NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES WITH γ-RAY BEAMS: A NOVEL EXPERIMENTAL APPROACH*

M. Ćwiok

for the eTPC Collaboration

University of Warsaw, University Technology Transfer Centre (UOTT)
Żwirki i Wigury 93, 02-089 Warszawa, Poland

(Received December 22, 2015)

An active-target Time Projection Chamber is being developed at the University of Warsaw to study photo-disintegration reaction of astrophysical interest at the relevant energies using the intense monochromatic γ-ray beams that will be available at the ELI–NP facility in Bucharest-Măgurele, Romania. As part of the R&D for this project, a prototype detector was constructed. The first results from tests with charged-particle ion beams are presented.

DOI:10.5506/APhysPolB.47.707

1. Introduction

The knowledge of the cross section and the reaction mechanism for thermonuclear reactions relevant for stellar nucleosynthesis is needed for stellar evolution modelling. Among them, there are several (p,γ) and (α,γ) reactions. These reactions take place in the interior of stars, in the hot plasma at temperatures of the order of 10^6–10^{10} K. In such conditions, thermonuclear reactions are efficient at energies well below the Coulomb barrier and are characterised by extremely low cross sections, often beyond the limits of the current experimental capabilities. Lack of experimental information on cross sections of astrophysical relevance at the relevant low energies requires extrapolations from high-energy regions where the cross sections are known. This procedure, however, is susceptible to large uncertainties. A systematic experimental study of such reactions will allow mapping of the astrophysical

* Presented at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 6–13, 2015.

S-factor at the energies relevant for different astrophysical scenarios, reducing dramatically the need for extrapolation to the low astrophysical energies or improving on its accuracy.

Among the reactions that are in need of being studied experimentally, the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is recognised as one of the most important. This reaction regulates the production ratio of oxygen and carbon. No level is available in $^{16}\mathrm{O}$ for resonant behaviour up to energies corresponding to $T = 2$ GK for production by fusion of $^{12}\mathrm{C}$ and α. Since oxygen can only be produced in stars, another mechanism must enable the reaction to proceed at a rate consistent with the observed carbon-to-oxygen ratio. Two mechanisms are, therefore, available for this: non-resonant direct-capture process and non-resonant type of capture into the tails of nearby resonances [1]. The problem of the Coulomb barrier can be overcome by studying the inverse photo-disintegration reaction

$$B(b,\gamma)A \rightleftharpoons A(\gamma,b)B \tag{1}$$

and using the principle of detailed balance in nuclear reactions

$$\sigma_{b\gamma} = \sigma_{\gamma b}\,\frac{g_{\gamma b}}{g_{b\gamma}}\,\frac{p_{\gamma b}^2}{p_{b\gamma}^2} = \sigma_{\gamma b}\,\frac{2J_A+1}{(2J_b+1)(2J_B+1)}\,\frac{E_\gamma^2}{E_{\mathrm{CM}}}\,\frac{1}{\mu_{bB}c^2}\,, \tag{2}$$

where the subscripts $b\gamma$ and γb indicate the direct capture and photo-disintegration reactions, respectively, g represents the spin factor, p the momentum, J the spin, E_γ the photon energy, E_{CM} the energy in the centre-of-mass frame for the $B+b$ channel and μ_{bB} the respective reduced mass.

The use of intense monochromatic γ-ray beams, like those that will soon be available at the Extreme Light Infrastructure–Nuclear Physics (ELI–NP) facility [2, 3], will allow to measure the cross section for the α-capture reaction by means of the inverse photo-disintegration reaction.

2. eTPC detector for ELI–NP

A new Time Projection Chamber with electronic strip-readout (eTPC) is being developed at the University of Warsaw to conduct such studies. The gas in the detector will act as a target for the nuclear reaction with photons, and the detector will be operated at low pressure to be able to detect low-energy particles. Full kinematic reconstruction of the charged-particle reaction products will be performed.

The active volume of the final eTPC detector, in which the reaction happens and the products are detected, will have a length of 35 cm and a square cross section of 20 cm × 20 cm, centered around the beam axis with a window for the gamma beam and another on the side for an alpha source.

