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First determination of an astrophysical cross section with a bubble chamber: The $^{15}N(\alpha,\gamma)^{19}F$ reaction

C. Ugalde [a,*], B. DiGiovine [b], D. Henderson [b], R.J. Holt [b], K.E. Rehm [b], A. Sonnenschein [c], A. Robinson [d], R. Raut [e,f,1], G. Rusev [e,f,2], A.P. Tonchev [e,f,3]

[a] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[b] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[d] Department of Physics, University of Chicago, Chicago, IL 60637, USA
[e] Department of Physics, Duke University, Durham, NC 27708, USA
[f] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA

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ABSTRACT

We have devised a technique for measuring some of the most important nuclear reactions in stars which we expect to provide considerable improvement over previous experiments. Adapting ideas from dark matter search experiments with bubble chambers, we have found that a superheated liquid is sensitive to recoils produced from γ rays photodisintegrating the nuclei of the liquid. The main advantage of the new target-detector system is a gain in yield of six orders of magnitude over conventional gas targets due to the higher mass density of liquids. Also, the detector is practically insensitive to the γ-ray beam itself, thus allowing it to detect only the products of the nuclear reaction of interest. The first set of tests of a superheated target with a narrow bandwidth γ-ray beam was completed and the results demonstrate the feasibility of the scheme. The new data are successfully described by an R-matrix model using published resonance parameters. With the increase in luminosity of the next generation γ-ray beam facilities, the measurement of thermonuclear rates in the stellar Gamow window would become possible.

1. Introduction

Thermonuclear burning in stars is responsible for the synthesis of most of the chemical elements heavier than lithium in the universe. This is a highly temperature dependent process in which progressively heavier nuclei are produced as the increasingly strong Coulomb barrier is overcome at higher and higher temperatures.

The determination of the reaction rates of some relevant nuclear processes is one of the leading problems in stellar structure, evolution, and nucleosynthesis [1], with experimentally measured values always preferred over theoretical predictions. However, since experiments at astrophysical energies involve minute cross sections and thin targets, most current determinations of reaction rates are performed by combinations of experiment and theory to various degrees. Here, we describe a novel technique using thick liquid targets that will be useful for measuring some of the most important nuclear reactions at energies relevant for stellar environments. The sensitivity of this technique is six orders of magnitude higher than that of some of the most sensitive direct measurements performed to date.

2. Method

The new method is based on two principles: the reciprocity theorem for nuclear reactions, which relates the cross sections of forward and time-inverse nuclear processes; and the ability of a superheated liquid to induce nucleation when exposed to radiation [2]. Reciprocity allows one to deduce the cross section σ_A for particle capture (X,γ) processes to the ground state by measuring the cross section σ_B for photodisintegration (γ,X) reactions, i.e.

$$\omega_A\frac{\sigma_A(X,\gamma)}{\lambda\!\!\!^{-}{}_\alpha^2}=\omega_B\frac{\sigma_B(\gamma,X)}{\lambda\!\!\!^{-}{}_\beta^2}, \quad (1)$$

where X is the captured particle, $\lambda\!\!\!^{-}_\alpha$ and $\lambda\!\!\!^{-}_\beta$ are the channel wavelengths for capture and photodisintegration, and ω_A and ω_B are

* Corresponding author.
[1] Present address: UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata, India.
[2] Present address: Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
[3] Present address: Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

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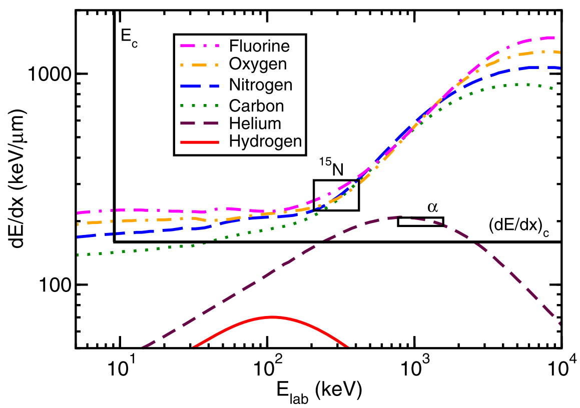

