

Reactions (lecture 1)

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Michigan State University

overview

Lecture 1:

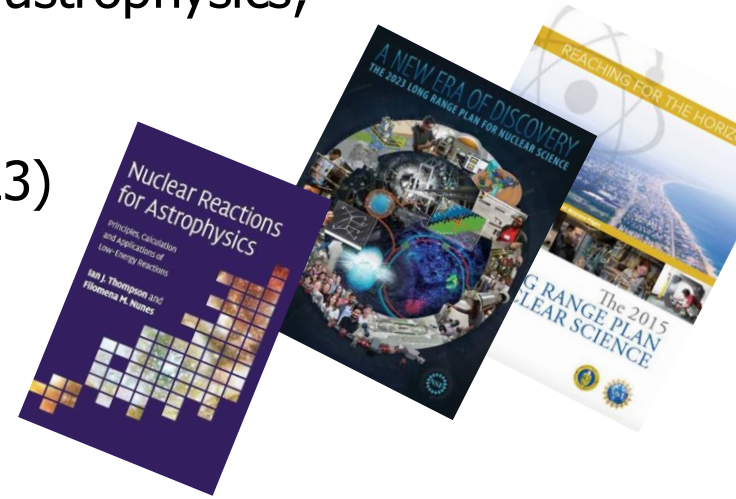
- why reactions?
- reactions and big science questions
- basic concepts in reactions
- production of the exotic nuclei and FRIB

Lecture 2:

- theories for nuclear reactions
- optical model
- Bayesian uncertainty quantification
- emulators for reactions
- hands-on example

Important references

- Thompson and Nunes, Nuclear reactions for astrophysics, Cambridge University Press
- Nuclear Physics Long Range Plan (2015, 2023)



Several pieces borrowed from many places:

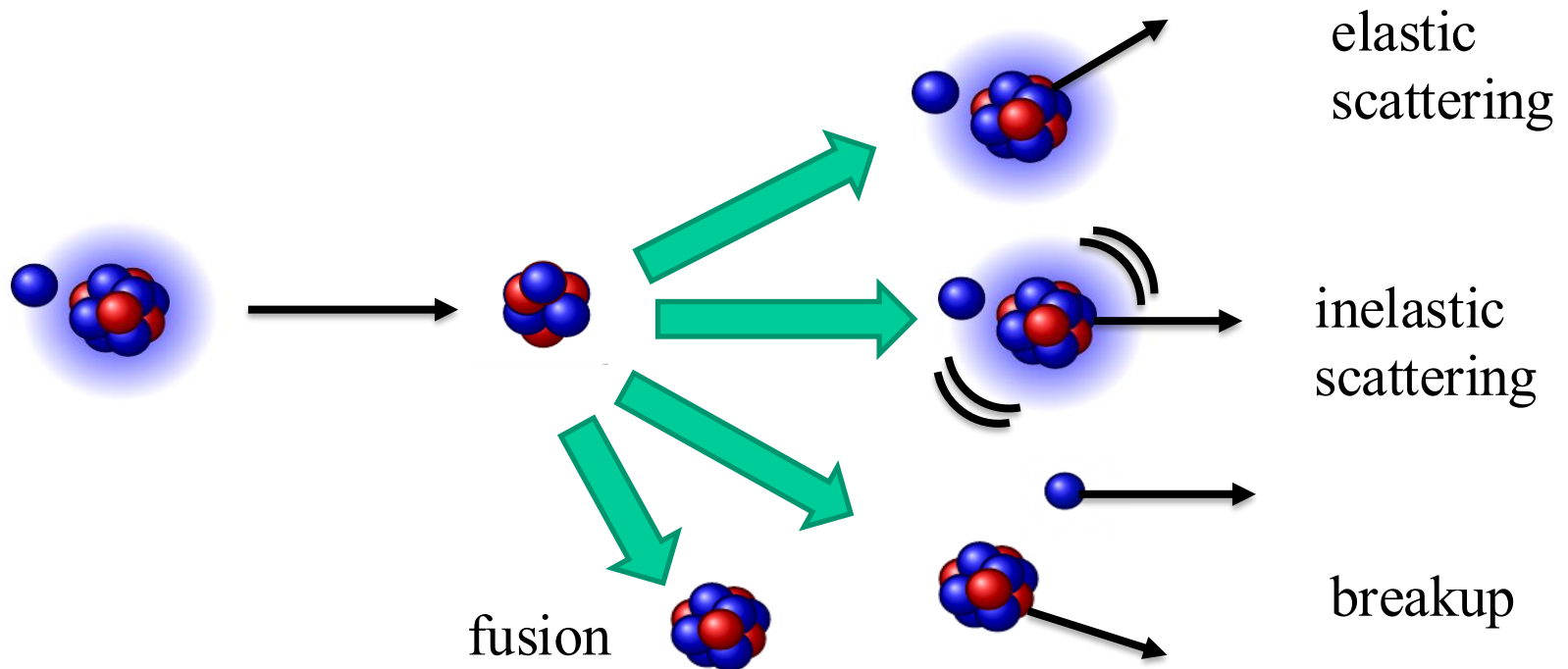
- Chloe Hebborn's lectures in nuclear reactions
XXII Escola de Verão de Física Nuclear Teórica 2025, Niteroi
- Gregory Potel's slides on the optical potential
Compound Nuclear Reactions Conference 2024
- Pablo Giuliani's slides on reduced order methods
STREAMLINE collaboration meeting 2026



