Bubble Chambers for Experiments in Nuclear Astrophysics

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26 Abstract

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

44 1. Introduction

45 All elements of the periodic table with $Z>3$ have been produced through
46 nuclear reactions in the interior of stars via quiescent or explosive burning pro-
47 cesses. The cross sections of these reactions however, are very small (typically
48 pb-fb) so that they are difficult to measure even at the high temperatures and
49 energies occurring in stellar explosions. In stellar environments this is com-
50 pensated by the large masses and long time scales involved in stellar evolution.
51 The thin targets which must be used in terrestrial reaction studies (typically
52 $\mu\text{g-mg}/\text{cm}^2$) result in very small luminosities and count rates, with the result
53 that up to now only very few astrophysical reaction cross sections have been
54 measured at stellar temperatures. Most of the other reactions are studied at

55 higher energies and the cross sections are then extrapolated towards the astro-
 56 physical energies of interest. In this paper we describe a new detector system
 57 working with active liquid targets, which for radiative capture reactions gives
 58 an increase in luminosity by several orders of magnitude. Together with existing
 59 and planned new accelerators this may enable measurements of many reactions
 60 of astrophysical interest under stellar conditions.

61 **2. Astrophysical background**

62 The radiative capture of hydrogen or helium (i.e. (p, γ) or (α, γ) reactions) on
 63 light nuclei such as carbon, nitrogen and oxygen are some of the most important
 64 processes in stellar nucleosynthesis. These capture reactions have been studied
 65 for many years by bombarding targets of carbon, nitrogen or oxygen with intense
 66 proton and α -particle beams or (in so-called inverse kinematics) by bombarding
 67 hydrogen and helium gas targets with heavier particles at energies of a few
 68 hundreds of keV/u and detecting the reaction products with suitable detectors.
 69 The thin targets ($\sim 10 \mu\text{g}/\text{cm}^2$) which are required at these energies together
 70 with the beam intensities available at present particle accelerators result in low
 71 luminosities with count rates that reach typically 1 count/day for cross sections
 72 in the pb region. Small improvements of these yields are still possible but quite
 73 long running times will nonetheless be required. If the reaction products from
 74 e.g. an (α, γ) reaction are stable, a considerable improvement of the luminosity
 75 can be achieved by studying the inverse (γ, α) process. One improvement in the
 76 expected count rate comes from the reciprocity theorem for nuclear reactions
 77 which relates the (γ, α) process to its inverse (α, γ) reaction [1]. The two cross
 78 sections are related via

$$\frac{\sigma(\gamma, \alpha)}{\sigma(\alpha, \gamma)} = \frac{\omega_{\alpha, \gamma} k_{\alpha, \gamma}^2}{\omega_{\gamma, \alpha} k_{\gamma, \alpha}^2}, \quad (1)$$

79 where $k_{\alpha, \gamma}$ and $k_{\gamma, \alpha}$ are the wave numbers for capture and photodisintegration
 80 channels, respectively, and $\omega_{\alpha, \gamma}$ and $\omega_{\gamma, \alpha}$ are the associated spin multiplic-
 81 ity factors. In the energy range discussed in this paper, the ratio can provide a

82 gain of approximately two orders of magnitude in cross section. Another gain in
 83 luminosity is obtained from the choice of the target. At the corresponding γ -ray
 84 energies for (γ, α) reactions of 5-10 MeV the large range of the incident γ -rays
 85 allows us to use targets with thicknesses of ~ 1 -10 g/cm², which corresponds
 86 to a factor of 10^{5-6} improvement in luminosity. Disadvantages of this method
 87 include the limitation of present tunable γ -ray sources to about 10^8 γ /s and
 88 the need for a detector that is insensitive to the incident γ -rays. The latter has
 89 been achieved by the use of superheated liquids in a bubble chamber to detect
 90 and measure the reaction products from the (γ, α) reaction since these detectors
 91 have a high insensitivity to γ -rays. This has been tested to a level of less than
 92 2×10^{-10} [2] .

93 One of the most important capture reactions in nuclear astrophysics is the
 94 $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction, sometimes called the “holy grail of nuclear astrophysics”,
 95 which can be studied with this technique by using a superheated liquid active
 96 target bubble chamber operating with an oxygen-containing liquid. While a
 97 study of this reaction is planned for the future, we describe in this paper a
 98 study of the capture reaction $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ via the photodissociation reaction
 99 $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ using fluorine containing liquids. This reaction is of interest to
 100 nuclear astrophysics since fluorine is the least abundant element in the mass
 101 range between 11 and 32 as shown by its solar abundance. This suggests that
 102 either it is very hard to synthesize or extremely fragile in stellar environments.
 103 Various scenarios for the nucleosynthesis of fluorine have been proposed. One
 104 includes the neutrino dissociation of ^{20}Ne in core collapse supernovae [4]. Others
 105 suggest that ^{19}F could be produced both during the thermal pulse phase in the
 106 intershell region of Asymptotic Giant Branch (AGB) stars. Another possibility
 107 includes hydrostatic burning in the helium shell of Wolf-Rayet stars. In both
 108 cases, the nuclear reaction sequence is the same, with the exception that in
 109 the AGB star case, the required neutron flux is induced by ^{13}C nucleosynthesis
 110 produced by the mixing of hydrogen from the envelope into the intershell region
 111 and captured by the increasingly abundant ^{12}C nucleus. For the latter part cross
 112 section measurements of the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reactions at astrophysical energies are

113 needed. In this contribution we describe such a measurement using this newly
114 developed detector using the inverse photodissociation process.

