Understanding the Universe: From Nuclei to the Stars

Dr. Adriana Banu
Biographical Sketch (L. Adriana Banu)

Professional Preparation
B.S. in Physics (*summa cum laude, top of the class*), July 2000, University of Bucharest, Romania
Ph.D. in Nuclear Physics (*magna cum laude*), July 2005, Mainz University, Germany
Postdoctoral Research Associate in Nuclear Astrophysics, 10/2005 – 08/2010, Cyclotron Institute, Texas A&M University, College Station, Texas, USA

Appointments
08/2010 – present: Assistant Professor, Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia 22807, USA

Honors, Awards, Grants
- Grant award by the Research Corporation for Science Advancement for the proposal “Determination of key astrophysical photonuclear reaction cross sections towards understanding the origin of p-nuclei” (2014-2016)
- Member of the CEU14 Review Committee for the 7th annual Conference Experience for Undergraduates held jointly with the DNP/JPS Fall Meeting, Waikoloa, HI (2014)
- Member of the International Scientific Committee of the Russbach School on Nuclear Astrophysics (2014-present)
- Invited lecture at “10th Russbach School on Nuclear Astrophysics”, Russbach, Austria (2013)
- Grant award by the Jeffress Memorial Trust for the proposal “Studying the (α,p)-process in X-ray bursts using rare isotope ion beams” to be executed at the Cyclotron Institute at Texas A&M (2012-2015)
- Invited seminar at Triangle University Nuclear Laboratories (TUNL), Durham, NC (2009).
- Selected for oral communication at the “10th Symposium on Nuclei in the Cosmos”, Mackinac Island, MI (2008).
- Over 100 citations in refereed publications.
- Scholarship at Padua University granted to outstanding European students through the European Cultural Exchange Programme ERASMUS, Padua, Italy (1999-2000)
- Fellowship at the GSI Summer Student School, Darmstadt, Germany (1999).
“The most incomprehensible thing about the universe is that it is comprehensible.”

—Albert Einstein
Nuclear Physics is basic to two major themes in astrophysics:

- the (nucleo)synthesis of all chemical elements
- the energy generation in stars and stellar environments
1. Where do the chemical building blocks of humankind come from?

2. What makes the stars shine?
In search of the building blocks of the Universe...
Charts of the nuclides:
What nuclear physicists like...

A chemical element (X) is uniquely identified by the atomic number $Z$!
Mass number: $A = N + Z$
Nucleosynthesis: the synthesis of Elements through Nuclear Reactions

Two original proposals:

*(full) Big-Bang nucleosynthesis*

All elements formed from protons and neutrons
sequence of n-captures and $\beta$ decays
soon after the Big Bang

*Stellar nucleosynthesis*

elements synthesised inside the stars
nuclear processes
well defined stages of stellar evolution

HINT: Investigate nuclear properties!

The Nobel Prize in Physics 1967

The Nobel Prize in Physics 1983

Which one is correct?
• **Big Bang Nucleosynthesis**

- occurred within the first 3 minutes of the Universe after the primordial quark-gluon plasma froze out to form neutrons and protons
- BBN stopped by further expansion and cooling (temperature and density fell below those required for nuclear fusion)
- BBN explains correctly the observed mass abundances of $^1$H (75%), $^4$He (23%), $^2$H (0.003%), $^3$He (0.004%), trace amounts (10^{-10}%) of Li and Be, and **no other heavy elements**

Mass stability gap at $A=5$ and $A=8$ !!!

**BBN**

**No way** to bridge the gap through sequence of neutron captures during BB ...

![Diagram showing the mass number (N) and atomic number (Z) of different elements, with a focus on the stability gap at A=5 and A=8.](image)
After that, very little happened in nucleosynthesis for a long time.

temperature and density too small!!!

It required galaxy and star formation via gravitation to advance the synthesis of heavier elements.

matter coalesces to higher temperature and density...

Because in stars the reactions involve mainly charged particles, stellar nucleosynthesis is a slow process.
Gamow peak