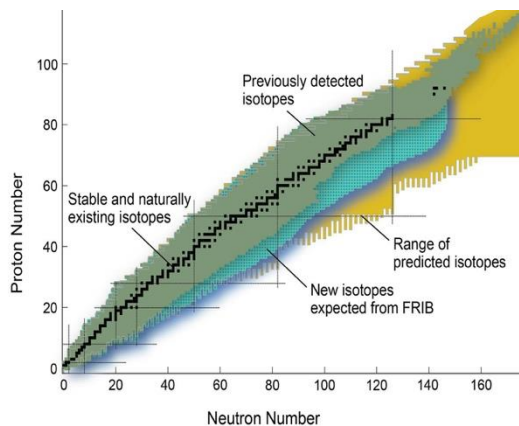
what is a nuclear reaction?

A nuclear reaction is a process in which the projectile collides with a target, and the nuclei involved change due to their interaction.

It can result in the formation of one or more nuclei that often release or absorb momentum and energy.



why do we care about reactions?



structure of matter



astrophysics



Stockpile stewardship



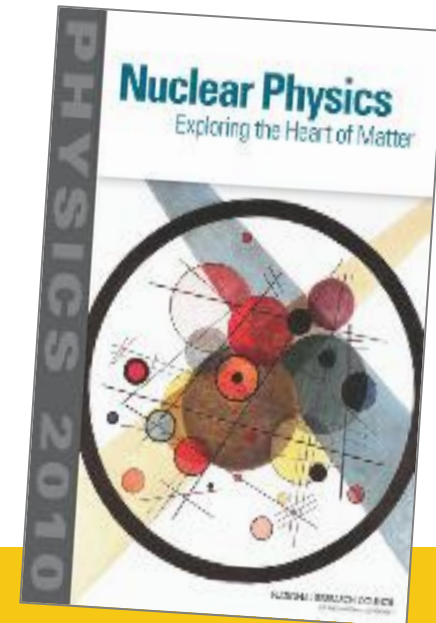
Nuclear energy and nuclear waste



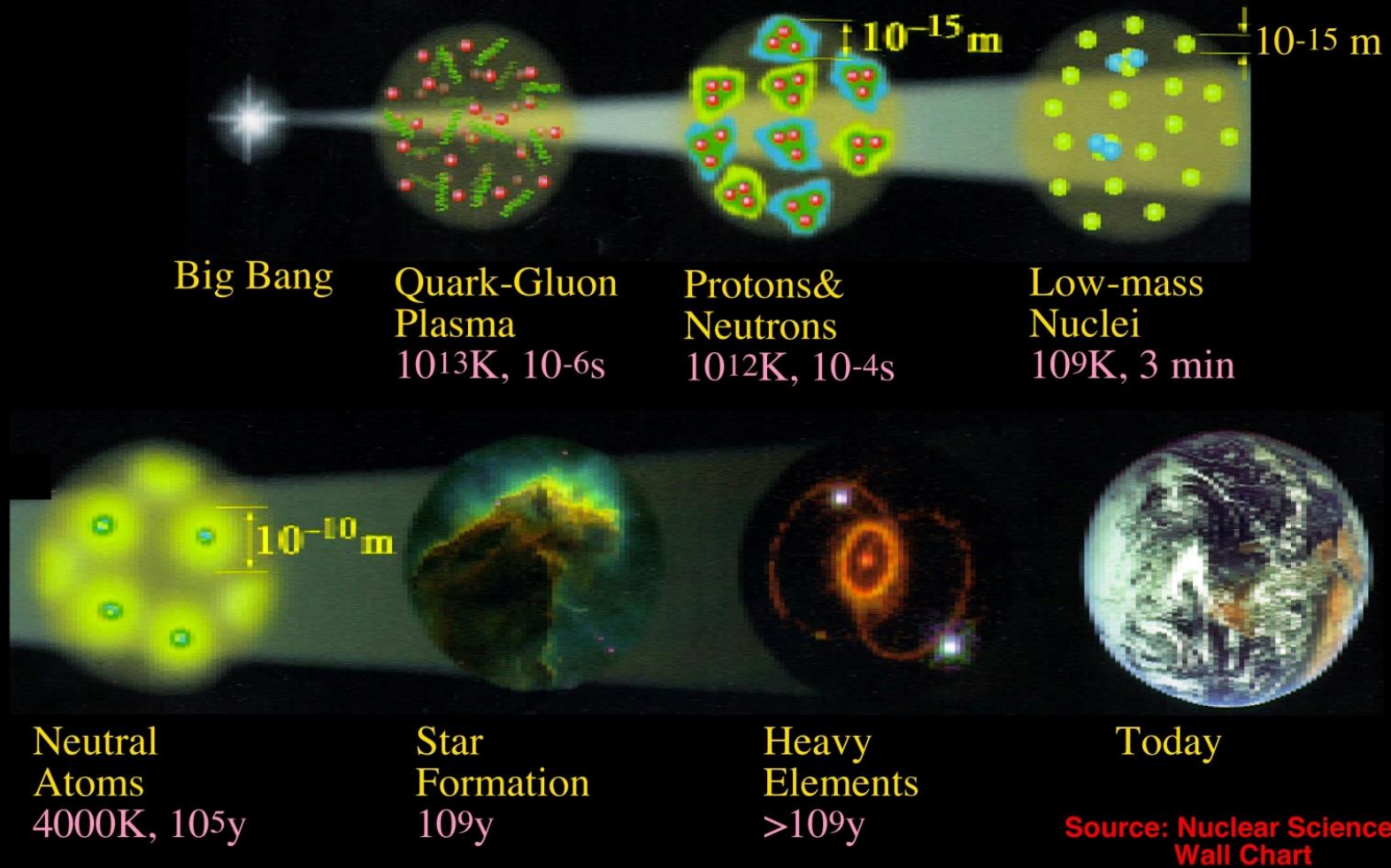
Nuclear medicine

reactions connect to the big science questions

- 1) *How did matter come into being and how does it evolve?*
- 2) *How does subatomic matter organize itself and what phenomena emerge?*
- 3) *Are the fundamental interactions that are basic to the structure of matter fully understood? and*
- 4) *How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?*



