for extension down to near energies of astrophysical interest, however the Gamow energy window (E_{cm}=1.5 ± 0.3 MeV) for stellar carbon burning has not yet been reached.

In general one of the largest experimental difficulties to overcome when measuring cross sections in the astrophysical regime is the presence of background. Beam induced background in particular originates from nuclear reactions between the beam and contaminants in the target and its intensity may vary during the course of the measurement. Thus, if an analysis can be made on the target that describes the contribution from each contaminant, then the background can be eliminated or subtracted. Ideally, identifying the contaminant and then choosing a target free of it, or reducing its concentration to negligible levels accomplishes this.

2. Experimental tests and analysis

An example of unlikely background radiation has been identified while measuring the $^{12}C(^{12}C,p)^{23}Na$ reaction well below the coulomb barrier with charged particle spectroscopy. In the experiment a high intensity beam (20-30 μA) of 2^+ carbon ions was produced by the 3 MV tandem accelerator CIRCE (Center for Isotopic Research on the Cultural and Environmental heritage) in Caserta (Italy). The beam bombards a carbon target of natural isotopic purity (thickness = 2mm) that is cooled to avoid target heating and deterioration. Protons from the $^{12}C(^{12}C,p)^{23}Na$ reaction are detected at backward angles (135° relative to the beam) by two particle detector telescopes. The telescopes consist of a thin (25μm) ΔE silicon detector and a thick E silicon detector of 300mm active area. The ΔE-E telescope serves for both particle identification (through energy loss) and cosmic ray veto (by a coincidence technique). Thus the only significant contribution to background arises from protons originating from the target and having the same energy as the carbon fusion protons. At low energies the carbon fusion protons produced by transitions directly to the ground state of the residual nucleus (p0) or the first excited state (p1) account for most of the total fusion cross section as contributions from higher lying states in ^{23}Na are negligible [5]. The carbon fusion protons for p0 and p1 are grouped close to each other and are in the same region of interest (ROI) in the ΔE-E matrix due to the small energy difference between the two states.

Due to the ease of forming bonds with carbon, hydrogen and deuterium are naturally found in carbon targets or are continually deposited on the surface from the vacuum rest gas during measurements. At backward angles it is kinematically impossible to find protons in the carbon fusion ROI from nuclear reactions of ^{12}C with ^{1}H or ^{2}H: The $^{1}H(^{12}C,p)^{12}C$ reaction will not produce protons at backwards angles, while the $^{2}H(^{12}C,p)^{13}C$ reaction produces protons with significantly lower energies than the carbon ROI. Therefore contributions to the matrix from ^{1}H are nonexistent, and those from ^{2}H should be well separated from the ROI.

Unfortunately a two-step process (Fig. 1) is possible in the presence of deuterium. When deuterium is elastically scattered by carbon at forward angles followed by the $^{12}C(d,p)^{13}C$ reaction in the target, the kinematics allow protons to be produced directly in the relevant ROI. One may expect that the yield from this two-step process would form a continuum in the proton energies formed from the reaction of the scattered deuterium with the carbon matrix because the initial step, Rutherford scattering, forms a continuum of scattered deuterium energies for a given incident beam energy (Fig. 2). The nuclear reaction products from the subsequent second step will have energies governed by the deuteron energy as well as the ejectile angle. Consequently this should lead to a continuous distribution of ejectile energies. However, this is only true in

the case of a non-structured reaction cross section. In fact the two-step protons are grouped in energy where the carbon fusion ROI is located making them impossible to separate and very difficult to identify. The reason for this grouping becomes evident from Figure 2 where the $^{12}C(d,p)^{13}C$ cross section is shown (lower curve) [9]. A resonance is observed near 1.2 MeV and therefore elastically scattered deuterons with this particular energy have a higher probability for the second step, i.e. the $^{12}C(d,p)^{13}C$ reaction. Since the energy of the proton ejectile is strongly dependent on the incident deuteron energy the ejectiles are grouped in energy according to this resonance.

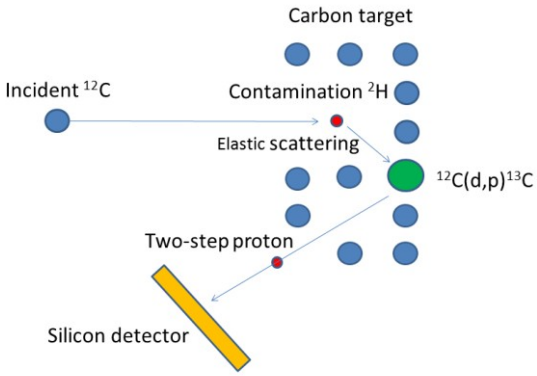

Figure 1 – Schematic of the two-step process where deuterium nuclei contained within the target are elastically scattered at forward angles by incident carbon nuclei and then impinge upon carbon within the target where a nuclear reaction takes place.

The effect of the two-step process on the proton yield is shown in Fig. 3 by the convolution of the two individual steps for a range of energies. The observed yield is the integral of each curve, e.g. the thick-target yield [10]. As the carbon beam energy decreases the scattered deuterons no longer attain the resonance energy kinematically. The integrated two-step proton yield decreases drastically and the resulting thick-target yield mimics a resonance-like structure in the reaction of interest (Fig. 4). Note that resonances appear as steps in a thick-target yield.

Thus it is of great importance to find targets with minimal exposure, as well as low intrinsic contamination, to hydrogen isotopes. Furthermore, the rest gas must be monitored and controlled to reduce hydrogen isotope contamination. Figure 4 shows thick-target yields for two levels of deuterium contamination. The 99.95% (quoted purity) target has two large apparent resonance-like structures (3 MeV and 4 MeV) caused by the two-step process. The 99.999% (quoted purity) target shows an increase in yield by a factor 10 below 6 MeV that is also caused by the two-step process.