Fig. 1. (Color online.) Nucleation thresholds for liquid C_4F_{10} at $P = 150$ kPa and $T = 310$ K. The curves are the stopping powers of the most abundant ions present in the liquid. The acceptance window is delimited by the black solid lines. The horizontal black line is the stopping power threshold $(dE/dx)_c$ and the vertical black line is energy threshold E_c. Particles above $(dE/dx)_c$ and to the right of E_c will induce nucleation while others remain undetected. The small black boxes represent some of the relevant energy and stopping power combinations for ions from $^{19}F(\gamma,\alpha)^{15}N$ at γ-ray energies between 5.0 and 6.0 MeV.

their respective spin factors. In the energy regimes discussed here, the transformation factor can provide a gain of over two orders of magnitude in cross section. The advantage of this principle has been used widely in the past in Coulomb dissociation experiments [3].

Capture reactions such as (α,γ), (p,γ), and (n,γ), are responsible for many nucleosynthetic processes occurring in stellar environments. If the reaction product of the (X,γ) process is a stable isotope then it can be studied experimentally by photodisintegration if a suitable target of the reaction product can be produced. For example, the $^{12}C(\alpha,\gamma)^{16}O$ and $^{15}N(\alpha,\gamma)^{19}F$ reactions can be studied via photodisintegration with $^{16}O(\gamma,\alpha)^{12}C$ [4] and $^{19}F(\gamma,\alpha)^{15}N$ using targets of oxygen or fluorine containing compounds, respectively. When nuclei are photodisintegrated, the residual particles acquire an energy equal to the photon energy minus the Q-value of the reaction. A limitation of the method is that it is not sensitive to capture into excited states of the residual nuclei.

In the case of the experiments discussed here, the residual particles were detected with a bubble chamber. Originally invented for particle physics experiments, superheated liquid detectors have recently found new applications in several dark matter searches [5–7]. Here, we describe the first application of such a detector for low count rate experiments in nuclear astrophysics.

A particle moving in a liquid deposits energy along its track until it stops. If enough energy is deposited in a short distance, the liquid will be vaporized and a critical size bubble will be formed. Bubbles larger than a critical size will grow uncontrolled and will become visible. The threshold conditions for forming visible bubbles are functions of the degree of superheat of the liquid. Therefore, it is possible to tune the sensitivity of the detector to reject some minimum ionizing particles, while making it sensitive to heavy ions. Also, such a detector is insensitive to a γ-ray beam at least at a level of one part in 1×10^9 [7].

Fig. 1 provides an example of stopping power curves for ions in liquid C_4F_{10} [8]. Electrons, neutrons, and γ rays do not deposit energy that can trigger the bubble chamber directly. However, these particles may transfer their momentum to other ions by scattering interactions. In that sense, while insensitive to neutrons, bubble chambers can be triggered by them when they elastically scatter from nuclei in the superheated liquid. Neutrons are very useful in the calibration of the detection thresholds. However, they are also unwanted sources of background. The dE/dx threshold condition for C_4F_{10} is very sharp, with a transition slope from no nucleation to full nucleation of only a few keV/µm, reaching a full nucleation efficiency of 100% [5].

The selection of the liquid to be used in the bubble chamber depends on several factors. Foremost, the molecular content of target isotopes whose photodisintegration cross section needs to be determined has to be maximized. Other isotopes present in the molecule of the liquid may be sources of background unless reactions involving them have Q-values above the γ-ray beam energy. Ideally, pure targets are desirable. However, even in very pure liquids, trace contaminants always exist, or the operating pressure and temperature conditions of the pure target in liquid form may be too extreme to work in a practical device. This is why, usually, the liquid of choice consists of more than one isotopic species. In principle, all liquids should nucleate in bubble chambers [9]. It is a matter of convenience to select materials that are liquid at normal pressure and temperature conditions. Transparent liquids are also a convenient choice as optical imaging techniques can be applied to detect the bubble events and trigger the pressure system that stops bubble growth and vaporization of the entire liquid volume.