Maxwell-Boltzmann distribution
\( \propto \exp(-E/kT) \)

\[ V \]

\[ E \]

\[ 0 \]

proton

charged particles \( \rightarrow \) Coulomb barrier

energy available: from thermal motion

\[ kT \sim 8.6 \times 10^{-8} \, T[K] \, \text{keV} \]

\[ T \sim 10^7 \, \text{K} \, (\text{our Sun}) \Rightarrow kT \sim 1 \, \text{keV} \]

\[ T \sim 10^9 \, \text{K} \, (\text{supernovae}) \Rightarrow kT \sim 100 \, \text{keV} \]

\[
\frac{1}{4\pi\varepsilon_0} \frac{Z_1Z_2e^2}{r}
\]

tunneling effect

Coulomb potential

\[ E_{\text{kin}} \sim kT \, (\text{keV}) \]

tunnelling probability:
\( \propto \exp(-2\pi\eta) \)

\[
\eta(E) = \frac{Z_1Z_2e^2}{\hbar\nu}
\]
• Stellar life cycle

Interstellar gas

BIRTH gravitational contraction

DEATH explosion

Stars

element mixing

thermonuclear reactions

- energy production
- stability against collapse
- synthesis of “metals”
• Hydrogen Burning
  
  • slow or fast (explosive) H-burning
  • almost 95% of all stars spend their lives burning the H in their core (including our Sun). Our Sun is a slow nuclear reactor (a fusion reactor we could not make!)
until hydrogen fuel is depleted $\Rightarrow$ the life time of our sun depends on the nuclear reaction rates

diagram:

Life Cycle of the Sun

- Birth
- Now
- Gradual warming
- Red Giant
- Planetary Nebula
- White Dwarf

Billions of Years (approx.)

to scale

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14

life time of stars depends on their mass: at larger masses burn faster! We are lucky!
• Helium Burning: Carbon formation

• BBN produced no elements heavier than Li due to the absence of a stable nucleus with 8 nucleons

• in stars $^{12}C$ formation set the stage for the entire nucleosynthesis of heavy elements

How is Carbon synthesized in stars?

$T \sim 6 \times 10^8 \text{ K and } \rho \sim 2 \times 10^5 \text{ g cm}^{-3}$

$^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be}$

$^8\text{Be}$ unstable ($\tau \sim 10^{-16} \text{ s}$)

$^8\text{Be} + ^4\text{He} \leftrightarrow ^{12}\text{C}$
• Helium Burning: **Oxygen formation**

- **Oxygen production from carbon:**

\[
^{12}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} + \gamma
\]

**Carbon consumption!**

Reaction rate is very small \(\Rightarrow\) not all C is burned, but Oxygen production is possible and Carbon-based life became possible...
Nucleosynthesis up to Iron

A massive star near the end of its lifetime has “onion ring” structure

- Carbon burning \[ \Rightarrow T \sim 6 \times 10^8 \text{K} \]
  \[ \rho \sim 2 \times 10^5 \text{gcm}^{-3} \]

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^{4}\text{He} + 4.6\text{ MeV} \]

- Neon burning \[ \Rightarrow T \sim 1.2 \times 10^9 \text{K} \]
  \[ \rho \sim 4 \times 10^6 \text{gcm}^{-3} \]

\[ ^{23}\text{Na} + ^{1}\text{H} + 2.2\text{ MeV} \]

- Oxygen burning \[ \Rightarrow T \sim 1.5 \times 10^9 \text{K} \]
  \[ \rho \sim 10^7 \text{gcm}^{-3} \]

\[ ^{20}\text{Ne} + \gamma \rightarrow ^{16}\text{O} + ^{4}\text{He} \]

\[ ^{20}\text{Ne} + ^{4}\text{He} \rightarrow ^{24}\text{Mg} + \gamma \]

- Silicon burning \[ \Rightarrow T \sim 3 \times 10^9 \text{K} \]
  \[ \rho \sim 10^8 \text{gcm}^{-3} \]

\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^{4}\text{He} + 10\text{ MeV} \]

\[ ^{31}\text{P} + ^{1}\text{H} + 7.7\text{ MeV} \]

The major ash: Fe

Stars can no longer convert mass into energy via nuclear fusion!
• Nucleosynthesis beyond Iron

**WE BELIEVE THAT**

**HALF of THE ELEMENTS BEYOND IRON ARE PRODUCED IN EXPLOSIONS of SUCH STARS**

**SUPERNOVAE**
Almost 5 billion years ago, our solar system began the journey with its gravitation collapse...

If we look around us today, we can see what elements were in our interstellar cloud...
• Abundance of the Elements

Data sources:
Earth, Moon, meteorites, stellar (Sun) spectra, cosmic rays...