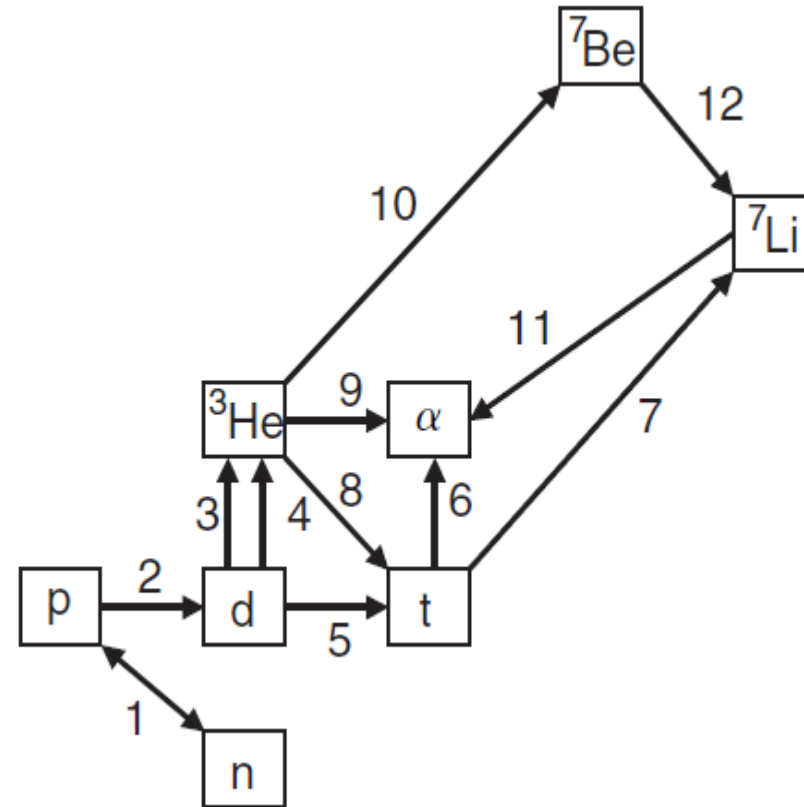
Big science questions: our history



Reactions play a role in our whole history, starting around 3 min after the BB!

primordial nucleosynthesis

- 1: $n \leftrightarrow p$
- 2: $p(n, \gamma)d$
- 3: $d(p, \gamma)^3\text{He}$
- 4: $d(d, n)^3\text{He}$
- 5: $d(d, p)t$
- 6: $t(d, n)\alpha$
- 7: $t(\alpha, \gamma)^7\text{Li}$
- 8: $^3\text{He}(n, p)t$
- 9: $^3\text{He}(d, p)^4\text{He}$
- 10: $^3\text{He}(\alpha, \gamma)^7\text{Be}$
- 11: $^7\text{Li}(p, \alpha)^4\text{He}$
- 12: $^7\text{Be}(n, p)^7\text{Li}$