115 **3. The Bubble Chamber for use in nuclear astrophysics experiments**

116 The bubble chamber makes use of the instability of superheated liquids
117 against bubble formation for the detection of charged particles from a nuclear re-
118 action. Detectors of this type have been exploited in high-energy physics exper-
119 iments for more than 50 years when D. A. Glaser suggested their use to visualize
120 the tracks of high-energy charged particles [5]. Later this technique also found
121 applications in low-energy physics for neutron detection [6]. Larger variants of
122 these detectors are currently employed in dark matter searches [7, 8, 9].

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

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

141 3.1. Thermodynamics of bubble detectors

142 The study of nucleation in a superheated system has a long history, and is
 143 still being investigated today [10, 11, 12]. The theory of bubble formation in a
 144 superheated liquid (the so-called “thermal spike” model) has been discussed in
 145 detail by Seitz [13] and will not be repeated here. In the following we provide
 146 only a few of the equations, which are necessary for understanding the operating
 147 principle. Figure 1 shows the phase diagram for C_4F_{10} .

148 The thick solid lines in figure 1 indicate the path that is being used to
 149 generate a superheated liquid. Starting at a point where the material is gaseous
 150 under ambient pressure and temperature (1), the pressure is first increased,
 151 liquifying the gas (2), followed by an increase in temperature (3). Decreasing
 152 the pressure below the liquid-gas phase boundary curve brings the fluid into its
 153 superheated state (4). For C_4F_{10} the operating temperatures are near 30°C and
 154 the superheat pressures are typically 1-4 bar. If left undisturbed, the fluid will
 155 remain liquid in this metastable state. If it experiences a disturbance, which
 156 deposits enough energy into the liquid within a certain distance, a critical barrier

157 can be overcome and a “proto-bubble” forms. If the “proto-bubble” exceeds a
 158 critical radius R_c it becomes unstable and the phase transition continues from
 159 superheated liquid into the vapor state creating a macroscopic bubble. The
 160 critical radius is given by energy conservation arguments as

$$R_c = \frac{2 \times \sigma}{(p_v - p_e)}, \quad (2)$$

161 where σ is the (temperature dependent) surface tension of the liquid, and
 162 $\Delta p = p_v - p_e$ the degree of superheat, i.e. the difference between the vapor pres-
 163 sure p_v at the operating temperature, and the fluid pressure p_e . Since the
 164 surface tension decreases with temperature, the critical radius R_c decreases to-
 165 wards higher temperatures. Typical values of R_c for the active fluid C_4F_{10} ,
 166 discussed in this paper, are between tens and hundreds of nm.

167 The energy E_c needed to form a bubble with a critical radius R_c , is given
 168 [10] by the equation

$$E_c = -\frac{4}{3}\pi R_c^3 \Delta p + \frac{4}{3}\pi R_c^3 \rho_v H_{lv} + 4\pi R_c^2 \left(\sigma - T \frac{d\sigma}{dT} \right) + W_{irr}. \quad (3)$$

169 In equation (3), ρ_v is the density of the material in its gas phase, H_{lv} is
 170 the latent heat of evaporation of the superheated liquid and W_{irr} is the energy
 171 that goes into irreversible processes such as sound. The first terms in equation
 172 (3) correspond, respectively, to the reversible work during the expansion, the
 173 energy needed to evaporate the liquid and the energy needed to generate the
 174 bubble surface of radius R_c . The irreversible contributions expressed by the last
 175 term W_{irr} are small and are usually neglected in the calculations. The various
 176 terms contributing to E_c for C_4F_{10} are compared in Fig. 2. The values for the
 177 thermodynamic parameters were obtained from the NIST code [14]. In these
 178 calculations, it was assumed that the pressure was 1.82 bar, which corresponds
 179 to the operating value used to superheat the liquid. As can be seen from Fig.
 180 2, the dominant contribution to E_c comes from the energy needed to evaporate

Figure 2: The four terms contributing to the critical energy necessary to form a bubble of critical radius at an operating pressure of 1.82 bar for the liquid C_4F_{10} .

the liquid, followed by the term originating from the temperature dependence of the surface tension. The contributions from the work needed to generate the surface of a bubble or from the reversible work during the expansion phase are a factor of ~ 10 smaller.

