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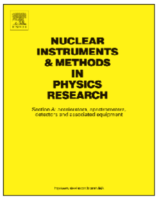

Bubble chambers for experiments in nuclear astrophysics

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ABSTRACT

A bubble chamber has been developed to be used as an active target system for low energy nuclear astrophysics experiments. Adopting ideas from dark matter detection with superheated liquids, a detector system compatible with γ-ray beams has been developed. This detector alleviates some of the limitations encountered in standard measurements of the minute cross-sections of interest to stellar environments. While the astrophysically relevant nuclear reaction processes at hydrostatic burning temperatures are dominated by radiative captures, in this experimental scheme we measure the time-reversed processes. Such photodisintegrations allow us to compute the radiative capture cross-sections when transitions to excited states of the reaction products are negligible. Due to the transformation of phase space, the photodisintegration cross-sections are up to two orders of magnitude higher. The main advantage of the new target-detector system is a density several orders of magnitude higher than conventional gas targets. Also, the detector is virtually insensitive to the γ-ray beam itself, thus allowing us to detect only the products of the nuclear reaction of interest. The development and the operation as well as the advantages and disadvantages of the bubble chamber are discussed.

1. Introduction

All elements of the periodic table with $Z > 3$ have been produced through nuclear reactions in the interior of stars via quiescent or explosive burning processes. The cross-sections of these reactions, however, are very small (typically pb–fb) so that they are difficult to measure even at the high temperatures and energies occurring in stellar explosions. In stellar environments this is compensated by the large masses and long time scales involved in stellar evolution. The thin targets which must be used in terrestrial reaction studies (typically $\mu g/cm^2$ to mg/cm^2) result in very small luminosities and count rates, with the result that up to now only very few astrophysical reaction cross-sections have been measured at stellar temperatures. Most of the other reactions are studied at higher energies and the cross-sections are then extrapolated towards the astrophysical energies of interest. In this paper we describe a new detector system working with active liquid targets, for which radiative capture reactions give an increase in luminosity by several orders of magnitude. Together with existing and planned new accelerators this may enable measurements of many reactions of astrophysical interest under stellar conditions.

2. Astrophysical background

The radiative capture of hydrogen or helium (i.e. (p,γ) or (α,γ) reactions) on light nuclei such as carbon, nitrogen and oxygen are some of the most important processes in stellar nucleosynthesis. These capture reactions have been studied for many years by bombarding targets of carbon, nitrogen or oxygen with intense proton and α-particle beams or (in the so-called inverse kinematics) by bombarding hydrogen and helium gas targets with heavier particles at energies of a few hundreds of keV/u and detecting the reaction products with suitable detectors. The thin targets ($\sim 10\ \mu g/cm^2$) which are required at these energies together with the beam intensities available at present particle accelerators result in low luminosities with count rates that reach

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typically 1 count/day for cross-sections in the pb region. Small improvements of these yields are still possible but quite long running times will nonetheless be required. If the reaction products from e.g. an (α, γ) reaction are stable, a considerable improvement of the luminosity can be achieved by studying the inverse (γ, α) process. One improvement in the expected count rate comes from the reciprocity theorem for nuclear reactions which relates the (γ, α) process to its inverse (α, γ) reaction [1]. The two cross-sections are related via

$$\frac{\sigma(\gamma,\alpha)}{\sigma(\alpha,\gamma)} = \frac{\omega_{\alpha,\gamma} k^2_{\alpha,\gamma}}{\omega_{\gamma,\alpha} k^2_{\gamma,\alpha}} \tag{1}$$

where $k_{\alpha,\gamma}$ and $k_{\gamma,\alpha}$ are the wave numbers for capture and photodisintegration channels, respectively, and $\omega_{\alpha,\gamma}$ and $\omega_{\gamma,\alpha}$ are the associated spin multiplicity factors. In the energy range discussed in this paper, the ratio can provide a gain of approximately two orders of magnitude in cross-section. Another gain in luminosity is obtained from the choice of the target. At the corresponding γ-ray energies for (γ, α) reactions of 5–10 MeV the large range of the incident γ-rays allows us to use targets with thicknesses of ~ 1–$10\ \mathrm{g/cm^2}$, which corresponds to a factor of 10^{5-6} improvement in luminosity. Disadvantages of this method include the limitation of present tunable γ-ray sources to about $10^8\ \gamma/\mathrm{s}$ and the need for a detector that is insensitive to the incident γ-rays. The latter has been achieved by the use of superheated liquids in a bubble chamber to detect and measure the reaction products from the (γ, α) reaction since these detectors have a high insensitivity to γ-rays. This has been tested to a level of less than 2×10^{-10} [2].