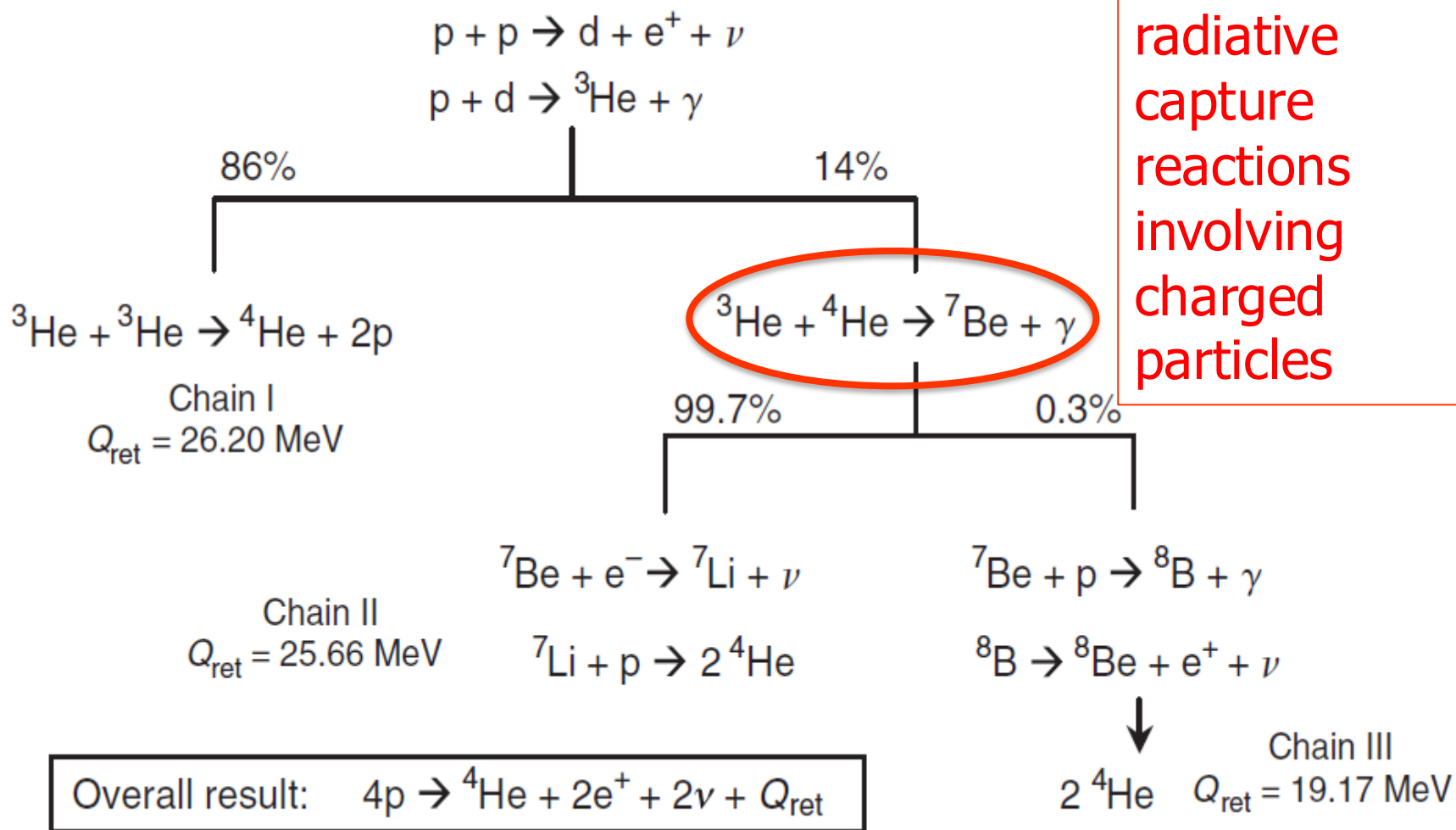


Q-value for $p(n, \gamma)d$ 2.26 MeV

$T(\text{universe to cool down to } E=2.26)=7 \text{ min}$

This is slightly less than $T(\text{free neutron decay})$

reactions in light stars



Coulomb effects in reactions are important

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

Astrophysical S-factor

$$\eta = Z_1 Z_2 e^2 / (\hbar v)$$