3. Experiment

For a proof of principle experiment we selected the $^{15}N(\alpha,\gamma)$-^{19}F reaction studied via the time inverse $^{19}F(\gamma,\alpha)^{15}N$ process. This process is the last link in the thermonuclear reaction chain leading to the nucleosynthesis of fluorine in Asymptotic Giant Branch (AGB) and Wolf–Rayet stars [10]. The choice of reaction to study was determined by the existence of a strong $J^\pi = 1/2^+$ resonance in ^{19}F at $E_x = 5.337$ MeV, which has been measured in direct (α,γ) experiments. C_4F_{10} was chosen as the fluorine containing liquid as it becomes superheated at room temperature and pressure.

Background reactions such as $^{19}F(\gamma,p)^{18}O$ or $^{12}C(\gamma,2\alpha)\alpha$ are energetically forbidden in the energy range $E_\gamma = 5$–6 MeV. Two-step processes like $^{13}C(\gamma,n)^{12}C$ followed by elastic scattering of the resulting neutron are suppressed by the low abundance of ^{13}C and by the small cross sections of the (γ,n) reactions at energies close to the threshold ($E_\gamma = 4.946$ MeV).

The C_4F_{10} liquid was contained in a cylindrical glass vessel with a length of 10.2 cm and an outer diameter of 3.8 cm. The length of the liquid target irradiated by the beam was determined to be 3.0 ± 0.1 cm. The uncertainty was mainly determined by the position of the γ-ray beam with respect to the center of the target. This effect contributed a 3% systematic error in the determination of the measured cross sections.

Pictures of the superheated liquid were taken at 10 ms intervals by two CCD cameras mounted at 90° relative to each other. The images were analyzed in real time by a computer and when a bubble was detected, the pressure in the glass vessel was increased within 40 ms of bubble formation from 160 to 900 kPa. This led to a quenching of the growing bubble thus preventing a boiling runaway of the liquid. The size of the bubbles was typically 1 to 2 mm and their location could be determined to a precision better than 1 mm.

The bubble chamber was exposed to γ rays produced at the HIγS facility at Duke University [11]. The narrow bandwidth photon beam was generated by intracavity Compton backscattering of free-electron-laser light from high-energy electron beam bunches. The photon beam was collimated with a series of three, 10 cm long, copper cylinders that had a 1 cm circular hole and were aligned at 0° with respect to the electron beam axis. The first collimator was located 52.8 m downstream from the collision point. We operated the storage ring in an asymmetric two-bunch mode

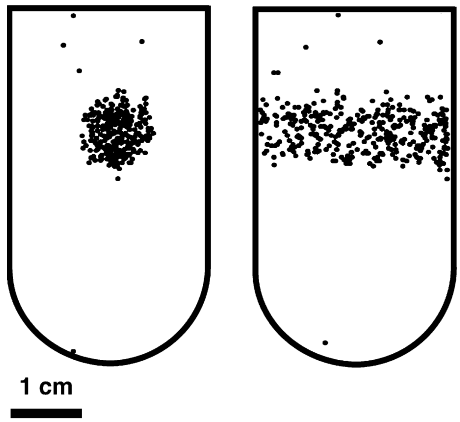

Fig. 2. Position of nucleation events parallel (left panel) and perpendicular (right panel) to the direction of the γ-ray beam as reconstructed from pictures taken by two cameras placed at 45° relative to the γ-ray beam direction. The cameras were positioned forming a 90° angle between them. The beam intensity was 5.7×10^3 γ/s and shown are events integrated over a period of 1 hour. Bubbles outside of the beam region correspond to background from neutrons produced either by cosmic rays or in the walls of the experimental hall. The beam (fiducial) region contains photodisintegration events from $^{19}\mathrm{F}(\gamma,\alpha)^{15}\mathrm{N}$ and from cosmic ray induced background. The target thickness as seen by the γ-ray beam was determined to be 3.0 ± 0.1 cm.

