Nuclear Astrophysics research at IFIN-HH

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Nuclear physics in stellar explosions Workshop ‘18
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Advances in nuclear astrophysics with direct and indirect methods at IFIN-HH

Results of doing nuclear astrophysics research in IFIN-HH Bucharest-Magurele in the last 3-4 years. There is progress on the two basic types of experimental activities:

• Direct measurements at low and very low energies with beams from the local 3 MV tandemron accelerator. Competitive for measurements into the Gamow window of reactions induced by light ions and alphas. Extra sensitivity is provided by the ultra-low background laboratory in a salt mine about 120 km away.

• Indirect measurements at international facilities with radioactive beams: TAMU, RIKEN

With help from IFIN-HH colleagues, I will mention some theory advances, too.

Complementary to earlier talks by Alexandra C. and Dana T.
1) 3 MV tandemron accelerator: 0.2 – 3.3 MV
   ▪ Good currents for alpha and light ion induced reactions
Detection
   ▪ Gamma-ray detection:
     ▪ Prompt
     ▪ From activation
   ▪ Large (120 cm diameter) new target chamber (+ several Si DSSSD detectors)
   ▪ Ultra-low background lab in salt mine

2) 9 MV pelletron + ROSPHERE + neutron dets
3 MV Tandetron™

Beam currents

860A Sputter Source

- $^{11}$B$^{3+}$ > 50 eμA
- $^{12}$C$^{3+}$ > 80 eμA
- $^{16}$O$^{3+}$ > 80 eμA
- $^{28}$Si$^{3+}$ > 70 eμA
- $^{31}$P$^{3+}$ > 70 eμA
- $^{58}$Ni$^{3+}$ > 20 eμA
- $^{63}$Cu$^{2+}$ > 20 eμA
- $^{75}$As$^{2+}$ > 10 eμA
- $^{197}$Au$^{2+}$ > 80 eμA

358 “Duoplasmatron” Source

- $^1$H$^+$ > 25 μA
- $^4$He$^+$ or $^3$He$^+$ > 3 μA

Na charge exchange canal

Activation and measurements in environments with ultralow background: (some) salt mines

Activation in nuclear laboratory (this is the 3 MV tandetron) → Measurement in salt mine Slanic Prahova (2.5 hrs from Bucharest - very low gamma-ray bkg)
Background spectra collected with a CANBERRA HPGe detector with 100% relative efficiency.

- Underground shielded: 2 cm Cu and 5 cm Pb
- Underground unshielded
- Ground unshielded

R. Margineanu, Krakow Epiphany Conference, 2010
• important reaction in nuclear astrophysics: $^{12}\text{C}+^{12}\text{C}$
• very difficult to measure, fluctuating due to resonances!

• No resonances observed in $^{13}\text{C}+^{12}\text{C}$! Obs: for most energies, the $^{12}\text{C}+^{12}\text{C}$ cross sections are suppressed!
• Only at resonant energies, the $^{12}\text{C}+^{12}\text{C}$ cross sections matches with those of $^{12}\text{C}+^{13}\text{C}$ and $^{13}\text{C}+^{13}\text{C}$!

• proposed tests of nucleus-nucleus models using $^{13}\text{C}+^{12}\text{C}$, measured in the Gamow window
Test react mech below barrier

• group
prof. X. Tang – IMP Lanzhou, China
The $^{13}$C+$^{12}$C Experiment: prompt and activation

In beam irradiation, thick targets

$^{12}$C($^{13}$C,p)$^{24}$Na

$^{24}$Na: $T_{1/2} = 15$ hr

$E_γ = 1369$, $2754$ keV

$^{13}$C$^{2+}$ beam

2-16 eμA

$^{13}$C beam energy 4.6 – 11. MeV ($E_{cm} = 2.3 – 5.4$ MeV), in steps of 0.2 MeV

