Nuclear reactions at astrophysical energies with $\gamma$-ray beams: a novel experimental approach

Chiara Mazzocchi
University of Warsaw

COMEX5, Kraków, September 17$^{th}$, 2015
Overview

✓ Physics motivations

✓ Where?

✓ How?
  - an active-target time-projection chamber: the e-TPC project

✓ Outlook
Physics motivations: nucleosynthesis

✓ Abundance of the elements in the Universe

- in weight: H - 74%, He - 24%, O - 0.85%, C - 0.39%, ...

✓ Abundance of elements in the human body:

- in weight: O - 65%, C - 18%, H - 10%, N - 3%, other 4%
Physics motivations: nucleosynthesis up to A=60

✓ H-burning:
  - $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu :: \text{pp-chain}, \text{CNO cycle, hot-CNO, NeNa cycle, MgAl cycle,...}$
  - synthesis of He

✓ He burning:
  - $3\alpha \rightarrow ^{12}\text{C}; ^{12}\text{C}(\alpha,\gamma)^{16}\text{O}, ^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}, ^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}$
  - synthesis of C, O, Ne

✓ C/O, Ne, Si burning:
  - synthesis of elements with $16<A<60$
Physics motivations: survival of $^{12}$C

✓ Carbon is the 4$^{th}$ most abundant element in the universe, after H, He and O

✓ $^{12}$C is created in the triple-$\alpha$ process or $3\alpha \rightarrow ^{12}$C

✓ Carbon/Oxygen ratio = 0.6

✓ Assumption: nuclidian material is synthesised mostly during the major quiescent burning phase of stellar evolution

- bulk of carbon abundance expected to be a direct product of the triple-$\alpha$ process

- oxygen expected to be the ash of the subsequent $^{12}C(\alpha,\gamma)^{16}O$

-->> He-burning of $^{12}$C must proceed at a moderate rate so that sufficient carbon remain after the He fuel is exhausted
Physics motivations: survival of $^{12}$C

✓ Properties of the $^{12}$C($\alpha$,\gamma)$^{16}$O reaction:
  - if there were resonance near in the energy-range (Gamow peak) corresponding to He-burning temperatures ($T_6=100$-200) then:
    • reaction would proceed at very high rate
    • carbon nuclei would be quickly destroyed
  - Energy level scheme of $^{16}$O shows no level available for such resonant behaviour up to $T_9=2$
  - oxygen can only be produced in stars —>> another mechanism must enable the reaction to proceed at a rate consistent with the observed C/O ratio
  - two mechanisms are available:
    • non-resonant direct-capture process
    • non-resonant type of capture into the tails of nearby resonances

sufficiently broad to influence the reaction-rate through its low-energy tail

by means of their high-energy tails they can enhance stellar burning
Physics motivations: He-burning and the reverse photo-disintegration reactions

The issue of the Coulomb barrier:

- at typical He-burning temperatures of $T_6 \sim 300$, $KT \sim 200$ keV $\ll E_{\text{coul}} (2 - 8 \text{MeV})$

\[
\sigma(E) = \frac{S(E)}{E} \exp \left( -31.29 \cdot Z_1 \cdot Z_2 \cdot \sqrt{\frac{\mu}{E}} \right)
\]

Nuclear reactions that generate energy and synthesise elements take place inside the stars in a relatively narrow energy window: the Gamow peak

Gamow Energy for He-burning reactions: few hundreds keV
Physics motivations: He-burning and the reverse photo-disintegration reactions

✓ Photodisintegration vs capture reaction: \[ B(b,\gamma)A \rightleftharpoons A(\gamma,b)B \]

✓ Principle of detailed balance in nuclear reactions:

\[
\sigma_{b\gamma} \cdot g_{b\gamma} \cdot p_{b\gamma}^2 = \sigma_{\gamma b} \cdot g_{\gamma b} \cdot p_{\gamma b}^2
\]

\[
\sigma_{b\gamma} = \sigma_{\gamma b} \cdot \frac{g_{\gamma b} \cdot p_{\gamma b}^2}{g_{b\gamma} \cdot p_{b\gamma}^2} = \sigma_{\gamma b} \cdot \frac{2J_{CN} + 1}{(2J_b + 1)(2J_B + 1)} \cdot \frac{E_{\gamma}^2}{E_{CM} \cdot \mu_{bb} c^2} \cdot 1
\]