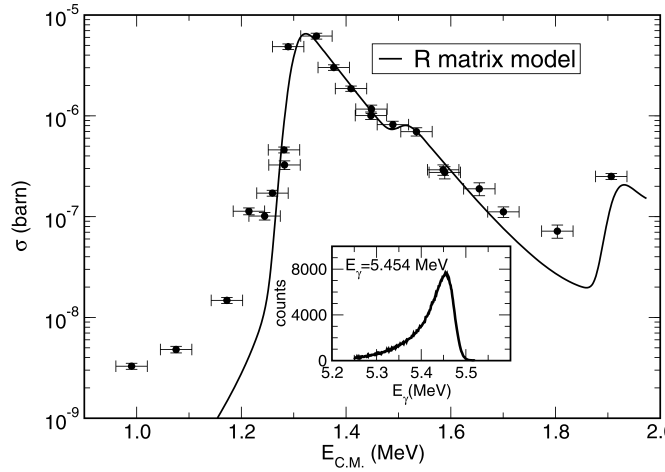

Fig. 3. Excitation function measured with a C_4F_{10} bubble chamber at $E_\gamma =$ 5.0–6.0 MeV ($E_{C.M.} =$ 1.0–1.9 MeV). The curve represents a model of the $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ reaction convoluted with the γ-ray beam profile. Solid circles represent the experimental data. The inset shows the energy distribution of an example of HIγS γ-ray beam (centroid at $E_\gamma = 5.454$ MeV) impinging on the bubble chamber.

in order to reduce the beam energy spread. The spatial distribution of the events obtained from the cameras correlated very well with the 1 cm diameter size of the γ-ray beam (see Fig. 2).

The beam intensity was measured with a high-purity germanium detector positioned downstream of the target. A thick aluminum absorber was placed between the bubble chamber and the γ-ray detector in order to limit the high photon flux incident on the germanium crystal. The γ-ray spectrum was corrected with a Monte Carlo simulation of the response function of the detector and the attenuation in the absorber. The resulting spectrum then represents the γ-ray beam incident on the bubble chamber (see inset in Fig. 3). The beam intensity ranged from 2×10^3 to 3×10^6 γ/s, with a systematic error in its determination better than 5% [12]. The beam energy spread was kept below 2%. When very narrow resonances are under scrutiny, the photon beam resolution affects the sensitivity of the technique, as only a fraction of the beam is effective in exciting the resonance. This problem is also present in charged particle beam experiments. However, in the technique discussed here, the interaction energy spread due to beam energy loss and straggling effects in the target is not present.

4. Analysis and results

The cross section obtained from the $^{19}\mathrm{F}(\gamma,\alpha)^{15}\mathrm{N}$ reaction converted to the $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ scale using Eq. (1) is given by the solid points in Fig. 3. The solid line in Fig. 3 is the result of an R-matrix [13] calculation performed with the AZURE code [14]. We used the resonance parameters of the $^{19}\mathrm{F}$ states in the $E_x = 5$–6 MeV range obtained from the direct $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$ measurement of [15] and folded the curve with the energy profile of the γ-ray spectrum (inset in Fig. 3).

For calculating the cross sections, a dead time of two seconds was determined by sampling the pressure in the bubble chamber at a rate of 1 kHz after each event trigger. The liquid becomes insensitive to charged particles when the superheat is removed by prompt compression. It is then left pressurized until the bubble is quenched so that the system becomes thermodynamically stable. The release of the high pressure superheats the liquid again. This pressure drop showed a gradual decline before the operating pressure and superheat were reached. This decline was the main source of uncertainty in the dead time, found to be 0.9 seconds and introducing a systematic error in the range from ±2% up to ±15% for measurements at the highest count rate achieved.