$^{24}$Na (14.9590 hr) Decay Scheme
“microBq” Lab

Offline $\gamma$-ray technique

**Lab:** $\mu$Bq
**Depth:** 208 m, 560 m w.e.

**UNIREA Salt Mine**

**2 h drive**

**Bucharest**

**R. Margineanu et al., Applied Radiation and Isotopes 66,1501–1506, 2008**

**80,000 m$^2$**

**W: 35 m x H: 60 m**
Low level background counting

activation: 3.4 days  measurements: 3.9 days
Thick target method

Cross sections were calculated starting from the experimental yield:

\[ Y(E) = \int_{0}^{E} \sigma(E) \, dE \]

\[ \sigma(E) = \frac{Y(E + \Delta E) - Y(E)}{n_t} \]
Test of Predictive Power
Test of Predictive Power

Submitted to PRL, Sept 2018
Summary C+C

- $^{12}\text{C} + ^{12}\text{C}$
  - Hindrance model based on systematics does not work
  - Upper and lower limits are proposed
  - New techniques needed
  - To be compared with THM measurements – *Nature*, May 2018

- Collaboration(s) leads to better science!
-51 thick targets of natural Ni were irradiated: 

\[
\begin{align*}
^6\text{Ni}(26.22\%), & ^{61}\text{Ni}(1.14\%), ^{62}\text{Ni}(3.63\%), ^{64}\text{Ni}(0.93\%) \\
\end{align*}
\]

\[
\begin{align*}
^58\text{Ni} + \alpha & \rightarrow ^{62}\text{Zn} + \gamma & Q=3.364\text{MeV} & T_{1/2}=9.193\text{h} \\
& \quad \rightarrow ^{61}\text{Cu} + p & Q=-3.108\text{MeV} & T_{1/2}=3.333\text{h} \\
& \quad \rightarrow ^{54}\text{Fe} + 2\alpha & Q=-6.399\text{MeV} \\
& \quad \rightarrow ^{60}\text{Ni} + 2p & Q=-7.908\text{MeV} \\
& \quad \rightarrow ^{57}\text{Co} + p + \alpha & Q=-8.172\text{MeV} & T_{1/2}=271.74\text{d}
\end{align*}
\]

Offline measurements:
1. NAG Lab
2. microBq (Slanic-Prahova)

Talk by Dana Tudor
Activation measurements. Preliminary results

Experimental cross section for $^{64}\text{Zn}(\alpha, p)^{67}\text{Ga}$
Summary – work at home

Accelerator/infrastructure:
- New 3 MV tandetron - competitive for alpha and light ion induced reactions
- Ultra-low background lab in salt mine - excellent possibilities for gamma-ray detection from activation

Other topics:
- Exp: \((\alpha, n\gamma)\) and \((\alpha, \gamma)\) with ROSPHERE + neutron dets.
- Theory: OMP
- New workline: search for SN remnants with AMS (w. S. Bishop @ TUM)

NOTE: IFIN-HH is a TNA lab: PAC & support for outside groups (51% of beam time) available under ENSAR2;
Next PAC Oct. 26-27, 2018; deadline for submission Oct 15th
Indirect measurements - at outside facilities

• Coulomb and nuclear breakup, w RIBs
  – \(^9\)C case at RIBF, RIKEN – exp NP1412-
  SAMURAI29R1 – performed June 2018

• \(\beta\)-delayed proton decay @ Texas A&M
  University
  – New ASTROBOX2 detector – \(^{31}\)Cl \(\beta\)p-decay,
    (Oct. 2016), \(^{35}\)K (Oct. 2017), \(^{27}\)P (accepted for
    2019)

• ASTROBOX2E detector, to be completed
  for work in Europe
Breakup

Transfer or breakup vs proton capt in \(^{8}\text{B}\)

Model-independent shape w. ANC (Whittaker function)

Transfer happens here

Breakup happens here

\((p,\gamma)\) happens here

Details in talk by Alexandra Chilug
Inclusive and exclusive breakup of $^9$C in nuclear and Coulomb fields

Spokesperson: Livius Trache

Purpose: nuclear and Coulomb breakup of $^9$C: C & Pb targets

Results:

- Sec beam $^9$C ~50kpps, 83% pure
- new: Si-detector system-1024 ch. & electronics w. wide dynamic range (> 3000) – works!
- Identified protons in front Si, at $\Delta E \sim 300$ keV
- Identified main reaction channels: p+$^8$B & 2p +$^7$Be
- Full analysis under way.

