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Determination of Astrophysical Thermonuclear Rates with a Bubble Chamber: The $^{12}C(\alpha,\gamma)^{16}O$ Reaction Case

B. DiGiovine*, J. Grames†, D. Henderson*, R. J. Holt*, D. Meekins†, M. Poelker†, K. E. Rehm*, A. Robinson**, A. Sonnenschein‡, R. Suleiman† and C. Ugalde**,§

*Argonne National Laboratory, Argonne IL 60439, USA
†Jefferson Lab, Newport News, VA 23606, USA
**University of Chicago, Chicago, IL 60637, USA
‡Fermilab, Batavia, IL 60510, USA
§email: cugalde@uchicago.edu

Abstract. The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate is considered one of the most important unknown parameters in the physics of structure and evolution of massive stars. While extensive experimental campaigns have been performed trying to improve the quality of the measurements, the rate still holds very large uncertainties. Here we discuss a new experimantal scheme to measure the cross section of this reaction with a bubble chamber and a bremsstrahlung beam. The main advantage of the technique is a gain in the luminosity of several orders of magnitude when compared to other ongoing experiments.

Keywords: Nuclear astrophysics, liquid target, bubble chamber, gamma ray beam, photodisintegration, 12C(a,g)16O
PACS: 26.20.-f

INTRODUCTION

Thermonuclear burning in stars is responsible for the synthesis of most of the chemical elements heavier than helium in the universe. Stars with a mass above 0.8 $M_\odot$ will evolve through core helium burning towards the end of their lifetime. This phase involves the formation of ^{12}C by the Salpeter process [1], in which three α-particles fuse sequentially in a two-step capture: first, two of them form the very unstable nucleus ^{8}Be, which in spite of its short lifetime, will be able to capture a third α-particle. This process occurs at conditions in which the stellar core is in an electron-degenerate state, so small temperature variations cannot be compensated by pressure changes. This makes the temperature rise very quickly to 0.12 billion K and as the Salpeter process has a rate with a very steep temperature dependence, the burning becomes violent and the helium core is ignited. The triple α-particle reaction proceeds through the $J^\pi=0^+$, E_x=7.65 MeV excited state in ^{12}C [2], the so called "Hoyle" state. At slightly higher temperatures, the $^{12}C(\alpha,\gamma)^{16}O$ reaction is activated and both processes compete with each other in setting the abundance of carbon in the stellar core. Further α-particle capture processes at these burning temperatures are blocked by the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction, which is suppressed because of parity conservation rules. Therefore, the $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction is resposible for defining the ratio of carbon to oxygen (two of the most important constituents of organic matter and life) in the stellar cores, and as a result, in the universe.

The abundance of most of the chemical elements is also affected by the $^{12}C(\alpha,\gamma)^{16}O$ reaction in one way or another. For example, such is the case of the α nuclei, which are some of the most common species in the universe after hydrogen and helium. These nuclei belong to the chain of even-even nuclei with the same number of protons and neutrons ranging from ^{16}O up to ^{56}Ni, which is unstable and decays to form the abundant ^{56}Fe. Neutron capture elements ranging from iron to zirconium (weak s-process elements) are also affected by the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate: a change in this rate within the current experimental uncertainties may change the nucleosynthesis yields by more than a factor of 2 [3]. The carbon to oxygen ratio, which is set by the $^{12}C(\alpha,\gamma)^{16}O$ reaction also has extreme consequences in the structure and evolution of late stellar burning stages and explosive scenarios. For example, the minimum main sequence stellar mass required to form a core collapse supernova depends on the core mass, which is determined by this reaction rate as well. In a similar way, hypernovae, collapsars, magnetars and their connection with gamma ray bursts depends on the core mass as determined by the $^{12}C(\alpha,\gamma)^{16}O$ at helium burning of the progenitors [4].

The $^{12}C(\alpha,\gamma)^{16}O$ reaction also has cosmological implications. Thermonuclear supernovae have been used as "standard candles" to determine the distance to galaxies and the rate of expansion (Hubble constant) of the universe [5]. It

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is thought that calibrated light curves of SNIa have consistent shapes, luminosity, and spectra that could be modeled if the C/O ratio in the progenitor is known. One of the leading Type Ia supernovae models is the combustion of a white dwarf in a degenerate state. Either from accretion from an evolved companion star or by merging with another white dwarf, a thermonuclear supernova will yield most of its mass as ^{56}Ni, the nucleus at the top for the α chain. The luminosity of the event is determined by the amount of ^{56}Ni produced, which decays sequentially to ^{56}Co and then to ^{56}Fe. It is the ^{56}Ni to ^{56}Co β-decay that determines the shape of the light curve observed after the explosion. The shape of the curve correlates very strongly with the luminosity of the event, so in spite of having "non standard" luminosities, these cosmological "standard" candles can be corrected to some degree to represent consistent distance indicators. Nevertheless, within the experimental error bars of the rate for the ^{12}C(α,γ)^{16}O reaction, the amount of ^{56}Ni produced in these events can vary up to 10%, affecting the cosmological distance determination as a result[6].