Features:
• 12 orders-of-magnitude span
• H ~ 75%
• He ~ 23%
• C → U ~ 2% (“metals”)

Abundance of elements and isotopes are UNIQUE finger prints of various cosmic processes. To interpret and understand them, diverse and vast nuclear physics knowledge is needed!!! Not fully solved!
Two big problems:
1. - reactions in stars involve(d) radioactive nuclei ⇒ use RNB
2. - very small energies and very small cross sections ⇒ indirect methods
RESOURCES:

Accelerator-based facilities for my current research in Nuclear Astrophysics

The most intense accelerator-driven γ-ray source in the world
The first sources of light:

Population III stars

First stars
about 400 million yrs.
Fate of Massive Pop III Stars

Dynamic instability

- \( T_c \approx 5 \times 10^7 \) K
- \( \rho_{\text{crit}} \approx 0.02 \) g cm\(^{-3}\)

Critical metallicity of CNO material for explosion:
- \( Z \geq 10^{-8} \), 250-300 \( M_\odot \) (Fryer et al., APJ 2000)
- \( Z \sim 10^{-9} \), 120-1000 \( M_\odot \) (Heger et al., APJ 2001)
Interest in $^{12}\text{N}(p,\gamma)^{13}\text{O}$

Hot pp chains and rap-process chains in low-metallicity objects

pp-I: $p(p,e^+\nu)d(p,\gamma)^3\text{He}(^3\text{He},2p)^4\text{He}$
pp-II: $^7\text{Be}(e^-,\nu)^7\text{Li}(p,\alpha)^4\text{He}$
pp-III: $^7\text{Be}(p,\gamma)^8\text{Be}(\beta^+\nu)^8\text{Be}(\alpha)^4\text{He}$

- process material from pp cycles into CNO nuclei

pp-IV: $^7\text{Be}(p,\gamma)^8\text{Be}(p,\gamma)^9\text{C}(\beta^+\nu)^9\text{B}(p)^8\text{Be}(\alpha)^4\text{He}$
pp-V: $^7\text{Be}(\alpha,\gamma)^{11}\text{C}(\beta^+\nu)^{11}\text{B}(p,2\alpha)^4\text{He}$
rp-I: $^7\text{Be}(p,\gamma)^8\text{Be}(p,\gamma)^9\text{C}(\alpha,p)^{12}\text{N}(p,\gamma)^{13}\text{O}(\beta^+\nu)^{13}\text{N}(p,\gamma)^{14}\text{O}$
rp-II: $^7\text{Be}(\alpha,\gamma)^{11}\text{C}(p,\gamma)^{12}\text{N}(p,\gamma)^{13}\text{O}(\beta^+\nu)^{13}\text{N}(p,\gamma)^{14}\text{O}$
rp-III: $^7\text{Be}(\alpha,\gamma)^{11}\text{C}(p,\gamma)^{12}\text{N}(\beta^+\nu)^{12}\text{C}(p,\gamma)^{13}\text{N}(p,\gamma)^{14}\text{O}$
rp-IV: $^7\text{Be}(\alpha,\gamma)^{11}\text{C}(\alpha,p)^{14}\text{N}(p,\gamma)^{15}\text{O}$
Indirect Methods: basic approach

- Measurement at lab energies
- Extract (nuclear structure) information
- Calculate astrophysical S-factor or reaction rates
- Compare with (reaction) calculations
- Compare with direct measurements
Radiative proton capture in stars: $B + p \rightarrow A + \gamma$ \([B(p,\gamma)A]\)

- Classical barrier penetration problem:
- low energies $\Rightarrow$ capture at large radii

\[
\sigma \propto |M|^2
\]

Reaction matrix element:

\[
M = \left\langle I_{Bp}^A (r_{Bp}) \hat{O}(r_{Bp}) \psi^+_l (r_{Bp}) \right\rangle
\]

At large radii:

\[
I_{Bp}^A (r) \approx C_{nlj} \frac{W_{-\eta,l+1/2} (2r\kappa)}{r}
\]

\[
\sigma_{capture} \propto \left( C_{Bp}^A \right)^2
\]
Measuring ANC in the laboratory

- e.g. $^\text{12}\text{N} + p \rightarrow ^\text{13}\text{O} + \gamma$ (astrophysical reaction of interest)

- *peripheral* proton transfer at lab. energy ($\sim 10$ AMeV): $^\text{12}\text{N} + ^\text{14}\text{N} \rightarrow ^\text{13}\text{O} + ^\text{13}\text{C}$

**Outside nuclear potential:**

\[
I_{bp}^A(r) \approx C_{nlj} \frac{W_{-\eta,l+1/2}(2\kappa r)}{r}
\]
ANC family tree

Asymptotic Normalization Coefficient
In nuclear structure & nuclear astrophysics

(courtesy Michael Wiescher)

ANC method (references):

