Jefferson Lab Bubble Chamber Experiment Update and Future Plans

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We implement a new detection technique for measurements of very small cross sections of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, which is fundamental to nuclear astrophysics. We measure the time reversal γ-ray induced reaction with a Bremsstrahlung beam produced by the electron injector at JLab and a superheated liquid target (bubble chamber). Together with an increase in cross section originating from reciprocity arguments, we get an increase in luminosity that allows a measurement of cross sections in the pb region. The features of the beam produced at JLab are ideal for making these measurements.

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The determination of the reaction rates of some relevant nuclear processes is one of the leading problems in stellar structure, evolution, and nucleosynthesis. However, since experiments at astrophysical energies involve minute cross sections and thin targets, most determinations of reaction rates require extrapolations down to stellar temperatures at which cross sections are well beyond those accessible to direct experiments. Our technique uses thick liquid targets and is useful for measuring some of the most important nuclear reactions in stellar environments. The sensitivity of this technique is orders of magnitude higher than that of some of the best direct measurements performed to date.

In the case of the experiments discussed here, the residual particles from the photodisintegration in the time reversal process can be detected with a bubble chamber. Originally invented for high energy particle physics experiments, superheated liquid detectors have recently found new applications in several dark matter searches and now, in nuclear astrophysics.

PREVIOUS WORK AT HIγS

The concept for measuring cross sections for photon induced processes was tested by exposing the bubble chamber to γ rays produced with the HIγS facility at Duke University. The narrow bandwidth photon beam was generated by inverse Compton scattering of free electron laser light from high-energy electron beam bunches.

Several oxygen liquids were tested in our experiments. The selection of the liquid depends on several factors. Foremost, the molecular content of target nuclei should be maximized. Other nuclei 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, the operating pressure and temperature conditions of the pure target in liquid form may be too extreme to work in a practical device. Usually the liquid of choice consists of more than one nuclear species.

In principle, all liquids should nucleate in bubble chambers —it is a matter of practicality 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.

The critical parameters in choosing the best liquid include the purity, critical pressures, temperatures, flammability, etc. In addition one has to consider that in the final experiment highly enriched ^{16}O has to be used, since γ-ray induced reactions on ^{17}O and ^{18}O have cross sections orders of magnitude larger.

In an oxygen engineering run at HIγS we tested the bubble chamber with both CO_2 and N_2O. It was found that CO_2 , while working well in a continuously operating two fluid bubble chamber, experiences another chemical complication originating from chemical reactions of the superheated fluid with the buffer fluid that formed hydrates at low temperatures and changed the transparency of the superheated liquid.

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In a series of commissioning runs we photodisintegrated fluorine from CH_2FCF_3 and C_4F_{10}. We obtained an excellent agreement between direct (α, γ) measurements and our time-inverse (γ, α) experiments. The cross section measured covers more than three orders of magnitude, ranging from about 3 nb to about 10 μb. Also, the excellent agreement between this experiment and other measurements confirms that the detection efficiency of the bubble chamber is 100%. The systematic error in the determination of the cross section was largely dominated by the dead time uncertainty of the bubble chamber.

The count rate tolerated by the bubble chamber ranges from 0.5 events per second down to 0.5 count per minute, or longer. This is limited by the level of background obtained in the experiment. The low level limit of 3 nb was dominated by a high energy Bremsstrahlung radiation background beam produced by the interaction of fast electrons with residual gas in the beam line.

PREVIOUS WORK AT JLAB

The first engineering run at JLab (September 2015) was done with a N_2O bubble chamber. The device was configured to operate in a two fluid mode and we selected mercury as a buffer fluid. Mercury is not soluble in N_2O and does not superheat at the temperature and pressure conditions of operation of the detector.

Several goals were achieved during this run. We were able to successfully suppress events from the photodisintegration of ^{14}N by reducing the amount of superheat in the bubble chamber. We also studied the effects on the bubble distribution as the electron beam position on the Bremsstrahlung radiator was shifted. We determined that both the collimator system and radiator had to be improved to get a consistent and reproducible beam position and event distribution.

While the photons are mostly produced at small angles with respect to the direction of the electron beam, a non-negligible γ ray flux is scattered in other directions. Cross section measurements for low energies require an increase of the electron beam current, and scattered radiation would hit the video camera that monitors the bubble events. This caused scintillation of the CCD that was interpreted by our software as bubble triggers. We concluded that our camera needed to be shielded from γ rays.