The “thermal spike” for creating a bubble can come from two sources: (1) In the photo-dissociation reaction $^{19}F(\gamma, \alpha)^{15}N$ two charged particles, ^{15}N and an α -particle are produced. Depending on the energy of the incoming γ -ray (5-6 MeV in the experiment described later) the energies are in the range of 200-500 keV for ^{15}N and between 800-1800 keV for the α particle, respectively. (2) In addition there are background reactions induced by neutrons from cosmic rays. While the liquid in the bubble chamber itself is insensitive to neutrons (neutrons themselves are unable to trigger nucleation), it can be triggered by the ^{12}C or the ^{19}F recoils produced in an elastic collision. For a 1 MeV neutron, these recoil energies are in the range of ~ 300 keV (^{12}C) or 200 keV (^{19}F), respectively, scaling with the energy of the incoming neutron.

In order to generate the thermal spike, these nuclei need to deposit this

Figure 3: Detection thresholds for the bubble chamber at two different superheats (see text). The curves represent stopping powers for various nuclei moving in C_4F_{10} . The liquid will nucleate (form bubbles) for particles in the region delimited by dE/dx_c and E_c , which are a function of the superheat in the liquid. These are dependent on the pressure and temperature of the liquid. Typical stopping powers and kinetic energies for the $^{19}F(\gamma, \alpha)^{15}N$ experiment described in this paper are shown by the small squares for α -particles and ^{15}N . The superheats used for the experiment must define detection thresholds that include the kinematics of the particles as represented in the small squares. When a photodisintegration event produces recoils within the thresholds, a visible bubble will be produced and detected with the CMOS cameras.

energy over a suitably short distance. This distance is somewhat debated in the literature [15] but typical values range from $2-6 \times R_c$.

If we integrate the energy-loss curves of the charged particles mentioned above over a typical range of $2-6 \times R_c$ we obtain the deposited energy E_{dep} which needs to be larger than E_c in order to initiate a macroscopic bubble. These conditions allow us to select the sensitivity thresholds for particle detection by choosing the proper temperatures and pressures (superheat) in the bubble chamber. In Fig. 3 the stopping power curves for several charged particles from hydrogen to ^{19}F in C_4F_{10} are shown as a function of the energy. Also included are the detection limits in dE/dx and E for operating the bubble chamber at $T=33^\circ C$ and $P=1.82$ bar, respectively (thick solid lines). As can be seen at these pressures, the bubble chamber is insensitive to protons. The detector can also

Figure 4: Schematic of the superheated liquid active target system, showing the main sub-systems of the apparatus.

209 be made insensitive to α -particles by choosing a smaller amount of superheat,
 210 as shown by the thin solid lines, which correspond to operating conditions of
 211 $T=30\text{ }^{\circ}\text{C}$ and $P=1.82\text{ bar}$.

212 4. Mechanical details

213 Figure 4 gives an overall schematic of the basic sub-systems of the bubble
 214 chamber. The containment vessel is filled with the active target fluid (bottom)
 215 and a so-called buffer fluid (top) fill the volume of the hydraulic system. The
 216 active fluid resides in a high pressure glass vessel allowing the less dense buffer
 217 fluid to fill the rest of the hydraulic system. A piston accumulator compen-

218 sates for volumetric changes during filling and temperature adjustments of the
 219 active fluid. The hydraulic system pressure is controlled via a pneumatically
 220 driven pressure control cylinder assembly. The pneumatic system has a high-
 221 and low-pressure reservoir, which are connected to the pressure control cylinder
 222 via a high-speed three way valve. The low- pressure reservoir is fed by a
 223 precision relieving regulator and sets the superheat pressure of the system. The
 224 high-pressure reservoir is fed directly from the regulated pneumatic supply and
 225 sets the compression pressure, which is typically a factor of 2-3 higher than
 226 the vapor pressure of the fluid at operating temperature. The glass pressure
 227 vessel resides within a containment vessel which protects operators and equipment
 228 in the event of glass failure. High speed CMOS cameras operated by a
 229 data acquisition and control (DAQ&C) system continuously monitor the active
 230 volume taking pictures every 10 ms, analyzing and capturing events in the super-
 231 heated fluid. The detection of an event is achieved by comparing successive
 232 pictures: subtracting the individual pixels from one image to the next. Upon
 233 event detection the system is repressurized within 60 ms, which liquifies the gas
 234 bubble and resets the system, allowing for subsequent depressurization back to
 235 the superheated state. A compression event is shown in figure 5.

236 The bubble chamber was operated for several weeks before the experimental
 237 campaigns were started. Cyclic fatigue was not observed as the device was
 238 subjected to pressure changes that induced the superheat in the liquid.