- Xu, Gagliardi, Tribble, Mukhadmedzhanov, Timofeyuk, PRL 73, 2027 (1994)
- A.M. Mukhadmedzhanov et al., PRC 56, 1302 (1997)
- C.A. Gagliardi et al., PRC 59, 1149 (1999)
- L. Trache, F. Carstoiu, C.A. Gagliardi, R.E. Tribble, PRL 87, 271102 (2001)
Experimental Setup for $^{12}$N(p,$\gamma$)$^{13}$O study via ($^{12}$N,$^{13}$O) proton transfer reaction

**Momentum Achromat Recoil Separator (MARS)**

Detection system: 4 dE-E Silicon detectors
(dE-detectors are position sensitive)

**Primary beam:** $^{12}$C$^{3+}$ @ 23 MeV/u
Primary reaction: p($^{12}$C,$^{12}$N)n

**Secondary beam:** $^{12}$N$^{7+}$ @ 12 MeV/u, $\sim$ 200 kHz
Purity: $\sim$ 99.8%
Secondary reaction: $^{14}$N($^{12}$N,$^{13}$O)$^{13}$C
Secondary target: melamine ($C_3N_6H_6$), 1.6 mg/cm$^2$
Beam spot size: $3.8 \times 4.3$ mm (FWHM)

$^{12}$N is radioactive!

$T_{1/2} = 11$ ms
Flight time in MARS < 0.5 $\mu$s
$^{14}\text{N}(^{12}\text{N},^{13}\text{O})$ proton-transfer react $\Rightarrow ^{12}\text{N}(p,\gamma)^{13}\text{O}$ (rap proc)

$C^2(^{13}\text{O}) = \frac{\sigma_{\text{exp}}^{\text{diff}}(\vartheta)}{\sigma_{\text{DWBA}}^{\text{DWBA}}(\vartheta)/b^2}$

$C_{p_{1/2}}^2(^{13}\text{O}) = 2.53 \pm 0.30 \text{ fm}^{-1}$


— What is dark matter?
— What is the nature of the dark energy?
— How did the Universe begin?
— Did Einstein have the last word on gravity?
— What are the masses of the neutrinos and how have they shaped the evolution of the universe?
— How do cosmic accelerators work?
— Are protons unstable?
— Are there new states of matter at exceedingly high density and temperature?
— Are there additional space-time dimensions?

✓ How were the heavy elements from iron to uranium made?
— Is a new theory of matter and light needed at the highest energies?
Overview of main astrophysical processes

Elemental Abundances and the Study of $p$-Nuclei

Research goals:

Understanding the origin of $p$-Nuclei

Acquiring experimental data for use to validate astrophysical models.

Formed in Stars (Fusion)

‘nuclear astrophysics $p$-nuts’
### $p$-Nuclei Abundances

<table>
<thead>
<tr>
<th>Isotope</th>
<th>% Abundance</th>
<th>Isotope</th>
<th>% Abundance</th>
<th>Isotope</th>
<th>% Abundance</th>
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</thead>
<tbody>
<tr>
<td>$^{14}$Se</td>
<td>0.87</td>
<td>$^{114}$Sn</td>
<td>0.66</td>
<td>$^{158}$Dy</td>
<td>0.0524</td>
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<tr>
<td>$^{78}$Kr</td>
<td>0.354</td>
<td>$^{115}$Sn</td>
<td>0.35</td>
<td>$^{158}$Dy</td>
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<td>$^{84}$Sr</td>
<td>0.56</td>
<td>$^{120}$Te</td>
<td>0.089</td>
<td>$^{162}$Er</td>
<td>0.136</td>
</tr>
<tr>
<td>$^{92}$Mo</td>
<td>15.84</td>
<td>$^{124}$Xe</td>
<td>0.126</td>
<td>$^{164}$Er</td>
<td>1.56</td>
</tr>
<tr>
<td>$^{94}$Mo</td>
<td>9.04</td>
<td>$^{126}$Xe</td>
<td>0.115</td>
<td>$^{168}$Yb</td>
<td>0.135</td>
</tr>
<tr>
<td>$^{96}$Ru</td>
<td>5.51</td>
<td>$^{130}$Ba</td>
<td>0.101</td>
<td>$^{174}$Hf</td>
<td>0.18</td>
</tr>
<tr>
<td>$^{98}$Ru</td>
<td>1.87</td>
<td>$^{132}$Ba</td>
<td>0.0097</td>
<td>$^{180m}$Ta</td>
<td>0.0123</td>
</tr>
<tr>
<td>$^{102}$Pd</td>
<td>0.96</td>
<td>$^{138}$La</td>
<td>0.091</td>
<td>$^{180}$W</td>
<td>0.135</td>
</tr>
<tr>
<td>$^{106}$Cd</td>
<td>1.215</td>
<td>$^{136}$Ce</td>
<td>0.193</td>
<td>$^{184}$Os</td>
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<tr>
<td>$^{108}$Cd</td>
<td>0.875</td>
<td>$^{138}$Ce</td>
<td>0.25</td>
<td>$^{190}$Pt</td>
<td>0.0127</td>
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<tr>
<td>$^{113}$In</td>
<td>4.28</td>
<td>$^{144}$Sm</td>
<td>3.09</td>
<td>$^{196}$Hg</td>
<td>0.146</td>
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<tr>
<td>$^{112}$Sn</td>
<td>0.96</td>
<td>$^{152}$Gd</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Z