The deuterium concentration, however, is probably not a constant parameter and may fluctuate with time due to target erosion, inhomogeneity or diffusion of deuterium within the target, and rest gas deposition of deuterium onto the target. Furthermore, due to exposure to the atmosphere and vacuum rest gas the absolute elimination of deuterium within a target is extremely difficult. Therefore, periodic analysis of deuterium concentrations is necessary for accurate background subtraction. Fortunately a method exists through scattering the target deuterium with an ion species other than ^{12}C. This may be accomplished simply by bombarding the target with an oxygen beam directly after a low energy carbon measurement and scaling the oxygen beam yield for two-step contribution. Since the contribution can be measured directly with an oxygen beam without the need for breaking vacuum, this is a reliable monitoring

method. This procedure has been tested with the target of highest deuterium contamination (99.999% quoted purity) and the oxygen beam yield is shown in Figure 4.

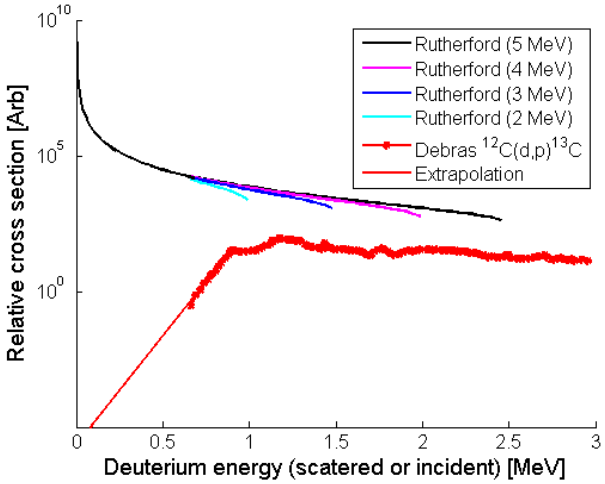

Figure 2 – Shown are Rutherford scattering cross sections (smooth solid lines) for deuterons being scattered at forward angles by incident carbon of 2, 3, 4, and 5 MeV as well as the measured cross section of the d(^{12}C,p)^{13}C fusion reaction (lower curve) and its extrapolation to low energy.

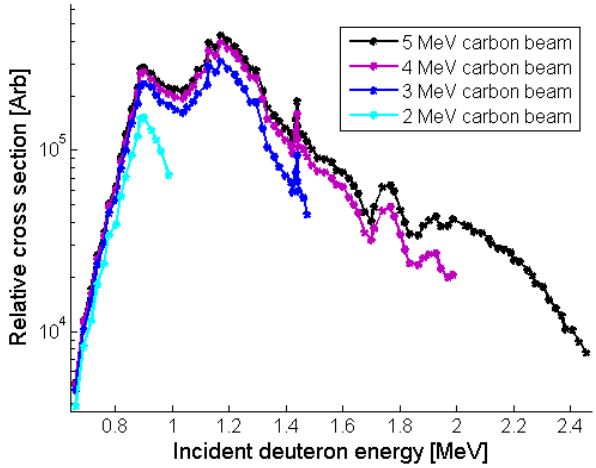

Figure 3 – A detail of the convolution peak region, the peak is responsible for the grouping of two-step protons in energy. The plot shows that as the beam energy is decreased the area of highest probability of the two-step reaction vanishes, thus the two-step yield drops with decreasing energy.

After improvements in the vacuum alone did not show sufficient reductions in deuterium levels it was concluded that the deuterium was intrinsic to the targets. We obtained a highly ordered pyrolytic graphite (HOPG) target which has been studied by [11] and shown to have hydrogen contamination levels on the order of 0.3 ppm. With natural abundances of hydrogen isotopes, one can expect deuterium levels on the order of 0.005 ppb within the target. This reduction in the deuterium levels, combined with our other improvements, may allow for measurement extensions to 4 MeV (E_{cm}=2 MeV) and below.

3. Summary

The two-step process involving scattered target contaminants incident upon other target nuclei is a process that is important when measured cross sections fall to levels of astrophysical interest. It also shows the importance of monitoring all target contaminants, especially those

less massive than the nucleus of interest. In order to push the carbon measurement to lower energies the abundance of deuterium will need to be decreased. Furthermore, future experiments should be aware of this type of beam-induced background to ensure reliable data.

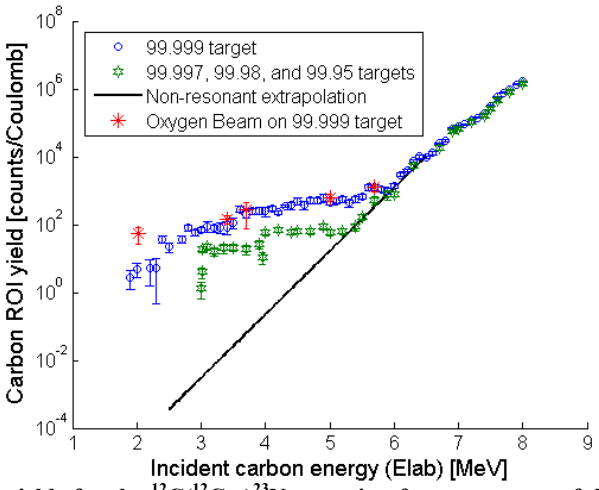

Figure 4 – Carbon ROI yields for the $^{12}C(^{12}C,p)^{23}Na$ reaction for two targets of different deuterium levels as well as an extrapolated non-resonant thick target yield to low energies. The plotted oxygen beam data coincide in center of mass energy with the plotted carbon data in the beam-deuterium center of mass system. Similar yields are found with both beams confirming the two-step hypothesis.

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