Michigan State University’s FRIB Project
Where Do the Atoms in Your Body Come From?

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Power of 100,000

10^{-15} m scale: Nuclei

10^{-10} m scale: Atoms

10^{-5} m scale: Cells

1 m scale: People

10^{5} m scale: Large City

10^{10} m scale: Earth + Moon system
Distance Moon-Earth = 3.8 \cdot 10^{8} m, distance Sun-Earth = 1.5 \cdot 10^{11} m
All matter is made of atoms!

• **118** known elements
• Hydrogen, Helium, Lithium, …, Copernicium, + 6 more yet to be named
• Each atom is characterized by its charge number = number of electrons
• The nucleus of the atom consists of protons and neutrons and contains almost all of the mass (electrons contribute ~1 part in 2000)
• # protons = # electrons; atoms electrically neutral
All matter is made of atoms!

Electrons arranged in shells. Electrons in outer shell(s) determine chemical properties.
Atomic Nuclei

- Nucleus is 10,000 to 100,000 times smaller than atom, but contains almost all mass
- Isotopes of a nucleus are distinguished by different number of neutrons
- 251 known stable isotopes (none for Z=43 technetium, Z=61 promethium, Z>83)
Lifetimes

![Graph showing lifetimes with axes labeled N and Z, color scale ranging from stable to $<10^{-8}$ s.]

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Decays

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Element Abundances

Bauer & Westfall, 2010

Left over from Big Bang

Element Abundances

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Big Bang

\[ T(t) = \frac{1.5 \cdot 10^{10}}{\sqrt{t}} \text{ K s}^{1/2} \]

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Big Bang Afterglow

WMAP CMB

June 1992 Earth Temperatures [K]

210 260 310

2.7248 K
2.7250 K
2.7252 K

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He/H ratio from Big Bang

• Coming out of QGP, $T \sim 10^{11} \text{ K} (\sim 10 \text{ MeV})$
• $p$ and $n$ in equilibrium
• Number of $p$ and $n$
determined by Boltzmann factors

\[
\frac{n_n}{n_p} = e^{(m_n c^2 - m_p c^2)/k_B T}
\]

• $T \sim 0.86 \text{ MeV}$: weak reactions too slow to maintain equilibrium
• Ratio freezes out at

\[
e^{-1.293/0.86} = 0.222
\]
He/H ratio from Big Bang

• So far \( t = 1 \text{ s} \): 22 n for every 100 p, \( T \) still too high for nuclei to form

• \( t = 100 \text{ s} \): \( T \approx 10^9 \text{ K} \), nuclei (alpha particles) can form
  – Due to \( n \) beta decay (half life 15 min), only \( \sim 16 \ n \) are left for every 100 p

• All free n can get trapped in alphas:
  – 16 n and 16 p can form 8 alphas
  – Mass fraction of alphas (= nuclei of helium) is then \( 4 \times 8/(100+16) = 27\% \)
  – Close to observed value of 23\%
  – Big success for early Big Bang cosmology!
Element Abundances

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Fusion inside stars

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Fusion

- In the Sun, hydrogen nuclei fuse into helium (and release a lot of energy)
- Once most hydrogen is used up, the helium fuses to carbon, oxygen, neon, ..., iron
- Once the stellar core is all iron, fusion stops, and the star dies
- Nothing heavier than iron can be made inside a star!
Element Abundances

How were these created?

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r(apid)-Process

Calculation: Shinja Wanayo, Tokyo

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r(apid)-Process - the movie
r(apid)-Process - the movie
How old are Atoms on Earth?

- Solar system formed 4.6 billion years ago from interstellar dust cloud via gravitational collapse
  - Dust cloud generated from previous supernova explosion
- Most atoms on Earth > 4.6 billion years old
All matter is made of atoms!

This includes us: We are made from the ashes of a dying star!

Mass Fraction, Human Body

- Oxygen 65%
- Carbon 18%
- Hydrogen 10%
- Nitrogen 3%
- Calcium 1.5%
- Phosphorus 1.2%
- Others 1.3%

Others: Sulfur, chlorine, sodium, magnesium, iron, cobalt, zinc, iodine, selenium, fluorine, ...