239 *4.1. Active target and buffer fluid*

240 Since in our application the bubble chamber must stay active for extended
 241 periods of time, extraneous bubble formation must be kept to a minimum. The
 242 active target fluid (C_4F_{10}) [16] has to be kept clean and must only contact
 243 very smooth surfaces. The fluid is therefore only allowed to come into contact
 244 with the glass pressure vessel or with the buffer fluid which provides a smooth
 245 interface for the transmission of pressure changes from the hydraulic system.
 246 The choice of the buffer fluid depends on several criteria. (1) It must have a
 247 lower density so that it floats on top of the active fluid. (2) It must be immiscible

Figure 5: Compression cycle of the liquid after bubble detection. The width of the pressurized state is about two seconds, corresponding to the time it took to liquify the bubble and stabilize the liquid before the superheat was induced again.

248 with the active fluid in order for a meniscus to form. (3) Solubility between the
 249 active fluid and the buffer fluid must be very low, and (4) it should not become
 250 superheated in the pressure/temperature range chosen for the experiment. For
 251 C_4F_{10} as an active fluid, water turns out to be an ideal buffer fluid and was
 252 utilized in this experiment.

253 4.2. Glass pressure vessel

254 The active fluid is contained within a cylindrical glass vessel [17] with an
 255 overall length of 102 mm, an inner diameter of 30 mm, and an outer diameter
 256 of 36 mm. The connection to the hydraulic system is provided by a threaded O-
 257 ring sealed bushing. In order to determine the maximum pressure at which this
 258 vessel could be operated, several studies were performed. A three-dimensional
 259 solid model of the vessel was created using a 3D CAD software package. This
 260 model was then used to perform stress analysis simulations, which predicted a
 261 failure of the vessel at pressures around 100 bar. Hydrostatic tests were then
 262 performed up to 80 bar on several vessels, with no failures observed. Considering
 263 simulations and hydrostatic testing, the glass vessel provided our system with
 264 a safety factor of about 8-10. Because of the brittle nature of glass and the

Figure 6: Schematic of the hydraulic system.

possibility of stress risers, which can occur in glass due to small scratches or imperfections, the glass vessel was housed within a secondary stainless steel containment vessel.

4.3. Hydraulic System

There are several requirements for the hydraulic system. (1) It provides the interface between the superheated liquid and the pneumatic pressure control system, (2) it allows for thermal expansion compensation, and (3) enables the filling of the pressure vessel with the active fluid. A schematic diagram is shown in Fig. 6. The hydraulic system pressure is controlled by utilizing an unbalanced piston and cylinder assembly which is the main interface between the hydraulic and the pneumatic system. The design of this piston assembly is shown in Fig. 7. The hydraulic side of the cylinder has a diameter of about 40% of the pneumatic side, allowing for higher pressures to be reached using standard off-the-shelf pneumatic control valves, regulators and tanks. The travel of the piston in both

Figure 7: Detail cut-away of the pressure transfer piston and cylinder assembly providing the interface between the pneumatic and hydraulic systems. The lower volume belongs to the hydraulic system, the upper volume is part of the pneumatic system.

279 directions is limited by flanges. This helps to prevent the complete vaporization
280 of the superheated fluid in case of an event that proceeds undetected by the
281 video cameras and the computer system.

282 An accumulator with an adjustable pneumatic charge is used for thermal ex-
283 pansion compensations and when significant temperature excursions are needed
284 during filling operations. Once the detector is filled and has reached its op-
285 erating temperature, the accumulator is valved off and put in standby. The
286 hydraulic system pressure is monitored by a fast response (<1 ms) pressure
287 transducer [18]. It is continuously monitored to ensure the correct superheat
288 and recompression pressure. Its value is also recorded for each detected event
289 and event triggering is possible on the pressure signal. This means that as
290 pressure rises due to bubble growth, the recompression cycle can be initiated
291 without the need of the optical signal from the video cameras.

292 A proper filling of the system with the various liquids is critical. Trapped
293 gases in the hydraulic system result in poor pressure response. Small amounts
294 of the active fluid in contact with rough surfaces outside the glass vessel cause
295 pressure control problems as well as rapid boiling during decompression. A
296 typical filling procedure involves the evacuation of the entire hydraulic system
297 to remove all trapped gases. Distilled and degassed water is then allowed into the
298 system through a filter until the entire volume of hydraulic system is filled with
299 water. The accumulator is then used to increase the pressure to slightly below
300 the vapor pressure of the active fluid at room temperature and the hydraulic
301 system is chilled. Once this is complete, gaseous C_4F_{10} is slowly allowed into the
302 glass pressure vessel through a filling stinger (see Fig. 6). The gas condenses
303 as it travels down through the stinger and sinks to the bottom of the glass
304 pressure vessel. The active fluid then displaces the buffer fluid in the bottom
305 of the glass vessel, and the change in fluid volume is taken up by the piston
306 accumulator. Visual inspection allows for the determination of the success of
307 the filling process. Once filling is complete, a sliding seal and a ball valve
308 facilitate the removal of the filling stinger. The accumulator is valved out of the
309 hydraulic system and proper pressure response is verified. The accumulator can

Figure 8: Schematic of the pneumatic system.

be valved back in to the system and the temperature can be increased to the operating temperature to prepare the system for operation.