PREVIOUS EXPERIMENTAL APPROACHES

The ^{12}C(α,γ)^{16}O reaction has been studied from a large variety of perspectives, both theoretical and experimental. The obvious experiment, which involves the detection of γ-rays from a beam impinging on a ^{12}C target, was performed for the first time by Larson *et al.* at Caltech in 1964 [7]. This experiment suffered from neutrons produced by the ^{13}C(α,n)^{16}O reaction from ^{13}C present in the target as a contaminant. More recent versions of this technique have always been limited by the same problem. Inverse kinematics experiments (a ^{12}C beam on a ^{4}He target) have been able to improve the situation as beam selection by mass with bending magnets can reduce ^{13}C contamination by several orders of magnitude. However, this technique requires a windowless gas target as foils exposed to beams tend to build-up carbon on their surfaces, and they also straggle (or stop) the heavy ion beam. On the other hand, windowless gas targets suffer from low density. It is the small number of target nuclei that has limited the capabilities of this technique.

Other experiments have approached the background reduction problem by detecting the γ-rays in coincidence with the ^{16}O nuclei. However, these methods usually have had very poor detection efficiency. Also, the detection of the ^{16}O recoils by selecting them from the beam particles has been done with mass separators. In this case, in order to maximize the detection efficiency, inverse kinematics needs to be used to focus the recoil particle in the forward direction into the mass separator. Again, this requires helium gas targets that have a very low density of nuclei. Experiments which also provide information relevant to ^{12}C(α,γ)^{16}O but still depend heavily on direct measurements include transfer reactions, β-delayed α decay of ^{16}N, and elastic scattering of α+^{12}C.

Measuring the cross section for this reaction at astrophysically relevant energies is not a simple task. Today, the most sensitive experiment [8] has been able to reach a 1×10^{-11} barn level, while the cross section in the Gamow window region is of the order of 1×10^{-17} barn. Similar to the Larson et al. technique discussed above, this experiment measured the γ-ray yield from an α-particle beam impinging on a ^{12}C target. This measurement was completed more than a decade ago, and for new experiments using these techniques, improvements are usually very small. This indicates that we have reached the limit of our capabilities for measuring this reaction with these techniques. Therefore, it is very important that new alternate experimental schemes are explored.

THE NEW APPROACH

Other possible methods for studying the ^{12}C(α,γ)^{16}O reaction include the irradiation of ^{16}O with a γ-ray beam. As both the strong and the electromagnetic interactions involved in the (α,γ) process are symmetric under time reversal, the forward and its reverse (γ,α) reaction share the same matrix elements and their cross sections can be related by the principle of detailed balance [9]. A very useful advantage of this fact is that there is a gain of almost two orders of magnitude in the cross section when measuring ^{16}O(γ,α)^{12}C instead of the (α,γ) process.

A model independent, direct method of measuring the (γ,α) cross section is to irradiate an oxygen target with a γ-ray beam. The new approach we have chosen uses a beam of real photons produced either by bremsstrahlung or by inverse Compton scattering. Alternate beam options would be virtual photons produced by electron inelastic scattering of the sample or by Coulomb dissociation. It is very important to keep in mind that the cross section being measured is extremely small, so both the beam intensity and the number of target nuclei need to be maximized. In this sense, gases containing oxygen will suffer from the small number of target nuclei. On the other hand, examples of dense targets would be solid and liquid materials. One technical difficulty of using thick and dense targets is that reaction products remain trapped in the target, so they cannot be detected outside of it unless the photodisintegration event occurs in a very thin layer near the surface. The solution is to turn the target into the detector itself (active target). A possible liquid

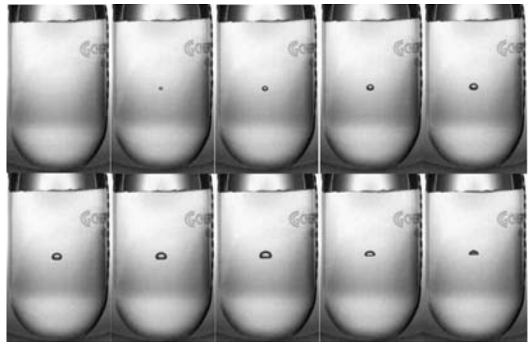

FIGURE 1. Bubble chamber photograph sequence of a photodisintegration event registered by a 100 Hz video camera. The whole set spans 0.1 s, at equally spaced time intervals. Bubble detection is triggered by a computer comparing the first two pictures in the sequence. Later on, at about 60 ms, the pneumatic system responds by quenching the bubble until it disappears, about another 100 ms later.

^{16}O active target would use, for example, the property of all liquids to nucleate (form bubbles) when superheated and exposed radiation. This property is the principle of operation of bubble chambers[10].