One of the most important capture reactions in nuclear astrophysics is the ${}^{12}\mathrm{C}(\alpha, \gamma){}^{16}\mathrm{O}$ reaction, sometimes called the “holy grail of nuclear astrophysics”, which can be studied with this technique by using a superheated liquid active target bubble chamber operating with an oxygen-containing liquid. While a study of this reaction is planned for the future, we describe in this paper a study of the capture reaction ${}^{15}\mathrm{N}(\alpha, \gamma){}^{19}\mathrm{F}$ via the photodissociation reaction ${}^{19}\mathrm{F}(\gamma, \alpha){}^{15}\mathrm{N}$ using fluorine containing liquids. This reaction is of interest to nuclear astrophysics since fluorine is the least abundant element in the mass range between 11 and 32 as shown by its solar abundance. This suggests that either it is very hard to synthesize or extremely fragile in stellar environments. Various scenarios for the nucleosynthesis of fluorine have been proposed. One includes the neutrino dissociation of ${}^{20}\mathrm{Ne}$ in core collapse supernovae [4]. Others suggest that ${}^{19}\mathrm{F}$ could be produced both during the thermal pulse phase in the intershell region of Asymptotic Giant Branch (AGB) stars. Another possibility includes hydrostatic burning in the helium shell of Wolf–Rayet stars. In both cases, the nuclear reaction sequence is the same, with the exception that in the AGB star case, the required neutron flux is induced by ${}^{13}\mathrm{C}$ nucleosynthesis produced by the mixing of hydrogen from the envelope into the intershell region and captured by the increasingly abundant ${}^{12}\mathrm{C}$ nucleus. For the latter part cross-section measurements of the ${}^{15}\mathrm{N}(\alpha, \gamma){}^{19}\mathrm{F}$ reactions at astrophysical energies are needed. In this contribution we describe such a measurement using this newly developed detector using the inverse photodissociation process.

3. The bubble chamber for use in nuclear astrophysics experiments

The bubble chamber makes use of the instability of superheated liquids against bubble formation for the detection of charged particles from a nuclear reaction. Detectors of this type have been exploited in high-energy physics experiments for more than 50 years when Glaser suggested their use to visualize the tracks of high-energy charged particles [5]. Later this technique also found applications in low-energy physics for neutron detection [6]. Larger variants of these detectors are currently employed in dark matter searches [7–9].

The most important difference between “standard” bubble chambers used in high-energy physics and the new class of bubble chambers is in their mode of operation. The bubble chambers of high-energy physics were pulsed with the beam bunches, which arrived at well defined time intervals. As a result the bubble chamber would only spend a fraction of a second in the superheated state. In our application the bubble chamber must stay continuously active until a nuclear reaction occurs in the superheated liquid. With the small cross-sections of interest, the active time can be minutes or hours, and so special care must be taken to prevent spurious boiling which is not caused by the nuclear reaction of interest. Another important difference between the device and experiments proposed here and those of high energy physics is that no tracks are left by the particle inducing nucleation. For the experiments relevant to nuclear astrophysics, the energies of the reaction products are so small that they are stopped in the liquid after a few microns. This means that no direct kinematic information can be obtained with this detector. Borrowing heavily from successful designs used in the search for dark matter [3,7,9], we have designed and tested a superheated active target system which will be described in the following sections.

3.1. Thermodynamics of bubble detectors

The study of nucleation in a superheated system has a long history, and is still being investigated today [10–12]. The theory of bubble formation in a superheated liquid (the so-called “thermal spike” model) has been discussed in detail by Seitz [13] and will not be repeated here. In the following we provide only a few of the equations, which are necessary for understanding the operating principle. Fig. 1 shows the phase diagram for C_4F_{10}.

The thick solid lines in Fig. 1 indicate the path that is being used to generate a superheated liquid. Starting at a point where the material is gaseous under ambient pressure and temperature (1), the pressure is first increased, liquifying the gas (2), followed by an increase in temperature (3). Decreasing the pressure below the liquid-gas phase boundary curve brings the fluid into its superheated state (4). For C_4F_{10} the operating temperatures are near 30 °C and the superheat pressures are typically 1–4 bar. If left

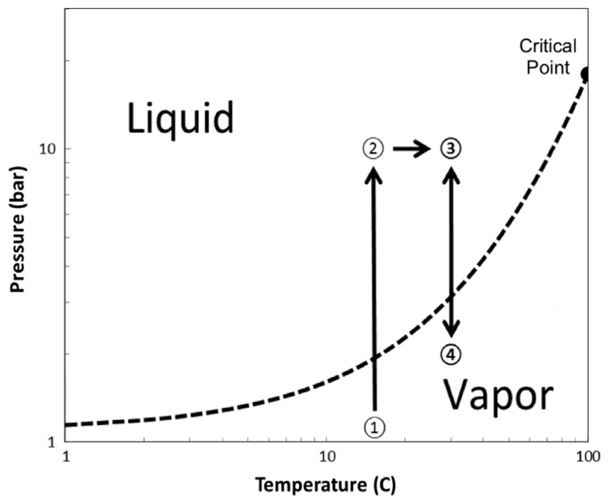

Fig. 1. Phase diagram of C_4F_{10}. The solid line represents the path used to bring the fluid into its superheated state.