Astrophysics and Nuclear Structure Challenges and Opportunities

- Overview
- The r-process
- X-ray bursts
- Neutron star crusts
- Supernovae

H. Schatz MSU/NSCL
Rare Isotopes in Nuclear Astrophysics

Future intensities (nuc/s)
- $>10^{12}$
- $10^{10}$
- $10^{6}$
- $10^{2}$
- $10^{-2}$
- $10^{-6}$

X-ray burst (RXTE)

Metal poor halo stars (Keck, HST)

Nova (Chandra)

Supernova

rp process

crust processes

protons

neutrons

Wavelength (Å)

4U1728-34

Novae (Chandra)
**r (apid neutron capture) process**

The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

**Open questions:**
- Where does the r process occur?
- Can we get from the r-process
  - Limits on the age of the universe?
  - Physics at extreme conditions?

Supernovae?

Neutron star mergers?
New Observations
r-process elements from single r-process events
in 3 very metal poor stars

Solar r-process elements from many events

→ Many more to come from ongoing surveys and followup campaigns (e.g. VLT)
Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie: H. Schatz, National Superconducting Cyclotron Laboratory
Calculation: K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame
Model: B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s
r-process reach of radioactive beam facilities
(example: fragmentation, reach for half-life measurement)

n-Skin in Na

Known half-life

Future Facility

New shell gap in O

Halo

"Li

208Pb

Suzuki et al. 1995 (GSI)

Thirolf et al. 2000 (MSU)

Stanoiu et al. 2003 (GANIL)

Known half-life

Brown 2003

Thirolf et al 2000 (MSU)

Stanoli et al. 2003 (GANIL)

Effective single-particle energy (MeV)

neutron number

5 10 15 20

5 10 15 20
Accreting neutron stars – X-ray burster

Neutron star
(H and He burn into heavier elements)

Companion star
(H + He envelope)

Accretion disk
(H and He fall onto neutron star)

X-ray burst

0 2000 4000 6000
Time (s)

0 1000 2000 3000 4000 5000
X-ray flux (cts/s)

New Observations:
(RXTE, SAX)

Superbursts
Nuclear Physics in the rp-process

**Theoretical reaction rate predictions:**

**Statistical model:** not applicable near drip line

(Rauscher et al. 1997)

**Shell model:** available up to A~63 but large uncertainties (often x1000 - x10000)

(Herndl et al. 1995, Fisker et al. 2001)

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**Rate measurements**

- Direct
- Indirect
  - Coulomb breakup
  - Transfer

**Mass measurements**

- ISOLTRAP, ANL, Yale
- ISOLDE, SPEG

**Decay measurements**

- GSI (FRS and Online Sep)
- GANIL, MSU, ORNL, ANL

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End: SnSbTe Cycle (Schatz 2001)
(p,d) in inverse kinematics at the NSCL

\[ p(^{34}\text{Ar},^{33}\text{Ar})d \]

\[ ^{34}\text{Ar} \rightarrow d \rightarrow \gamma \quad \text{(SEGA)} \]

\[ ^{33}\text{Ar}^* \rightarrow ^{33}\text{Ar} \quad \text{(S800 spectrometer)} \]

\[ \gamma \text{ in } ^{33}\text{Ar coincidence} \]

\[ ^{33}\text{Ar} \text{ level energies:} \]

- 3819(4) keV (150 keV lower)
- 3456(6) keV (104 keV lower)

New astrophysical \(^{32}\text{Cl}(p,\gamma)^{33}\text{Ar} \) rate

![Graph showing new and previous shell model rates with reduced uncertainty from x3000 to ~x2]

R. Clement et al.
To be published

Individual nuclear levels matter!
The fate of matter in the neutron star crust

Neutron star surface

Atmosphere (rp-process)

Ocean (e⁻ capture)

Crust (pycnonuclear reactions)

Border of known masses

Future facility reach

Neutron star surface

Electron capture

Electron capture and n-emission

Pycnonuclear fusion

Ni (28)
Fe (26)
Cr (24)
Ti (22)
Ca (20)
Ar (18)
S (16)
Si (14)
Mg (12)

(1.5 x 10¹² g/cm³)

(2.5 x 10¹¹ g/cm³)

(1.5 x 10⁹ g/cm³)

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Chandra observations of X-ray transients

KS 1731-260 (Wijands 2001)

Bright X-ray bursters 1998 - 2001
Accretion shut off early 2001
Observe heated crust directly
  • Constrain quiescent phase
  • Constrain cooling mechanisms

Far future: Constellation-X?
Supernovae

Pre collapse evolution of electron fraction:

- $^{55}\text{Fe}$, $^{53}\text{Mn}$, $^{59}\text{Ni}$
- $^{57}\text{Co}$
- $^{56}\text{Fe}$
- $^{57}\text{Fe}$, $^{53}\text{Cr}$
- $^{61}\text{Ni}$, $^{55}\text{Mn}$

$Y_e$ vs. Time till core collapse (sec)

- WW
- LMP

Need e-capture rates on nuclei (Langanke et al. 2003)

Experiments:
- Charge exchange (n,p) (d,2He) (t,3He),
- Normal and inverse kinematics

→ need fast beams

Electron density:
- Nucleosynthesis
- Dynamics
Conclusions

- **Unstable nuclei shape important aspects of the cosmos**

- **Fundamental open questions:**
  - The origin of the elements
  - Physics under extreme conditions – the cosmos as a laboratory?
  - What are the limits of nuclear existence?
  - How does nuclear structure evolve towards the limits?

- **Huge progress in astronomical observatories has to be followed by similar progress in nuclear physics**

- **Restaging of some of the most extreme astrophysical processes in the laboratory is now within reach with new facilities**

- **Complementary approach needed to get the data:**
  - Need all types of RIB facilities
  - Need stable beam facilities
  - Need nuclear theory: - not everything can be measured
    - Corrections for nuclei in stellar plasma