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How Many Atoms Inside of Us?

- Assume a mass of 70 kg (~155 lb)
- Approximately $6.7 \cdot 10^{27}$ atoms
- $6,700,000,000,000,000,000,000,000,000,000$

Stack 10 million atoms on top of each other:
Thicknes of a fingernail
Atom Exchange

• Our bodies constantly exchange atoms with environment
  – Breathing (produces ~1 kg of CO₂/day)
  – Eating, drinking
  – Transported to each of our ~100 trillion cells via blood vessel network of ~100,000 km total length

• Exchange >10 times our body weight with biosphere each year
  – ~50,000 kg during average life time
Where do Exchanged Atoms go?

- Majority of atoms expelled from body are contained in CO₂ and H₂O
  - CO₂ enters atmosphere
  - H₂O distributed in biosphere
- Rapid (order of days to years) mixing with other atoms and distribution throughout the biosphere
Weight of the Atmosphere

Air pressure ~ 101,000 N/m²

Force of the atmosphere on surface of Earth = Weight of atmosphere

- Weight = \( m g \)
- Force = \( p A = p \, 4\pi \, r^2 \)
- Weight = Force
  
  \[ m \, g = p \, 4\pi \, r^2 \]

- \( m = p \, 4\pi \, r^2 / g \)
  
  \[ = (1.01 \cdot 10^5 \text{ N/m}^2) \, 4\pi (6.37 \cdot 10^6 \text{ m})^2 / (9.81 \text{ m/s}^2) \]

  \[ = 5.2 \cdot 10^{18} \text{ kg} \]
Size of the Biosphere

Atmosphere: \(~100 \text{ km thick, } m = 5.2 \cdot 10^{18} \text{ kg}\)
- equivalent 10 m water depth

Biosphere:
- Oceans of average depth ~ 3 km
- Land mass with soil, plants, animals
- Factor ~10^2 more mass than atmosphere

Total mass of biosphere ~ \(5 \cdot 10^{20} \text{ kg}\)
How many atoms do you have from ...?

• Probability that a given atom has been part of the body of a given person (historical figure)

\[ p = \frac{50,000 \text{ kg}}{5 \cdot 10^{20} \text{ kg}} = 1 \cdot 10^{-16} \]

• Number of atoms in your body right now that once belonged to <fill in the blank>

\[ N = p \cdot N_{\text{atoms}} = (7 \cdot 10^{27}) (1 \cdot 10^{-16}) = 7 \cdot 10^{11} \]

Approximately a trillion atoms!!!
Alchemy

• Primary Objective:
  • (Re)Creation of the Philosopher’s Stone
  • =“Magnum Opus”

• Philosopher’s Stone
  • Turns common metals (lead, iron) into silver or gold
  • Elixir of life

• Attempted for many centuries
Success in the 20th Century

- “Gold can be extracted from mercury, but mercury cannot be transmuted into gold.” 1924 Editors of Scientific American
- “It was not until 1941 that gold was actually prepared from a base metal. By bombarding mercury with fast neutrons, Sherr, Bainbridge, and Anderson obtained three radioactive isotopes of gold. Even that did not fulfill the dream of the alchemists; the gold was radioactive and the process did not produce wealth; it consumed it.” A Philatelic Ramble Through Chemistry (Heilbronner and Miller; Verlag 1998)
NSCL, National Superconducting Cyclotron Laboratory
Layout of NSCL
Overview of Coupled Cyclotrons

K500
Superconducting Cyclotron

K1200
Superconducting Cyclotron

A1900 Fragment Separator
Fly-by of NSCL Coupled Cyclotron Facility
The next step: FRIB
MSU Project Management Team

The MSU FRIB Project Management Team designs and establishes FRIB as a Department of Energy Office of Science national user facility to support the mission of the Office of Nuclear Physics. Once FRIB is completed the FRIB Project will cease to exist and the MSU FRIB Laboratory will operate FRIB as a national user facility.