\( g_{b\gamma}, g_{\gamma b} = \) spin factors
Physics motivations: He-burning and the reverse photo-disintegration reactions

✓ Photodisintegration vs capture reaction: \( B(b, \gamma)A \iff A(\gamma, b)B \)

✓ Principle of detailed balance in nuclear reactions:

\[
\sigma_{by} \cdot g_{by} \cdot p_{by}^2 = \sigma_{\gamma b} \cdot g_{\gamma b} \cdot p_{\gamma b}^2
\]

\[
\sigma_{by} = \sigma_{\gamma b} \cdot \frac{g_{by}}{g_{\gamma b}} \cdot \frac{p_{by}^2}{p_{\gamma b}^2} = \sigma_{\gamma b} \cdot \frac{2J_{CN} + 1}{(2J_b + 1)(2J_B + 1)} \cdot \frac{E_{\gamma}^2}{E_{CM}} \cdot \frac{1}{\mu_{bb} c^2}
\]

\( g_{by}, g_{\gamma b} = \text{spin factors} \)

\( \Rightarrow \) measure the cross section for the \( \alpha \)-capture reaction by means of the inverse photo-disintegration reaction
Physics motivations: He-burning and the reverse photo-disintegration reactions

✓ Photodisintegration vs capture reaction: \( B(b,\gamma)A \rightleftharpoons A(\gamma,b)B \)

✓ Principle of detailed balance in nuclear reactions:

\[
\sigma_{by} \cdot g_{by} \cdot p_{by}^2 = \sigma_{\gamma b} \cdot g_{\gamma b} \cdot p_{\gamma b}^2
\]

\[
\sigma_{by} = \sigma_{\gamma b} \cdot \frac{g_{\gamma b} \cdot p_{\gamma b}^2}{g_{by} \cdot p_{by}^2} = \sigma_{\gamma b} \cdot \frac{2J_{CN} + 1}{(2J_b + 1)(2J_B + 1)} \cdot \frac{E_{\gamma}^2}{E_{CM}} \cdot \frac{1}{\mu_{bb}c^2}
\]

\( g_{by}, g_{\gamma b} = \text{spin factors} \)

⇒ measure the cross section for the \( \alpha \)-capture reaction by means of the inverse photo-disintegration reaction

⇒ intense monochromatic \( \gamma \)-ray beams are needed
✓ Production of monochromatic $\gamma$-ray beams: Gamma Beam System (GBS)
Compton Back Scattering (CBS) of photons on ultra-relativistic electrons
*(the most efficient frequency amplifier)*

$$E_\gamma = 2\gamma_e^2 \cdot \frac{1 + \cos \theta_L}{1 + \left(\gamma_e \theta_\gamma\right)^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L \approx 4\gamma_e^2 E_L$$

$\theta_L \ll 1$
✓ OTPCs with GEMs (FUW): Optical-readout TPC with active areas of 20 x 20 and 35 x 20 cm$^2$

- developed for studying 2-proton radioactivity of exotic nuclei
- employed at NSCL, GSI, ISOLDE, Dubna
The inspiration

✓ OTPCs with GEMs (FUW): decays of $^{45}$Fe and $^{43}$Cr (NSCL/MSU, 2007)

NSCL/MSU, 2007

Pomorski et al., Phys. Rev. 83 (2011) 014306

Miernik et al., PRL 99 (07) 192501
the e-TPC project

✓ Next generation:

- an active-target TPC (e-TPC) to study reaction cross-sections of astrophysical interest where the reaction products are charged particles

- electronic readout:
  