After several days of operating the bubble chamber we observed a build up of particulates in the superheated liquid. These became a problem as they induced nucleation that eventually dominated our count rates. We interpreted this as chemical reactions with the mercury. Also, while wetting of glass by mercury is minimal, as other compounds became present in the bubble chamber, it was observed that small drops of liquid started accumulating on the glass surface. This is a problem as bubble events can be obscured behind the drops and missed by the camera. Overall, while mercury has some useful features as a buffer fluid, its use compromises the correct operation of the bubble chamber. We decided to eliminate buffer fluids and redesign the bubble chamber as a single fliud device.

An engineering run in May 2018 was performed with a C_3F_8 single fluid bubble chamber. The selection of the liquid was made based on the simplicity of the thermodynamic operating conditions of the device and on the fact that we have measured in the past an excitation function for the $^{19}F(\gamma,\alpha)^{15}N$ that can be used to test the both the new detector and the process of cross section deconvolution from the Bremsstrahlung yields.

A new lead shield for the video camera together with an improved beam collimator system solved the problem of scintillation. Also, as the determination of the electron beam parameters is fundamental for the characterization of the γ ray beam, a new beam profiling system was tested and proved to operate successfully. This system included an X-ray viewer and a set of beam position monitors.

At the highest energies (above 5.1 MeV), the cross section extracted from the experiment is in excellent agreement both with the literature and with our previous measurements at HIγS. Lower energy measurements were limited by a source of background that was identified as neutrons from the photodisintegration of deuterium present in the hydraulic fluid surrounding the glass vessel in the detector. These neutrons elastically scatter from carbon and fluorine in the superheated liquid. These heavy recoils were the source of triggers in the bubble chamber. A Geant4 simulation produced a background of 4×10^{-3} Hz/μA that is consistent with the value determined from the analysis of the experimental data. This corresponds to a cross section measurement at a level of 80 pb in the $^{15}N(\alpha,\gamma)^{19}F$ reaction. This is the most sensitive measurement ever done for this important astrophysically reelevant reaction.

FUTURE EXPERIMENTS

We plan to perform three engineering runs: one with a C_3F_8 liquid for the spring of 2019, second with natural N_2O for the summer of 2019, and a last one with depleted $^{17,18}O$ N_2O for the summer of 2020. For the first, we will aim to control the deuterium background by replacing the hydraulic hydrocarbon liquid with a fluorinated oil. Also, we will reduce the distance between the glass vessel and the beam entrance window of the pressure vessel in the bubble chamber. Another possible source of background that we need to prevent from dominating any future measurements is α-particle decay of heavy radioactive nuclei, such as U and Th, or from neutron induced reactions on ^{10}B, which is part of the natural boron in the borosilicate glass that contains the superheated fluid. These can be substantially reduced by replacing the glass with fused silica vessel. While most of these events would appear on the surface of the glass that is in contact with the superheated fluid, a second video camera would allow for stereoscopic vision that can help identifiying of this background. We plan to implement this with a set of prisms and mirrors, and by improving the resolution of the CCDs. This requires replacing the computer and most of the acquisition system hardware. We will focus our efforts in achieving the proposed error bars of 10% statistical uncertainty at a level of 10 pb.

An engineering run with the oxygen containing liquid will be performed to show a single fluid operation of the bubble chamber. The pressure and temperature operating conditions for a N_2O detector are different: low temperature (11 ^oC) for the single fluid will be demonstrated.

Natural oxygen has two heavy isotopes, ^{17}O and ^{18}O, that will also photodisintegrate and will be a source of background when measuring ^{16}O(γ,α)^{112}C. We have acquired two liters of heavy-oxygen depleted water that has been analyzed to have ^{16}O dominating to a level of at least $1{\times}10^6$ over ^{17}O and ^{18}O. An independent analysis confirming this figure needs to be performed. Once this is confirmed, a chemical conversion of this liquid to N_2O will be needed. We are investigating possible paths to follow to achieve this.

SUMMARY

We have successfully commissioned a single liquid bubble chamber using the electron injector at JLab to produce a Bremsstrahlung γ-ray beam. Our initial tests have proved that the experimental method is viable for measuring some of the most important cross sections of astrophysical relevance. A successful measurement of the cross section of the ^{12}C(α,γ)^{16}O reaction will require a campaign consists of engineering runs using first a C_3F_8 liquid to test for removal of the beam induced backgrounds, and a second N_2O as the active detector with natural oxygen and oxygen depleted of the heavy ^{17}O and ^{18}O isotopes.