The detector will operate at pressures lower than atmospheric (~ 100 mbar), with the gas density optimised for the given reaction. The active volume of the TPC detector is immersed in a uniform electric field. The electrons from primary ionisation are drifting towards the amplification structure, consisting of three layers of Gas Electron Multiplier (GEM) [4] foils followed by the segmented anode. The anode has a strip readout made of interconnected diamond-shaped pads. The strips are arranged in a redundant three-coordinate system (at 60° from each other) forming virtual pixels [5, 6]. The fast digitising electronics of adjustable sampling rate (1–100 MS/s) is employed. The virtual pixels allow for two-dimensional reconstruction of the reaction products in a given time slice. Synchronous sampling of the pulses collected on the strips allows to reconstruct the vertical coordinate of each time slice for a given drift velocity. It is expected that the final eTPC detector will need about 10^3 channels of electronics and will be triggered by the 100 Hz clock of the synchronous γ-ray beam of the ELI–NP facility [7].

The experimental rates for the flagship reaction $^{12}C(\alpha,\gamma)^{16}O$ were estimated assuming an average beam spectral density of 2.5×10^4 γ/s/eV, beam energy resolution of 0.5% [3, 7] and CO_2 gaseous target at 100 mbar. At $E_{\mathrm{CM}} = 1.1$ MeV ($E_\gamma = 8.26$ MeV), about 70 events/day are expected, assuming the astrophysical S-factor as parametrised in the latest NACRE compilation [1]. Beam-induced background on other isotopes, *e.g.* carbon, will be clearly distinguishable on the basis of Q-value considerations. The background due to creation of e^+e^- pairs, generated by the interaction of γ rays with the entrance window material, will be suppressed by placing the window in a constant magnetic field and away from the active volume.

A smaller scale demonstrator detector operating at atmospheric pressure (mini-eTPC) was constructed and tested with alpha-beam at the Tandem facility of the IFIN-HH in Bucharest-Măgurele, Romania. In this paper, we report on the status of this development.

3. Detector prototype

The mini-eTPC prototype was constructed in order to perform feasibility tests of 3D track reconstruction. It has 10.6 cm $\times$ 10.6 cm readout surface and drift length of 20 cm. It is equipped with 256 readout strips of 1.5 mm pitch, which are read by the Generic Electronics for TPCs (GET) [8] developed for low-energy nuclear physics imaging experiments. In Fig. 1, a photograph of the assembled internal cage of the mini-eTPC is shown. The detector chamber has four ports placed in the middle of the drift length, one on each side of the cage. They are used for the beam entrance window and to insert an alpha calibration source.

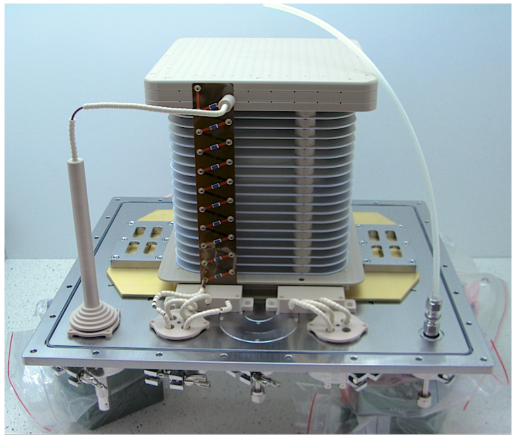

Fig. 1. Fully assembled internal parts of the mini-eTPC detector.

First proof-of-principle tests of the mini-eTPC were performed recently with an alpha beam of 15 MeV energy from the 9 MV Tandem of the IFIN-HH facility in Bucharest-Măgurele, Romania. The algorithm for track reconstruction was validated with the data collected. The detector was operated at atmospheric pressure with 50% He + 50% CO_2 gas mixture. Gas mixtures based mostly on CO_2 will be used in the future eTPC measurement of $^{16}O(\gamma,\alpha)^{12}C$, since pure O_2 is too reactive to be employed.

The 256 readout strips of the mini-eTPC detector are arranged in three groups: 72 for U-coordinate, 92 for V-coordinate and 92 for W-coordinate. During beam tests, the U-strips were perpendicular to the beam axis, as shown in Fig. 2. The Cartesian XYZ system used in raw-data reconstruction is also shown in the figure. One expects that events corresponding to the accelerator beam should have a broad distribution of hits along U-strips starting from strip $U72$. Since the beam was continuous, the data acquisition was operated in self-triggering mode for capturing events with a given minimal strip multiplicity. In the offline analysis, the pedestals from each channel were subtracted on event-by-event basis. Afterwards, the signals were clustered in space and time. For a given time bin, only hits confirmed by all three redundant coordinates (U, V and W) were used for further 3D track reconstruction.