  --> full unambiguous reconstruction of multiple-particle events is possible

  --> more gas mixtures can be uses: no need to have gases emitting photons in the visible (pure CO₂ can be used!!)
the e-TPC project

✓ Active target:
  - active volume: 35 cm x 20 cm x 20 cm
  - under-pressured (~100 mbar): low-energy particles!
  - gas-mixture tailored for the reaction of interest

✓ Charge-amplification:
  - 3 or 4 GEM structures

✓ Electronic read-out:
  - 3 independent linear sets of strips crossing at 60° (u-v-w)
  - fast multi-channel ADC (~1000 chn, 100 MS/s)
  - external trigger from the time-structure of the γ beam (100 Hz)
the e-TPC project: cross-section
the e-TPC project: read-out electrode

multilayer printed circuit

virtual pixel

Interconnected pads

U - strips

W - strips

V - strips
the e-TPC project: Monte Carlo simulations

✓ GEANT4 simulation of the γ-beam induced background with superimposed 0.5 MeV α particle (parallel to the readout plane at an angle of 45° with respect to the beam direction)

✓ Background: mainly electrons from γ conversion in the entrance window

✓ Time window: single macro-bunch in the e-TPC detector (CO₂ gas @100 mbar)
the e-TPC project: proof-of-principle studies

✓ Demonstrator detector:
  - active volume: 10 cm x 10 cm x 3 cm
  - u-v-w strip read-out: 192 channels (3x64)
  - 3 GEM foils
  - gas: 70% Ar + 30% CO2 @ 1 atm
the e-TPC project: proof-of-principle studies

✓ Demonstrator detector:

- tested first with 2-GEM configuration
- 16 read-out channels (oscilloscopes), point-like $^{55}$Fe X-ray source

*Aleksandra Lis (Univ. of Warsaw, 2013)*
the e-TPC project: proof-of-principle studies

✓ **Demonstrator detector:**

- detection of α-particle tracks (5.5 MeV from $^{222}$Rn decay)
the e-TPC project: proof-of-principle studies

✓ Demonstrator detector:

- detection of α-particle tracks (5.5 MeV from $^{222}$Rn decay)

- step 1: raw data

Jan S. Bihałowicz, Bsc Thesis (UW, 2014)
the e-TPC project: proof-of-principle studies

✓ Demonstrator detector:

- detection of $\alpha$-particle tracks (5.5 MeV from $^{222}$Rn decay)

- step 2: clusterization

Jan S. Bihałowicz, Bsc Thesis (UW, 2014)
✓ **Demonstrator detector:**

- detection of α-particle tracks (5.5 MeV from $^{222}\text{Rn}$ decay)
- step 3: reconstruction in 2D...

*Jan S. Bihałowicz, Bsc Thesis (UW, 2014)*
the e-TPC project: proof-of-principle studies

✓ Demonstrator detector:

- detection of α-particle tracks (5.5 MeV from $^{222}$Rn decay)
- step 3: ...and in 3D...

Jan S. Bihałowicz, Bsc Thesis (UW, 2014)
the e-TPC project: outlook

✓ The intense and monochromatic $\gamma$-ray beams of the ELI-NP facility will enable the measurement of photo-disintegration cross-sections for nuclear reactions relevant for thermonuclear reaction-rates in stars

✓ An active-target TPC detector with electronic strip-readout is being developed at the University of Warsaw (in collaboration with ELI-NP and University of Connecticut) to perform these studies

✓ R&D is in progress:
  - first tests with a model demonstrator detectors showed that unambiguous reconstruction of tracks can be performed
  - Monte Carlo simulations are being performed to study the beam-induced background

✓ First tests with low-energy $\gamma$-beams at ELI can be performed at the end of 2017

✓ First experiments with high-energy $\gamma$-beams at ELI in 2018
the e-TPC collaboration

**FUW**
J.S. Bihałowicz, M. Ćwiok, W. Dominik, Z. Janas, T. Matulewicz, C. M., K. Mikszuta, M. Pfützner

**ELI-NP**
Ovidiu Tesileanu

**Yale and UConnecticut**
M. Gai