Fig 1. Beam PID

Fig 2. PID in silicon strip detectors (SSD system) placed between target and FDC0. (up-right: proton signals in Si det)

Fig 3. PID in HODOs detectors (with gate on $^9$C beam)
Team

- **L. Trache**, A. Chilug, D. Tudor, I. Stefanescu, A. Spiridon, F. Carstoiu – *IFIN Bucharest*
- V. Panin, K. Yoneda, N. Togano, N. Aoi, S. Takeuchi, M. Kurokawa, H. Murakami, T. Motobayshi, ... – *RIKEN Nishina Center*
- Z. Halasz, Zs. Fulop, Z. Elekes, L. Stuhl, ... – *ATOMKI*
- LG Sobotka et al., *Wash Univ at St. Louis*
- S. Shimoura, E. Ideguchi, S. Go – *CNS, Univ Tokyo*
- K.I. Hahn,.. – *Ewha Womans University*
- **Jeff Blackmon, C. Rasco** – *Louisiana State University*
- A. Bonaccorso – *INFN Pisa*
- K. Ogata, ... – *RCNP Osaka*
Indirect methods. Beta-delayed proton decay measurements

4.1 Indirect Method: **Spectroscopy of resonances**

For radiative proton \((p,\gamma)\) reactions, use the inverse phenom:
\(p\)-decay of the same states populated by beta-decay

Proposed while at TAMU and studied with:

- very thin DSSD Si detectors
- A special gas detector ASTROBOX-1
- Cases: \(\beta p\)-decay of \(^{23}\text{Al},^{31}\text{Cl},^{35}\text{K}\) and \(^{27}\text{P}\)

4.2 Construction and measurements off-line and in-beam with the ASTROBOX 2 detector at Texas A&M University.

4.3 Construction of ASTROBOX2E in Magurele
Decay of $^{31}\text{Cl}$

$3/2^+$

$^{31}\text{Cl}$

$\Gamma_p$  

$\Gamma_\gamma$

$S_P$

Conditions:

$Q_{EC} > S_p + 2m_e c^2$

$J=1/2^+, 3/2^+, 5/2^+$

$^{31}\text{S}$

Resonant Capture

$^{30}\text{P}(p,\gamma)^{31}\text{S}$

Resonant contributions to reaction rate:

$\left\langle \sigma v \right\rangle_{re}$

Lower proton energies most important, but very difficult:

- lower branching
- increased exp difficulties (det windows, background, etc...)

Need energy, $J_r$ and resonance strength
Decay spectroscopy
Beta- and beta-delayed proton-decay

Explosive H-burning in novae
&
IAS in $T_z=-3/2$ nuclei
Isospin mixing
GT strength distribution

$^{22}\text{Na}$ depletion in novae
$^{23}\text{Al}\rightarrow^{23}\text{Mg}^* \Rightarrow ^{22}\text{Na}(p,\gamma)^{23}\text{Mg}^*$
& $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$

See Jordi’s list!
Experimental setup – thin Si detectors

MARS implantation station

Energy degrader

thermocooler

connectors

`E = E_p + kE_{recoil} + \langle \Delta E_\beta \rangle`

- **p-detector** – very thin DS Si strip 65 or 45 µm
  - W1-65  BB2-45

- **β-detector** – thick Si det 1 mm

- **γ-detector** – HPGGe 70% effic

M. McCleskey, LT et al, NIM A700, 124 (2013)
Comparison Si – gas detector

FIG. 7: (Color online) Full collected statistics for the $^{22}$Al data (black, solid) and the $^{22}$Mg data (blue, dashed). The energy is the total measured decay energy. Smoothed $^{22}$Mg spectrum, scaled to match the $^{22}$Al spectrum at 150 keV is shown with red dots and corresponding uncertainties. Upper panel shows only the low energy part where the proton group at $\sim 270$ keV is clearly visible on top of the $\beta$ background, whereas the lower panel shows the total spectra.

