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At the cradle of oxygen: Brand-new detector to reveal the interiors of stars

The most intense source of gamma radiation constructed to date will soon become operational at the ELI Nuclear Physics research facility. It will be possible to study reactions that reveal the details of many processes occurring within stars, in particular those leading to the formation of oxygen. An important part of the equipment will rely on a particle detector built by physicists at the University of Warsaw. A prototype has recently concluded the first round of testing.

Oxygen is essential for life: we are immersed in it yet none of it actually originates from our own planet. All oxygen was ultimately formed through thermonuclear reactions deep inside stars. Laboratory studies of the astrophysical processes leading to the formation of oxygen are extremely important. A big step forward in these studies will be possible when work commences in 2018 at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility near Bucharest, using a state-of-the-art source of intense gamma radiation. High energy protons will be intercepted using a specially-designed particle detector acting as a target. A demonstrator version of the detector, constructed at the Faculty of Physics, University of Warsaw (FUW), has recently completed the first round of tests in Romania.

In terms of mass, the most abundant elements in the Universe are hydrogen (74%) and helium (24%). The percentage by mass of other, heavier elements is significantly lower: oxygen comprises just 0.85% and carbon 0.39% (in contrast, oxygen comprises 65% of the human body and carbon 18% by mass). In nature, conditions supporting the formation of oxygen are present only within evolutionarily-advanced stars which have converted almost all their hydrogen into helium. Helium becomes then their main fuel. At this stage, three helium nuclei start combining into a carbon nucleus. By adding another helium nucleus, this in turn forms an oxygen nucleus and emits one or more gamma photons.

“Oxygen can be described as the ‘ash’ from the thermonuclear ‘combustion’ of carbon. But what mechanism explains why carbon and oxygen are always formed in stars at more or less the same proportion of 6 to 10?” asks Dr. Chiara Mazzocchi (FUW). She goes on to explain: “Stars evolve in stages. During the first stage, they convert hydrogen into helium, then helium into carbon, oxygen and nitrogen, with heavier elements formed in subsequent stages. Oxygen is formed from carbon during the helium-burning phase. The thing is that, in theory, oxygen could be produced at a faster rate. If the star were to run out of helium and shift to the next stage of its evolution, the proportions between carbon and oxygen would be different.”

The experiments planned for ELI-NP will not actually recreate thermonuclear reactions converting carbon into oxygen and photons gamma. In fact, researchers are hoping to observe the reverse reaction: collisions between high-energy photons with oxygen nuclei to produce carbon and helium nuclei. Registering the products of this decay should make it possible to study the characteristics of the reaction and fine-tune existing theoretical models of thermonuclear synthesis.

“We are preparing an eTPC detector for the experiments at ELI-NP. It is an electronic-readout time-projection chamber, which is an updated version of an earlier detector built at the Faculty’s Institute of Experimental Physics. The latter was successfully used by our researchers for the world’s first observations of a rare nuclear process: two-proton decay,” says Dr. Mikolaj Cwiok (FUW).

The main element of the eTPC detector is a chamber filled with gas comprising many oxygen nuclei (e.g. carbon dioxide). The gas acts as a target. The gamma radiation beam passes through the gas, with some of the photons colliding with oxygen nuclei to produce carbon and helium nuclei. The nuclei formed through the reaction, which are charged particles, ionise the gas. In order to increase their range, the gas is kept at a reduced pressure, around 1/10 of the atmospheric one. The released electrons are directed using an electric field towards the Gas Electron Multiplier (GEM) amplification structures followed by readout electrodes. The paths of the particles are registered electronically using strip electrodes. Processing the data using specialised FPGA processors makes it possible to reconstruct the 3D paths of the particles.

The active region of the detector will be 35x20x20 cm^3, and at nominal intensity of the photon beam it should register up to 70 collisions of gamma photons with oxygen nuclei per day. Tests at ELI-NP used a demonstrator:a smaller but fully functional version of the final detector, named mini-eTPC. The device was tested with a beam of alpha particles (helium nuclei).

“We are extremely pleased with the results of the tests conducted thus far. The demonstrator worked as we expected and successfully registered the tracks of charged particles. We are certain to use it in future research as a fully operational measuring device. In 2018, ELI-NP will be equipped with a larger detector which we are currently building at our laboratories,” adds Dr. Mazzocchi.