4.4. Pneumatic pressure control and temperature monitoring

The pressure in the hydraulic system is controlled by the pneumatic system as shown in Fig. 8. A fast response (10 ms) high flow rate, three-way pilot-operated pneumatic solenoid valve [19] is directly connected to the cylinder head of the pressure control cylinder. This valve is controlled by a signal from the DAQ&C computer, which allows for rapid pressure changes from superheat to compressed conditions. The valve is also connected to two pneumatic tanks which act as reservoirs. The main compression tank is fed directly from a compressed air source and regulated to achieve the proper compression pressure. A connection from this supply is routed to a precision self-relieving regulator,

322 which feeds the superheat pressure tank. This regulator is an electropneumatic
323 transducer [20], which allows for remote control of its output pressure. This
324 enables fine control of superheat pressure without the need to access the device.

325 Since the temperature of the system has to be stable to within 1°C the
326 interior of the containment vessel is thermally insulated. Several resistance
327 temperature detectors (RTDs) are mounted on the glass vessel to monitor the
328 temperature of the superheated liquid. The signals from the RTDs are fed
329 into temperature controllers which display and control the temperature in the
330 chamber by activating a small heater installed near the bottom of the safety
331 vessel. Thermal gradients across the active volume are smaller than 0.5°C .

332 4.5. CMOS cameras, lighting and data acquisition

333 The containment vessel has two viewing ports located at $\pm 45^{\circ}$ with respect
334 to the incident γ -ray beam. Two 100 Hz high-sensitivity CMOS area scan
335 cameras [21] are continuously monitoring the active volume of the glass vessel.
336 To increase contrast and sensitivity, a high intensity diffuse LED backlight is
337 mounted opposite to each camera. One of the cameras acts as master and one as
338 slave. The DAQ&C computer continuously subtracts each new frame provided
339 by the master camera from the previous frame and evaluates the difference. It
340 takes about 5 ms to analyze the frames, which allows us to take full advantage
341 of the speed of the camera (10 ms per frame). Once a difference above a certain
342 threshold has been detected, the system is triggered by sending a signal to the
343 control system to repressurize. A time stamp is assigned to this event and a
344 sequence of 10 consecutive frames from the master camera as well as one frame
345 from the slave camera is written to disk. This provides spatial information
346 about the event within the vessel. Pressure and temperature condition of the
347 bubble chamber at the time of the event are also recorded. As an example
348 Fig. 9 exhibits the sequence of 10 pictures from the master camera which show
349 the growth and the recompression of one bubble event. The bubble is found
350 to grow for the first 40-50 ms, which is the time needed to (1) recognize a
351 difference in two subsequent frames, (2) send a signal to a fast relay which

Figure 9: Series of 10 pictures taken by the CMOS camera showing the development of a bubble generated in superheated C_4F_{10} via the $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ reaction. The time difference between individual pictures is 10 ms.

energizes the pneumatic valve, and (3) pressurize the pneumatic volume of the pressure control cylinder. This initiates a pressure increase sufficient to quickly liquify the bubble. After an (adjustable) time difference, typically of 1 to 5 s, which is the main component to the dead time (see figure 5 for a compression of 2.1 s), the DAQ&C system decompresses the bubble chamber again so that it is ready for the next event.

Given the small growth rate of a bubble during the first 10 ms after nucleation, the bubble chamber is able to resolve the site of bubble formation with a resolution of the order of the resolving power of the video camera. This is well below 1 mm, i.e. smaller than the size of the γ -ray beam which is defined by a 10 mm collimator.

5. Experimental Details

5.1. Production of the γ -ray beam

Linear or circular polarized γ -rays with energies ranging from 5 to 10 MeV are produced at the High Intensity γ -ray Source (HI γ S) at Duke University [22]. A full description of this facility can be found elsewhere and only a few details will be discussed here. The γ -rays are produced through inverse Compton scattering of a two-bunch electron beam circulating in an electron storage ring

370 with the photons from a high-power free electron laser (FEL) beam. Each
 371 electron bunch had different charges: a big one to induce the FEL (~ 40 mA) and
 372 a small one (~ 1 mA) to produce the γ -ray beam by inverse Compton scattering.
 373 This scheme helped reducing the bandwidth of the γ -ray beam profile.