Two different kinds of background sources can contribute to the bubble count rate in the detector. The first contribution produces events that are spread evenly over the whole volume of the sensitive liquid. The second produces events that appear in the same spatial region as the γ-ray beam inside the superheated liquid. The first type can be determined in a straightforward manner by two independent methods: first, the count rate of events appearing outside of the beam region is compared to that of events in the path of the beam, while the γ-ray beam is irradiating the target. This is one of the reasons for which a good spatial resolution of the bubble chamber is required. In the experiment, this background contribution was determined to be about 8% of the count rate registered outside of the beam region. This value is in good agreement with the background observed in a second method, where the bubble chamber was moved to the side of the beam so that the liquid was not in the path of the γ rays. Sources of this background are fast neutrons produced by cosmic rays and by the photodisintegration reactions in the beamline and accelerator materials that are scattered into the bubble chamber. The measured count rates were corrected for this background source. It would also be possible in the future to reduce this background contribution by passively shielding the bubble chamber detector with a neutron absorbing material.

The other background source cannot be easily corrected for by using the information from events outside of the fiducial volume. These background events are produced in the same spatial region as those from the photodisintegration reaction of interest. The main contributors to the count rate in this case are other reactions induced by processes such as higher-energy bremsstrahlung from collisions between the electrons circulating in the storage ring and the residual gas atoms in the ring. Assuming a vacuum of 2×10^{-10} Torr, an interaction length of 35 m, a beam energy of 400 MeV, an electron beam current of 41 mA, $Z = 10$ residual gas [16], a 3 cm thick target with a (γ,n) cross section of 15 mb between 15 and 30 MeV and 0.5 mb elsewhere the count rate for this bremsstrahlung induced background source would be about 0.1 counts per second, in agreement with the count rate values measured at the lowest cross sections. This background source was studied in the experiment by varying the flux of incident γ rays over two orders of magnitude at an energy of 5 MeV. The presented experimental data points have not been corrected for this background source as further beam profiling studies need to be performed. At an incident flux of 3×10^6 γ/s the background allowed us to set an upper limit on the cross section for the $^{15}N(\alpha,\gamma)^{19}F$ reaction at a level of 3 nb.

Neutrons produced upstream in the beam line and collimated in the same region as the γ-ray beam are also a possible contributor to the count rate. This set of background sources can be suppressed by (a) choosing the threshold conditions in the bubble chamber such that their interactions do not trigger bubble formation, (b) by a subtraction of yields in which contaminant reactions are carefully accounted for, (c) by placing a neutron absorber upstream in the beam line, and (d) by identifying the neutron induced reactions through the sound they produce when nucleating in the superheated liquid [17].

The agreement between the R-matrix model and the time-inverse cross section measurement of the $^{19}F(\gamma,\alpha)^{15}N$ reaction is very good at values above 100 nb. Otherwise, the background inside the fiducial region dominates the measurements. Extrapolating to the highest flux that can be obtained at the HIγS facility, one expects to measure cross sections down to 200 pb. This is a considerable improvement over the 30 nb cross section value that have been measured in direct experiments [15], and in this work, where below $E_{C.M.} = 1.18$ MeV, only upper limits for the $^{15}N(\alpha,\gamma)^{19}F$ reaction have been obtained. A more detailed description of the experiment, including a comparison of the direct $^{15}N(\alpha,\gamma)^{19}F$ data with the R-matrix calculation will be published separately.

5. Summary

We developed a new detection technique for measurements of very small cross sections which are of interest in nuclear astrophysics. By studying the time reverse (γ,α) reaction with a γ-ray beam one can use targets which are thicker by six orders of magnitude. Together with an increase in cross section originating from reciprocity arguments, one obtains an increase in luminosity that allows a measurement of cross sections in the pb region even with the modest beam intensities available at existing facilities. Next generation facilities [18–20] will have considerably higher intensities which might open the possibility to obtain experimental cross sections for capture reactions at astrophysical energies.

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