The project is carried out in collaboration with researchers from ELI-NP/IFIN-HH (Magurele, Romania) and the University of Connecticut in the US. The Warsaw team, led by Prof. Wojciech Dominik, brings together physicists and engineers from the Division of Particles and Fundamental Interactions and the Nuclear Physics Division and students from the University of Warsaw: Jan Stefan Bihalowicz, Jerzy Manczak, Katarzyna Mikszuta and Piotr Podlaski.

Extreme Light Infrastructure (ELI) is a research project valued at 850 million euro, conducted as part of the European Strategy Forum on Research Infrastructures roadmap. The ELI scientific consortium will encompass three centres in the Czech Republic, Romania and Hungary, focusing on research into the interactions between light and matter under the conditions of the most powerful photon beams and at a wide range of wavelengths and timescales measured in attoseconds (a billionth of a billionth of a second). The Romanian ELI – Nuclear Physics centre, in Magurele near Bucharest, conducts research into two sources of radiation: high-intensity radiation lasers (of the order of a 10^{23} watts per square centimetre), and high-intensity sources of monochromatic gamma radiation. The gamma beam will be formed by scattering laser light off the electrons accelerated by a linear accelerator to speeds nearing the speed of light.

Physics and Astronomy first appeared at the University of Warsaw in 1816, under the then Faculty of Philosophy. In 1825 the Astronomical Observatory was established. Currently, the Faculty of Physics' Institutes include Experimental Physics, Theoretical Physics, Geophysics, Department of Mathematical Methods and an Astronomical Observatory. Research covers almost all areas of modern physics, on scales from the quantum to the cosmological. The Faculty's research and teaching staff includes ca. 200 university teachers, of which 88 are employees with the title of professor. The Faculty of Physics, University of Warsaw, is attended by ca. 1000 students and more than 170 doctoral students.

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SCIENTIFIC PAPERS:

1. “Nuclear reactions at astrophysical energies with gamma-ray beams: A novel experimental approach”; M. Cwiok; Acta Physica Polonica B Vol. 47 No 3 (2016); DOI:10.5506/APhysPolB.47.707

2. “Perspectives for photonuclear research at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility”; D. Filipescu et al.; Eur. Phys. J. A 51, 185 (2015); DOI:10.1140/epja/i2015-15185-9

RELATED LINKS:

http://www.eli-np.ro/
ELI Nuclear Physics (ELI-NP), Magurele, Romania.

https://eli-laser.eu/
European consortium Extreme Light Infrastructure (ELI).

http://www.esfri.eu/roadmap-2016
European Strategy Forum on Research Infrastructures roadmap.

http://www.fuw.edu.pl/
Faculty of Physics, University of Warsaw.

http://www.fuw.edu.pl/informacje-prasowe.html
Press office of the Faculty of Physcis, University of Warsaw.

IMAGES:

FUW160602_fot01s.jpg **HR:** http://www.fuw.edu.pl/press/images/2016/FUW160602b_fot01.jpg
Installation of the mini-eTPC demonstrator detector during on-line test beams at the 9 MV Tandem accelerator facility at IFIN-HH, Magurele, Romania. From left: Jan Stefan Bihalowicz, Lukasz Janiak, Marcin Zaremba. (Source: Faculty of Physics, University of Warsaw)

FUW160602_fot02s.jpg **HR:** http://www.fuw.edu.pl/press/images/2016/FUW160602b_fot02.jpg
Example track of an alpha particle (energy 15 MeV) from the test beam registered with the demonstrator detector mini-eTPC. Read-out electrodes of the detector are parallel to the X-Y plane, the direction of the drift electric field is along the Z axis. (Source: Faculty of Physics, University of Warsaw)

FUW160602_fot03s.jpg **HR:** http://www.fuw.edu.pl/press/images/2016/FUW160602b_fot03.jpg
Artistic view of the registration of the photodisintegration of an oxygen nucleus in the eTPC detector at ELI-NP. (Source: Faculty of Physics, University of Warsaw)

FUW160602_fot04s.jpg **HR:** http://www.fuw.edu.pl/press/images/2016/FUW160602b_fot04.gif
3D visualisation of the track of an alpha particle (energy 15 MeV) from the test beam registered with the demonstrator detector mini-eTPC. Read-out electrodes of the detector are parallel to the X-Y plane, the direction of the drift electric field is along the Z axis. (Source: Faculty of Physics, University of Warsaw)