Thomas Glasmacher
Project Manager

Donna Donovan
Deputy Project Manager

Al Zeller
Associate Project Manager

Jie Wei
Accelerator Systems Division Director

Georg Bollen
Experimental Systems Division Director

Brad Bull
Conventional Facilities Division Director

Peter Grivins
Environmental, Safety, Health, and Quality Manager

Robert Lowrie
Environmental, Safety, and Health Deputy Manager

Dan Stout
Project Chief Engineer

The MSU FRIB Laboratory will operate FRIB as a national user facility once the FRIB Project is complete. During design and establishment of FRIB, the FRIB Laboratory interacts with the scientific community on MSU's behalf.

Konrad Gelbke
FRIB Laboratory Director

Bradley Sherrill
FRIB Chief Scientist
A decade-long battle for a Mega-Project in Michigan: status as of 2007

RIA at MSU Projected Site

*RIA is the 900 million dollar Rare Isotope Accelerator being pursued by MSU*
A decade-long battle for a Mega-Project in Michigan: status as of 2009

FRIB: Preliminary Design
A decade-long battle for a Mega-Project in Michigan: status as of now

FRIB Final Design: Cutaway Drawing
FRIB: Proposed Experiment Areas
FRIB 3-Stage Fragment Separator
Timeline for FRIB

- FRIB timeline is dependent on funding by Congress and approval by Department of Energy

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Construction Status

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Construction Status
Construction Status
Industrial Partners

• Industry-built superconducting RF cavity
  – Successfully tested at JLAB
  – March 4, 2012
What New Nuclides Will FRIB Produce?
Key: All Produced are Available for Study

- FRIB will produce more than 1000 NEW isotopes at useful rates
- Interaction with Theory is key to making the right measurements
- Exciting prospects for study of the drip line to mass 120 (compared to 24)
- Production of most of the key nuclei for astrophysical modeling
- Harvesting prospects near stability

Rates are available at http://groups.nscl.msu.edu/frib/rates/

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Reach of FRIB: Will Allow Modeling of the r-Process; We will understand the Origin of our Elements!

- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields

Current reach:
- First experiments
- FRIB reach for half-lives
- Known half-life

FRIB reach for (d,p):
- N=126
- Key Nuclei:
  - (66) Dy
  - (68) Er
  - (69) Tm
  - (70) Yb

Future Reach:
- RISAC

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Rare Isotopes For Society

• Isotopes for medical research
  – Examples: $^{47}$Sc, $^{62}$Zn, $^{64}$Cu, $^{67}$Cu, $^{68}$Ge, $^{149}$Tb, $^{153}$Gd, $^{168}$Ho, $^{177}$Lu, $^{188}$Re, $^{211}$At, $^{212}$Bi, $^{213}$Bi, $^{223}$Ra (DOE Isotope Workshop)
  – $\gamma$-emitters $^{149}$Tb, $^{211}$At: potential treatment of metastatic cancer
  – Example: Ca-isotopes for bone research

• Reaction rates for stockpile stewardship – non-classified research
  – Determination of extremely high neutron fluxes by activation analysis
  – Rare isotope samples for $(n,\gamma)$, $(n,n')$, $(n,2n)$, $(n,f)$ e.g. $^{88,89}$Zr
    • Same technique important for astrophysics
  – More difficult cases studied via surrogate reactions $(d,p)$, ...

• Tracers for Geology, Condensed Matter Physics ($^8$Li), Material Science, Biology ...

Isotope harvesting is included in the FRIB scope

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Example: Technetium Scan

- Rare isotopes for medical imaging / treatment
- Future isotope use will allow to focus on particular element and allow study of biological processes on different time scales, from milliseconds to years

Bauer & Westfall, 2010

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Summary

• Atoms in our bodies are *immortal*
• We constantly *exchange* atoms with the environment
• ~*trillions* of atoms in our bodies have been in those of historical figures
• We have achieved the alchemists’ ultimate goal and can *trans-mutate* atoms
• *Designer isotopes* can be used for fundamental studies and for medical and technical applications
• **FRIB** will be Mid-Michigan’s world-leading entry into this field
Final Word

• You can follow my musings on Twitter: http://twitter.com/BauerWestfall

• Email: bauer@pa.msu.edu

• Bring your friends & families
  – NSCL /FRIB tours
    • (Planetarium is next door, too)