In our version of the bubble chamber, the liquid is contained in a transparent glass vessel. In order to superheat the liquid, it is pressurized, heated above the boiling temperature and then depressurized. When the pressure is reduced, the liquid enters a metastable state in which vaporization may be induced by small perturbations. As the beam of γ-rays enters the vessel, nuclei in the liquid are photodisintegrated if the energy is above the Q-value of the reaction. The reaction products move in the liquid and for the small γ-ray energies of interest to the astrophysical scenario, will deposit all their energy inside the liquid inducing vaporization and forming tiny bubbles. When the amount of thermal energy (superheat) in the liquid is high enough, the bubbles will grow unstopped to a macroscopic size. A fast video camera monitors the liquid for the appearance of bubbles at 10 ms intervals (see figure 1). When a bubble is detected, it is immediatly quenched by a pneumatic system. Failure to promptly compress the bubble will result in the runaway of the whole volume of the superheated liquid into a gas.

The metastable state of the superheated liquid can be maintained for time periods up to hours. In an experiment where very small count rates are expected, such as the $^{16}O(\gamma,\alpha)^{12}C$ measurement, it is very important that the detector remains active for the longest time possible. In practice this can be achieved by shielding it from cosmic rays, by making sure the liquid is free of dust particles that could induce bubble formation, by removal of sharp edges or rough surfaces that are in contact with the sensitive liquid, and by the right selection of the amount of superheat available for nucleation. In preliminary tests we have been able to achieve active detection times well over 99% of the time.

We have tested several liquids as active materials in the bubble chamber: two fluorine containing liquids and three oxygen liquids. The fluorine liquids were the refrigerants CH_2FCF_3 and C_4F_{10}, while the oxygen cases were N_2O, CO_2, and H_2O. The two refrigerants superheat at ambient temperatures and pressures, and from the engineering point of view, they make excellent choices for prototyping the detector. They also were useful for establishing proof of principle of the technique [11] by measuring an excitation function of the $^{19}F(\gamma,\alpha)^{15}N$ with a narrow bandwidth γ-ray beam produced by inverse Compton scattering at Duke University's HIγS facility.

More recently, we irradiated with γ-ray beam the oxygen containing liquids N_2O and CO_2 using the same beam facility. In these experiments we successfully tested the suppression of background coming from photodisintegration reactions of nuclei different from ^{16}O in the target. This could be done by selecting the right amount of superheat (pressure and temperature) conditions in the liquid.

An alternate method for producing γ-rays from electron beams is the bremsstrahlung technique. This experimental program will be performed at Jefferson Lab and will include the irradiation of a thin copper film with electrons produced by the beam injector. The electrons will lose energy going through the film and will produce bremsstrahlung photon radiation. Down the beamline, before hitting the detector, electrons will be bent from their path by a sweeper magnet (see figure 2). This measurement technique will require deconvolution [12] of the continuous spectrum of γ-rays used to irradiate the target from the excitation function of the $^{16}O(\gamma,\alpha)^{12}C$ reaction. The equipment required for these experiments is currently under construction and should help improving the longstanding situation of the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section.

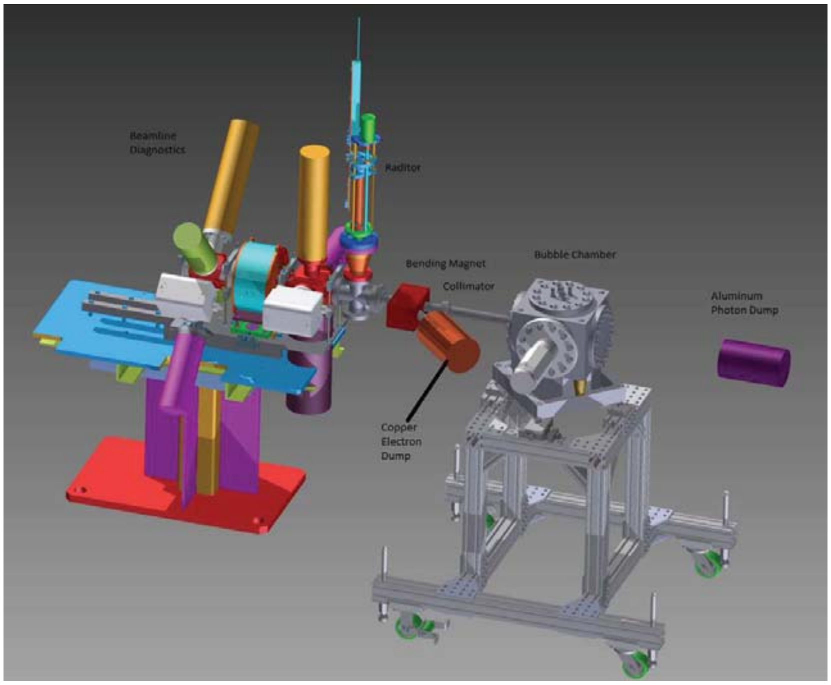

FIGURE 2. Bubble chamber setup for the bremsstrahlung beam technique.

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