In Fig. 3, an example of the reconstructed track, generated by an alpha particle from the beam that entered the detector perpendicular to the drift electric field lines and parallel to the readout plane, is depicted. The collected beam test data serve as a baseline for optimizing the next steps of the R&D such as: data acquisition system, detector geometry, read-out board segmentation and reconstruction algorithms.

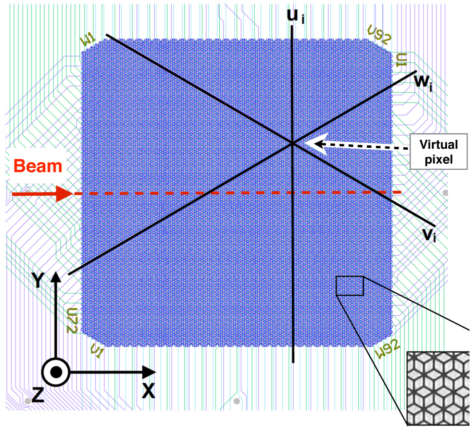

Fig. 2. Details of the readout PCB of the mini-eTPC detector having: 72 U-strips, 92 V-strips and 92 W-strips. The Cartesian XYZ coordinates used in the event reconstruction are also shown. The direction of the ion beam is represented with the dashed line. View toward readout pads along direction of drifting electrons. The inset shows diamond-shaped pads having sides of 1 mm length.

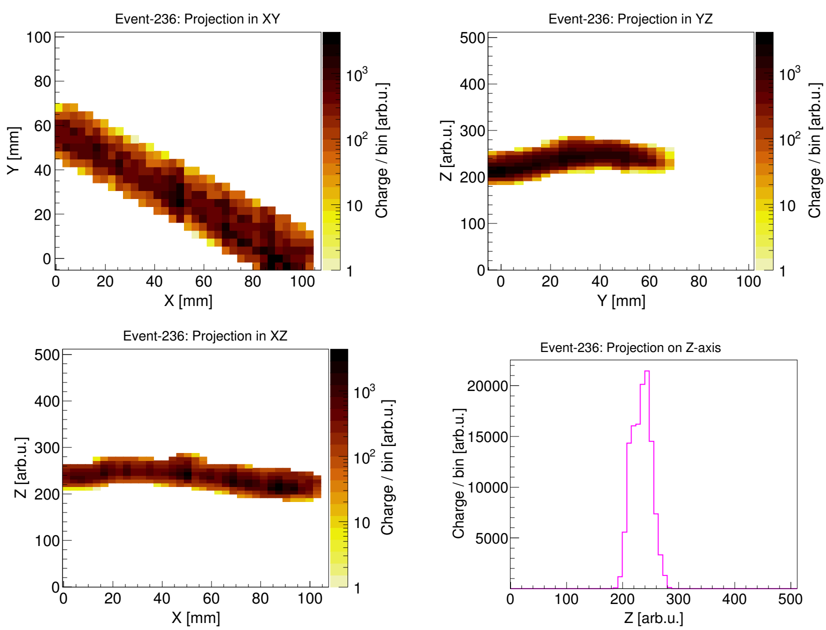

Fig. 3. Example event of a beam particle reconstructed in 3D. Projections on the XZ, XY, YZ planes and the total charge projected on Z-axis are displayed clockwise from the bottom left panel, respectively. The Z-axis is represented in arbitrary units since electron drift velocity was not measured during beam test.

4. Summary

The small scale eTPC prototype detector was constructed and tested with charged-particle beam. The feasibility of using the GET front-end electronics for the final eTPC detector proposed for the ELI–NP γ-ray beam was demonstrated. The next steps will include operation of the detector at low pressure with gas mixtures containing CO_2 and tests with pilot γ-ray beams at the ELI–NP during the facility commissioning phase in 2017–18. For stable, long-term operation of the eTPC detector, the continuous monitoring of: gas gain, electron drift velocity and diffusion, as well as corrections for non-uniformity of the drift electric field will need to be implemented.

This work was partially supported by the IFIN-HH, Romania under one-year R&D contract No. 3 of 1/10/2014. The author would like to thank: H. Czyrkowski, R. Dąbrowski, Z. Sałapa (Faculty of Physics, University of Warsaw), as well as C. Balan, D. Ghita, O. Tesileanu (IFIN-HH) and entire staff of the 9 MV tandem accelerator in Bucharest-Măgurele for their excellent technical support.

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