374 The energy of the electrons was typically 400 MeV with a 532 nm wavelength
 375 of the laser light. With this technique intensities up to about 10^8 γ /s can be
 376 achieved. The γ -ray beam was collimated to a diameter of 10 mm with a series of
 377 oxygen-free Cu collimators. The (γ, n) thresholds of $^{63,65}\text{Cu}$ are at 10.85 MeV
 378 and 9.90 MeV, respectively, preventing the production of neutrons which, as
 379 discussed earlier, can be a source of background in the experiment. For the same
 380 reason the entrance window of the safety vessel of the bubble chamber consisted
 381 of 3 mm thick Al flanges. At the low γ -ray energies used in this experiment
 382 contributions from (γ, n) reactions on other isotopes (such as ^{57}Fe and ^{29}Si) do
 383 not result in any neutron background that trigger the bubble chamber. As will
 384 be discussed later, neutrons can be produced through collisions of the electron
 385 beam with the residual gas in the storage ring. The flux of the incident γ -ray
 386 beam was controlled by inserting a set of Cu attenuators into the beam path.
 387 Typical beam intensities used in the experiment ranged from 2×10^3 to 5×10^6
 388 γ /s.

389 5.2. Beam profile

390 Two γ -ray spectra measured with a 123% efficiency HPGe γ -ray detector
 391 (detection efficiency at 1.33 MeV relative to that of a standard 3-in.-diameter,
 392 3-in.-long NaI(Tl) scintillator) placed ~ 173 cm downstream after the bubble
 393 chamber are shown in Fig. 10. The count rate in the detector was kept under
 394 50 kHz by attenuating the flux with 10 cm thick Al slab or a 23.6 cm thick Cu
 395 absorber placed between the bubble chamber and the γ -ray detector.

396 The measured spectrum was corrected for the background produced by the
 397 γ -ray beam scattered from the exit window of the bubble chamber and the Al
 398 or Cu absorber and also corrected for the detector response of the HPGe de-
 399 tector using GEANT [24] simulations. The full energy peak detection efficiency

Figure 10: γ -ray spectra measured with a 123% HPGe detector placed downstream of the bubble chamber. Inverse Compton Scattering γ rays produced by the HI γ S facility have a centroid energy of $E_\gamma=5.44$ MeV. The spectra show the total count numbers during 39 minutes of beam measurement. The spectrum in black was taken with a 23.6 cm thick Cu absorber between the bubble chamber and the HPGe detector, while the spectrum in gray was acquired with no attenuator in place. Energy calibration for the spectra was performed by placing a ^{60}Co source next to the HPGe detector. The flux of γ -rays incident on the target was kept constant at 2.8×10^3 γ/s between both runs. Here, the peaks at 5.44 MeV correspond to the photopeaks, while those around 4.93 MeV are the first escape peak, and those at 4.42 MeV correspond to the second escape peak.

Figure 11: Reconstruction of the incident γ -ray beam at $E_\gamma=5.44$ MeV obtained from a Monte Carlo simulation. The solid line represents the parameterization of the Monte Carlo data. The error bars contain statistical contributions only. An extra 3% error bar for systematic effects needs to be added to the data.

was simulated using the energy spatial correlation of the γ -rays in the beam
[25] unique for each measurement. The γ -ray flux was obtained by dividing
the background corrected spectrum by the efficiency and the live time of the
measurement.

An *Exponentially Modified Gaussian* (EMG) distribution with the form

$$f(E) = \frac{ac\sqrt{2\pi}}{2d} \exp\left(\frac{b-E}{d}\right) + \frac{c^2}{2d^2} \left[\frac{d}{|d|} - \operatorname{erf}\left(\frac{b-E}{\sqrt{2}c} + \frac{c}{\sqrt{2}d}\right) \right] \quad (4)$$

was assumed to obtain the measured flux.

Here a , b , c , and d are the fitting parameters, and E is the γ -ray energy. A comparison of the experimental and the Monte Carlo simulated flux is shown in Fig. 11 with the solid line representing the EMG distribution.

6. Experimental results

For a proof-of-principle study of this detector system we have measured the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reaction via photodissociation of ^{19}F , i.e. through the $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$

411 reaction [26]. Resonance parameters for the (α, γ) reaction have been measured
 412 previously [27]. Using these values in a Breit-Wigner model we obtain a pre-
 413 dicted spectrum shown in Fig. 12 plotted as function of the excitation energy
 414 in ^{19}F with cross sections ranging from 100 pb to 30 μb . In our measurement
 415 with the bubble chamber we have studied this excitation energy region with
 416 γ -rays from 5-6 MeV. The beam intensities ranged from 2×10^3 to 5×10^6 γ/s
 417 depending on the cross section. The typical running time for one energy was
 418 about 1 hour. From the information of the two CMOS cameras located $\pm 45^\circ$
 419 with respect to the incident beam one can calculate the shape of the intersec-
 420 tion between the beam and the glass vessel. This is shown in Fig. 13, where
 421 the location of bubbles measured during one run appear looking along and per-
 422 pendicular to the γ -ray beam. No corrections for refraction in the walls of the
 423 glass vessel have been made as the position shifts observed were minimal with
 424 and without the superheated liquid. The dimensions of the fiducial area are in
 425 good agreement with the expectation. The events outside the fiducial volume
 426 are present even without a γ beam and are caused by ^{12}C and ^{19}F recoils after
 427 elastic scattering of cosmic ray induced neutrons. The neutron-induced back-
 428 ground rate in the fiducial volume is about 1×10^{-3} events/s. The number of
 429 bubbles, N_{counts} , measured at a given energy and corrected for background was
 430 then used to calculate the reaction yield, given by