N

\[ (\gamma, n) \quad \beta^+ \quad (\gamma, p) \quad (\gamma, \alpha) \]
Study of the $^{94}$Mo($\gamma$,n)$^{93}$Mo Photodisintegration Cross Section at H$\gamma$S

Duke Free-Electron Laser Laboratory (H$\gamma$S Facility)

To attain results with a good degree of accuracy, a high photon flux is needed.

H$\gamma$S produces the most intense quasi-monoenergetic photon beam in the world, making it ideal for studying $^{94}$Mo($\gamma$,n).
Working at Duke University’s HIGS facility (spring 2014)

http://jmuphysics.blogspot.com/search?updated-max=2014-07-17T17:24:00-04:00

Proposal funded by Research Corporation!
How HlyS Works: Laser Compton Backscattering (LCB)

Relativistic electron \rightarrow \text{Compton scattering} \leftarrow \text{laser beam (eV)} \rightarrow \gamma-ray (MeV)

\[ E_\gamma = \frac{\hbar \omega \left(1 - \beta \cos \theta_i\right)}{1 - \beta \cos \theta_f + \frac{\hbar \omega}{E_{\text{electron}}} \left(1 - \cos \theta_{\text{photon}}\right)} \approx 4\gamma^2 \cdot E_{\text{laser}} \]

Example:

\[ E_{\text{laser}} = 3.3 \text{ eV} \]
\[ E_{\text{electron}} = 450 \text{ MeV} (\gamma = 882) \]
\[ E_\gamma = 10 \text{ MeV} \]

Experimental \((\gamma,n)\) Cross Section

\[
\gamma + ^{94}_{\downarrow}Mo \rightarrow ^{93}_{\downarrow}Mo + n
\]

The cross section, \(\sigma\), is similar to the probability of reaction.

Along with the dimensionalities of the reaction, this probability changes with \(E_\gamma\).

\[
\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \varepsilon_n}
\]

- \(N_n\) – number of neutrons detected using \(^3\)He counters
- \(N_\gamma\) - number of incident photons
- \(N_t\) – number of target atoms per unit area (enriched target)
- \(\varepsilon_n\) – neutron detection efficiency
Experimental Setup
Acknowledgments

This research is funded by the Research Corporation for Science Advancement – The Cottrell College Science Award

Triangle Universities Nuclear Laboratories (host of HIγS facility)
My research undergrads in action....
From HlγS to JMU

Madison Radiation Laboratory (2016)

Bremsstrahlung Radiation
Away from Stability!

Understanding nuclear processes at the extreme density and temperature conditions of stellar environments!

Facility for Rare Isotope Beams (FRIB) (located at Michigan State University)
What is the origin of the elements in the cosmos?

- **p process**
- **s process**
- **r process**

**FRIB reach**

- **Big Bang**
- **Stellar burning**

**Experimental data needed to interpret astronomy data and to test various r-process models against data (~20 r-process nuclei have been reached by experiments)**

Site unknown!
• Messages to take away...

Nuclear reactions play a crucial role in the Universe:

1. they provide the energy in stars including that of the Sun.
2. they produced all the elements we depend on.
3. nucleosynthesis is on-going process in our galaxy

There are ~300 stable nuclei in the Universe. By studying reactions between them we have produced ~3000 more (unstable) nuclei.

There are ~4000 more (unstable) nuclei which we know nothing about and which will hold many surprises and applications. Present techniques are unable to produce them in sufficient quantities.

It will be the next generation of accelerators and the next generation of scientists (why not some of you?!?) which will complete the work of this exciting research field.
“If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words?

*Everything is made of atom* - Richard Feynman

*Nobel Prize in Physics, 1965*

“If you want to make an apple pie from scratch, you must first create the universe…”

“We are star-stuff…” - Carl Sagan
Just As Your Parents Told You
You Really Are Star Material!

Courtesy Prof. J. Natowitz