A. Saastamoinen, LT et al, PRC 83 (2011)
E. Pollacco, LT et al., NIM 2014

L. Trache - Natal 2015
Design and construction of the micromegas detector for AstroBox2. Measurements, data and nuclear structure calculations

Chamber: design and prod: TAMU
Micromegas: Bucharest, Saclay, CERN
Electronics: Bucharest
Gas (P10) handling: existing at TAMU
Assembly and source tests: Saclay + TAMU
In-beam test and use: Bucharest, Saclay, TAMU
$^{31}\text{Cl}$ $\beta p$ decay - AB2 exp Oct 2016
Some theory: Optical Model Potentials for nucleus-nucleus collisions

OMP for nucleus-nucleus collisions

Collaboration with F. Carstoiu – our interest (and his hobby!) on description of elastic scattering data and potentials to be used in the description of indirect measurements for nuclear astrophysics using RIB

- 4 papers published on p-transfer experiments used for NA – ANC method for $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ and elastic scattering of $^{17}\text{O}$ and $^{18}\text{O}$ at 12 MeV/nucleon

- 3 papers published to Rom. J. Phys.; I will not address here the details
NA events by IFIN-HH in 2018

Events organized by us (in collaboration or single):

a) COST training school CA 16117 ChETEC “An experiment of Nuclear Physics for Astrophysics using direct methods”, Bucharest-Magurele, Apr. 10-20, 2018

b) Carpathian Summer School of Physics 2018 (CSSP18), “Exotic Nuclei and Nuclear/Particle Astrophysics (VIII)”, Sinaia, Romania, July 8 – 21, 2018: 92 participants

c) ECT* workshop “Indirect methods in Nuclear Astrophysics”, Trento, Italy, Nov 5-9 , 2018
(w. C. Bertulani, A. Bonaccorso, T. Motobayashi and Zs. Fulop)
ChETEC training school: "An experiment of Nuclear Physics for Astrophysics using direct methods“

L. Trache and Mihai Straticiuc – in charge

Activities

From 10th to 21st of April 2018, consisting in classes and hands-on activities @ IFIN-HH, Magurele:

1. In a target laboratory.
2. Performing an experiment at the 3MV Tandetron™ (7 days around the clock, PAC approved in Oct. 2017).
3. Gamma-ray measurements at the 9 MV tandem and the ROSPHERE array.
4. De-activation measurements in a low background underground laboratory "microBequerel" in the Slanic-Prahova salt mine.

http://chetec-school.nipne.ro
http://www.chetec.eu/

“Trainers”:

• Prof. Marialuisa Aliotta (Univ. of Edinburgh) – Introduction to Nuclear Astrophysics
• Dr. Gyorgy Gyurky (ATOMKI Debrecen, TBC) – Experimental methods in NA: direct measurements
• Prof. Silvia Leoni (Univ. of Milano) – Gamma-ray spectroscopy in NA
• Dr. Romulus Margineanu (IFIN-HH)
• Dr. Raluca Marginean (IFIN-HH)
• Dr. Mihai Straticiuc (IFIN-HH)

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Carpathian Summer School of Physics, Sinaia, July 1-14, 2018

Two weeks of good science!!!
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  - NAG in Bucharest
    • Florin Carstoiu – theory collaborator
    • Alexandra Spiridon
    • Alexandra Chilug
    • Dana Tudor
    • Ionut Stefanescu
    • Iuliana Stanciu – now in PhD program at TU Muenchen
    • Madalina Radvar – now in master program at Uni Koeln/Bonn
  - MARS group at Texas A&M
  - RIKEN collaborators
  – AB2 collaborators: Lolly Pollacco (CEA/IRFU Saclay), Ruiz de Oliveira (CERN, G. Pascovici (IFIN-HH)

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Thank you for your attention!