$$Yield = \left(\frac{N_{\text{counts}}}{\phi_\gamma} \right) \frac{1}{\Delta t - t_{\text{dead}} * N_{\text{bubble}}}. \quad (5)$$

431 Here ϕ_γ is the energy integrated flux of γ -rays hitting the target (see Fig.
 432 10), Δt the running time, t_{dead} the dead time of the detector discussed earlier
 433 ($t_{\text{dead}}=2$ s) and N_{bubble} the number of bubbles observed in the whole active
 434 volume of the detector.

435 The cross section of the $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ reaction was then calculated from the
 436 reaction yield in equation 5 by

$$\sigma(\gamma, \alpha) = \frac{Yield}{L} \frac{1}{\nu \rho} \frac{N_A}{A}, \quad (6)$$

437 where L is the target thickness ($L=3\text{cm}$), ν is the number of fluorine atoms
 438 per C_4F_{10} molecule ($\nu=10$), ρ is the density of the liquid at superheated con-
 439 ditions ($\rho = 1.45 \text{ g/cm}^3$), N_A is Avogadro's number, and A is the molecular
 440 weight of C_4F_{10} in a.m.u. ($A=238$). The cross section of the $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$ reac-
 441 tion was then used to calculate $\sigma(^{15}\text{N}(\alpha, \gamma)^{19}\text{F})$ with equation 1. The results of
 442 the cross sections assuming a detection efficiency $\epsilon=1$ are shown as the points
 443 in Fig. 14 with the appropriate uncertainties in E and σ . The error bar for the
 444 cross section corresponds to the statistical uncertainty, while the error bar for the
 445 energy was obtained from the FWHM of the γ -ray beam as modeled in Fig.
 446 11 and converted to E_{lab} in the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ reference system.

447 The cross sections range from about $10 \mu\text{b}$ at the peak of the resonance to
 448 about 3 nb at the lowest energy. At the highest cross section the beam intensity
 449 had to be reduced to about $2 \times 10^3 \gamma/\text{s}$, confirming the high luminosity of this
 450 detector system. The solid line corresponds to the excitation function folded
 451 with the resolution function of the beam as described in Fig. 11. As can be
 452 seen an excellent agreement between the experimental data and the theoretical
 453 prediction is observed, so the assumption of $\epsilon=1$ for the detection efficiency of
 454 the reaction products is also confirmed. This is in agreement with the results
 455 presented in Ref. [7].

456 6.1. Beam-induced background

457 As can be seen from Fig. 14, the experimental cross sections at the lowest
 458 energies saturate at $\sim 3 \text{ nb}$, overestimating the value predicted by the Breit-
 459 Wigner distribution (see Fig. 12). The count rate measured at these energies
 460 contain a contribution from a beam induced background source that has not
 461 been accounted for so far. These background signals cannot be distinguished
 462 from the signal of interest from $^{19}\text{F}(\gamma, \alpha)^{15}\text{N}$, as they appear in the same spa-
 463 tial region when the beam is incident on the target. They are caused by a
 464 Bremsstrahlung radiation component produced by the electrons and the resid-
 465 ual gas in the beam line. While small in comparison with the main γ -ray beam
 466 component, these γ -rays have energies ranging from the electron beam energy

Figure 12: Cross section for the $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ reaction computed with a Breit-Wigner model using parameters from [27]. In solid black, the cross section is presented, while in dashed black, the curve folded with the resolution function (see Fig.11) of the beam is shown.

Figure 13: Sites of nucleation for a beam-on-target run. The profile of the γ -ray beam can be clearly observed. Some background events are also seen.

Figure 14: Cross sections calculated with a Breit-Wigner model with resolution function and corrected with a Bremsstrahlung background component. The data points were obtained experimentally and are in good agreement with the model. The dashed curve represents the background while the solid line is the sum of the dashed line of figure 12 and the Bremsstrahlung background.

(some hundreds of MeV) down to zero. Thus even a small amount of high-energy Bremsstrahlung γ -rays can dominate the yield at the lowest energies.

