Why Produce Rare Isotopes?

- Nuclear Physics
- Astrophysics
- Medical Applications
- Stockpile Stewardship
- Material Science
Nuclear Physics: Go to the Limits

Neutron Drip Line?

Proton Drip Line?

Known Nuclei

Heavy Elements?

Fission Limit?
To boldly go where no one has gone before

- The neutron-dripline determines the end of the nuclear universe
- It is largely unexplored
- The quest for the unknown
“The thrill is that our ignorance exceeds our knowledge, the exciting part is what we don’t understand yet.”

Eric Cornell, 2001

“What Was God Thinking? Science Can't Tell”, *Time Magazine*, November 15, 2005
Fundamental Physics

Rocks → Crystals → Atoms → Nuclei → Quarks

Molecules
I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, “What are the strange particles?”) but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations.

Richard Feynman
From Simplicity to Complexity

Human life
Cells
Cell nucleus
DNA
Molecules
Atoms
Complexity in Nuclear Physics

High-energy physics is in the “What?” phase

What are the strange particles?

Nuclear physics is in the “How?” phase

… tell us much of great interest about the strange phenomena that occur in complex situations.
Push for the extremes, how far can one go:

- High energies
- High angular momentum
- Large Z, Superheavies
- Large N/Z ratio
- Largest Z/N ratio
New Physics at the Limits

Excitation Energy:
Perfect liquid

Angular Momentum:
Super-deformation, Hyper-deformation

Largest Z:
Island of superheavies

Largest N/Z:
Halos, Neutron skins, Changes of shell structure

Largest Z/N:
Two-proton emitter
Limits of Nuclear Stability

Neutron-bound: $T_{1/2} > 10^{-20}$ s

Neutron-unbound: $T_{1/2} < 10^{-20}$ s

Proton Drip Line?

Known Nuclei

Heavy Elements?

Fission Limit?
Known Limit of Neutron-Rich Nuclei
The neutron dripline has only been reached up to Z = 2 !!!
However, extrapolations:

\[ T_{1/2}^{35\text{Na}} = 1.5 \text{ ms} \]

\[ T_{1/2}^{37\text{Na}} \text{ also bound} \]

\[ T_{1/2}^{41\text{Si}}: -20 \pm 1930 \text{ keV} \]

\[ T_{1/2}^{43\text{Si}} \text{ also bound} \]
Homework

Data

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$y = -5.6033 \ln(x) + 197.91$

$y = -0.0139x^3 + 0.75x^2 - 11.843x + 241.42$
Possible Source of Data

- Possibly something concerned with increasing or decreasing # of protons/neutrons and atomic size….
- Maybe an average lifespan/half life for rare isotopes around the atomic weight of 185 (Tungsten, Rhenium)…
- Perhaps the data has to do with radioactivity trends as an element is pushed further and further away from its stable state.
- Energy required to penetrate into the nucleus of an atom in kilo-joules per mol.
- Decay chart for a radioactive element. x could be the number of years and y the remaining atomic mass. This element could be somewhere near Uranium.
- I have no idea as to what this data could possibly be.
  I have no clue on what this function could be.
Mass Predictions

Model Difference (MeV)

$S_p = 0$  \hspace{1cm} r-process  \hspace{1cm} $S_n = 0$

Known Masses

$N (Z=55)$
1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. .....
NASA: Timeline of the Universe

- Element Formation in Stars
- Planetary System Formation
- The Big Bang
- Forming Earth-like Planets
- Forming Jupiter-like Planets
- Chemistry of Life
The Origin of the Elements

X-ray burst (RXTE)

r process

rp process

Supernova (HST)
E = mc²

Total binding energy:
\[ B_{\text{tot}}(A,Z) = [ZM(1\text{H})+(A-Z)M(n)]c^2 - [M(A,Z)]c^2 \]

Neutron Separation Energy:
\[ S_n = B_{\text{tot}}(A,Z) - B_{\text{tot}}(A-1,Z) \]

Proton Separation Energy:
\[ S_p = B_{\text{tot}}(A,Z) - B_{\text{tot}}(A-1,Z-1) \]
**Total Energy (Mass) for Decay or Reaction**

**Reaction: Yes, gains energy:**
\[ {}^{120}\text{Sn} + n \rightarrow {}^{121}\text{Sn} + 6.2\text{MeV} \]

**Decay: NO, needs energy:**
\[ {}^{120}\text{Sn} + \gamma(6.2\text{MeV}) \rightarrow {}^{121}\text{Sn} \]

**Reaction: Yes, needs energy, but falls apart again:**
\[ {}^{158}\text{Sn} + n(0.7\text{MeV}) \rightarrow {}^{159}\text{Sn} \]

**Decay: YES, gains energy:**
\[ {}^{159}\text{Sn} \rightarrow {}^{158}\text{Sn} + n + 0.7\text{MeV} \]
Nuclear Stability

Binding Energy per Nucleon:

![Graph showing binding energy per nucleon vs mass number. The graph is labeled with 'Iron .56'.]
r-process

close to stability

120Sn + n

6.2MeV

121Sn

r-process path

136Sn + n
2.1MeV

137Sn

beyond the dripline

158Sn + n

-0.7MeV

159Sn

(γ,n) competes with (n, γ)
Flow of the r-process

Temperature: ~1-2 GK
Density: 300 g/cm³ (~60% neutrons !)

neutron capture timescale: ~ 0.2 μs

Rapid neutron capture

(γ,n) photodisintegration

β-decay

Equilibrium favors “waiting point”
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 Facilities
Hot CNO Cycle

- **Hot CNO Cycle** (T_e = 0.2)
- **Hot CNO Cycle** (T_e = 0.4)
- Breakout Reactions

**The Hot CNO Cycle**

\[ { }^{12}\text{C} \xrightarrow{(p, e)} { }^{12}\text{N} \xrightarrow{\beta^+} { }^{13}\text{P} \xrightarrow{e^+} { }^{13}\text{O} \xrightarrow{(p, y)} { }^{14}\text{N} \xrightarrow{T_9 = 0.4} { }^{14}\text{O} \xrightarrow{(p, y)} { }^{15}\text{O} \xrightarrow{T_9 = 0.2} { }^{15}\text{N} \xrightarrow{(p, e)} { }^{15}\text{O} \xrightarrow{T_9 = 0.2} { }^{15}\text{N} \xrightarrow{(p, y)} { }^{16}\text{O} \xrightarrow{(p, y)} { }^{17}\text{O} \xrightarrow{(p, y)} { }^{18}\text{O} \xrightarrow{(p, y)} { }^{19}\text{O} \xrightarrow{T_9 = 0.5} { }^{20}\text{O} \xrightarrow{T_9 = 0.5} { }^{21}\text{O} \xrightarrow{T_9 = 0.5} { }^{22}\text{O} \]

**CNO Cycle**

- \[ { }^{12}\text{C} \xrightarrow{(p, e)} { }^{12}\text{N} \xrightarrow{T_{1p} = 9} { }^{13}\text{N} \xrightarrow{(p, p)} { }^{14}\text{O} \]
- \[ { }^{14}\text{O} \xrightarrow{T_{1p} = 9} { }^{14}\text{N} \xrightarrow{(p, p)} { }^{15}\text{O} \xrightarrow{T_{1p} = 6} { }^{15}\text{N} \xrightarrow{(p, p)} { }^{16}\text{O} \xrightarrow{T_{1p} = 5} { }^{16}\text{N} \xrightarrow{(p, p)} { }^{17}\text{O} \xrightarrow{T_{1p} = 4} { }^{17}\text{N} \xrightarrow{(p, p)} { }^{18}\text{O} \xrightarrow{T_{1p} = 3} { }^{18}\text{N} \xrightarrow{(p, p)} { }^{19}\text{O} \xrightarrow{T_{1p} = 2} { }^{19}\text{N} \xrightarrow{(p, p)} { }^{20}\text{O} \xrightarrow{T_{1p} = 1} { }^{20}\text{N} \xrightarrow{(p, p)} { }^{21}\text{O} \xrightarrow{T_{1p} = 0} { }^{21}\text{N} \xrightarrow{(p, p)} { }^{22}\text{O} \]

**Seeds for rp Process**

- \[ { }^{12}\text{C} \xrightarrow{(p, e)} { }^{12}\text{N} \xrightarrow{T_{1p} = 9} { }^{13}\text{N} \xrightarrow{(p, p)} { }^{14}\text{O} \xrightarrow{T_{1p} = 6} { }^{15}\text{N} \xrightarrow{(p, p)} { }^{16}\text{O} \xrightarrow{T_{1p} = 5} { }^{16}\text{N} \xrightarrow{(p, p)} { }^{17}\text{O} \xrightarrow{T_{1p} = 4} { }^{17}\text{N} \xrightarrow{(p, p)} { }^{18}\text{O} \xrightarrow{T_{1p} = 3} { }^{18}\text{N} \xrightarrow{(p, p)} { }^{19}\text{O} \xrightarrow{T_{1p} = 2} { }^{19}\text{N} \xrightarrow{(p, p)} { }^{20}\text{O} \xrightarrow{T_{1p} = 1} { }^{20}\text{N} \xrightarrow{(p, p)} { }^{21}\text{O} \xrightarrow{T_{1p} = 0} { }^{21}\text{N} \xrightarrow{(p, p)} { }^{22}\text{O} \]
rp-process
$^{68}\text{Se}(2p,\gamma)^{70}\text{Kr}$

$^{68}\text{Se}+2p \quad ^{69}\text{Br}+p \quad ^{70}\text{Kr}$

$\Delta Q \quad -Q_z \quad Q_{z+1}$
Reduction of Stellar Lifetime