In order to estimate the flux from this background source we assume electrons circulating in a storage ring in which the vacuum has a typical value of 2×10^{-10} Torr. The section of the beam line in the ring where the electrons move in the direction of the bubble chamber has a length of 35 m. Assuming a beam energy of 400 MeV, an electron beam current of 40 mA, $Z=10$ residual gas [30], a 3 cm thick C_4F_{10} target with (γ, n) cross sections of 15 mb between 15-30 MeV and 0.5 mb elsewhere the count rate for this Bremsstrahlung induced background source would be about 0.1 counts per second, which is in good agreement with the count rate values measured at the lowest cross sections in our experiments. Converting this background yield into cross sections and plotting it in the $^{15}\text{N}(\alpha, \gamma)^{19}\text{F}$ plot gives the dashed line in Fig. 14. Adding this contribution to the folded Breit-Wigner distribution results in an excellent agreement with the experimental data.

There are two possible ways of reducing this background contribution: the

483 first includes the suppression of the Bremsstrahlung radiation by rearranging
 484 the accelerator beamlines at the region where the laser-electron collision takes
 485 place. The electron beam length in the direction of the γ rays could be reduced
 486 by bending their path with a magnet right before the collision point. The second
 487 possibility includes the separation of neutron-induced events from the heavy ion
 488 recoils by using the sound produced by the nucleation events. This technique
 489 has been successfully used in superheated liquid devices built for dark matter
 490 detection. The different spectral characteristics of the sound produced by these
 491 two types of events allow for their separation [28].

492 *6.2. Other backgrounds and systematic uncertainties*

493 Contributions to the count rate that are accounted for as backgrounds and
 494 are unrelated to the γ -ray beam or its production process include cosmic ray in-
 495 duced neutrons and muons, radioactivity in the vessel from the chemical makeup
 496 of the glass, and neutrons photodisintegrated with γ -rays produced by the ex-
 497 perimental room walls. All these backgrounds were measured by operating the
 498 bubble chamber without an electron beam in the accelerator ring. Cosmic ray
 499 induced events will appear evenly distributed over the whole volume of the su-
 500 perheated liquid. They can be reduced by passive shielding around the bubble
 501 chamber. Radioactivity from the glass only triggers nucleation on the super-
 502 heated liquid in close contact with the vessel walls.

503 These backgrounds can be identified by using the good spatial resolution
 504 capabilities of the bubble chamber. By knowing the fiducial region where the
 505 γ -ray beam irradiates the superheated liquid, the majority of these background
 506 events can be suppressed. It is only those produced in the fiducial region that
 507 need to be accounted for by doing background runs without beam in the accel-
 508 erator. In these tests, the average time between consecutive nucleation events
 509 was of two minutes, while the typical count rate of the detector when γ -ray
 510 irradiated it was of the order of 0.1 Hz. This results in an average 8.3% con-
 511 tribution to the count rate coming from these sources of background combined.
 512 While some bubbles were observed next to the glass walls (one or two per hour

of operation), the contribution to the whole count rate from these was insignificant. These nucleation sites could be associated with α -particle decays from radioactive nuclei in the glass.

An additional background contribution that was studied in this work was that originating from photo-induced neutrons produced upstream in the accelerator by the interaction of γ -rays with beam line components. We measured this contribution by moving the bubble chamber to the side out of the γ ray beam path and determining a count rate. These bubbles were distributed evenly in the superheated liquid volume and account for 8% of the count rate measured in runs with the γ -ray beam impinging on the bubble chamber.

Other systematic uncertainties come from the determination of the beam intensity, which ranged from 2×10^3 to 3×10^6 γ /s, with an error bar under 5%, as discussed in [29]. The dead time (see figure 5), determined to be 2.1 seconds, had a systematic error in the range from $\pm 2\%$ up to $\pm 15\%$ for measurements at the highest count rate achieved. 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. The detection efficiency (discussed above) contributes a systematic uncertainty that is negligible compared to other systematic effects.

7. Summary

The long life of stars can be understood in the context of the strong Coulomb barriers which prevent nuclei from fusing. It is this same reason that complicates measurements of very small reaction cross sections in the laboratory. Therefore, new state-of-the-art detectors have to be developed to deal with the extremely low count rates. Since bubble chambers allow us to use liquid target material the density is much higher when compared to gas targets which is advantageous for measuring the small cross sections of time-inverse (α , γ) reactions. The bubble chamber described in this paper is one of the possible approaches. Since these

542 detectors are practically insensitive to γ -rays only the charged particle reaction
543 products are detected in the active liquid.

544 We have constructed a device for performing the measurements and estab-
545 lished the technique. Future facilities for producing γ -rays using inverse Comp-
546 ton Scattering will benefit from results obtained in this work. In particular,
547 upcoming facilities using external lasers that do not have significant residual gas
548 in the path of the electron beam and in the same direction of the γ ray beam
549 will allow measuring the low cross sections relevant to nuclear astrophysics as
550 high energy Bremsstrahlung radiation will be significantly reduced.

551 This feature is required regardless of the particle identification method or
552 kinematic information obtained by a detector trying to measure these small
553 cross sections.

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