Sommerfeld parameter

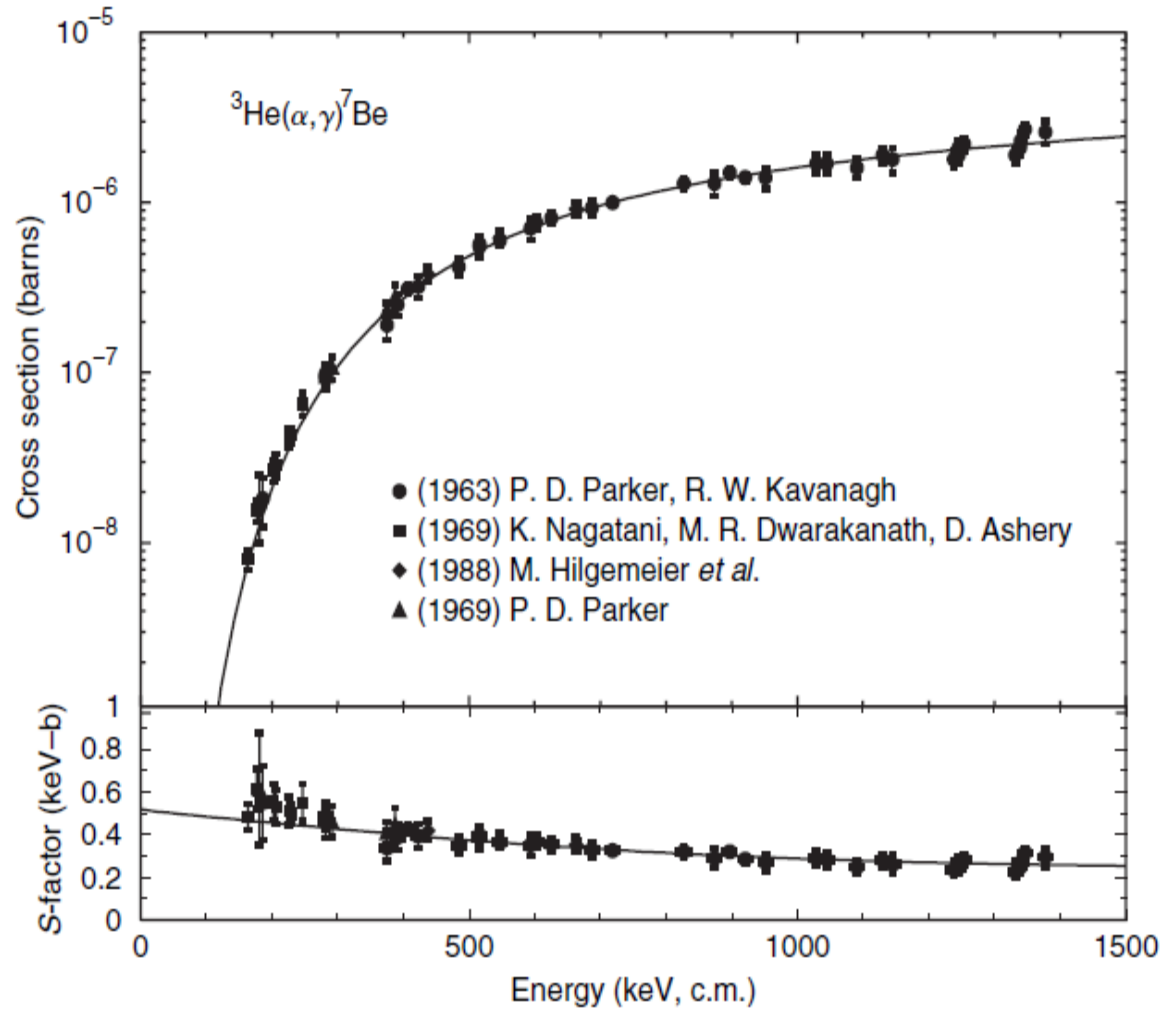


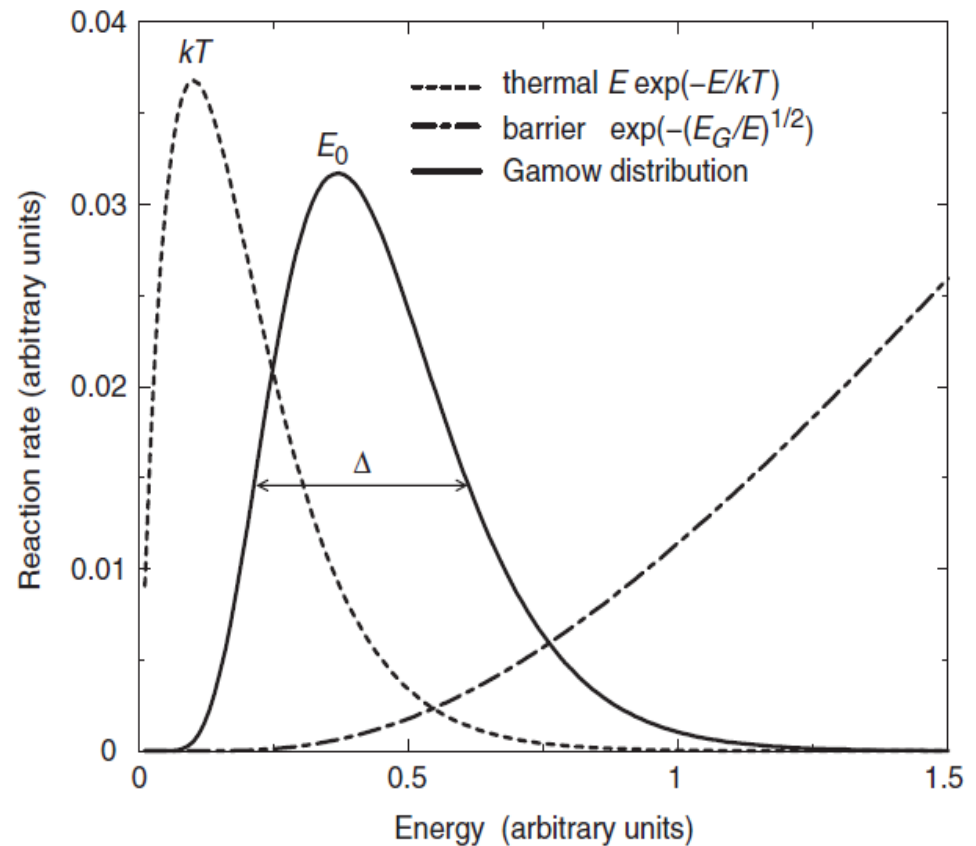
Fig. 1.4. Dependence of cross section and $S(E)$ on energy, for the reaction ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$. The solid curve is a calculation to be discussed in Appendix B.

reaction rates and the Gamow peak

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu_{12} (k_B T)^3}} \int_0^\infty S(E) \exp\left(-\frac{E}{k_B T} - \sqrt{\frac{E_G}{E}}\right) dE.$$

$$E_G = 4\pi^2 \eta^2 E = 2\mu_{12} (\pi Z_1 Z_2 e^2)^2 / \hbar^2$$

$$E_0 = \left(\frac{E_G k_B^2 T^2}{4} \right)^{\frac{1}{3}}$$



solar neutrino puzzle

status in the nineties:
measured solar neutrino flux \ll predicted flux

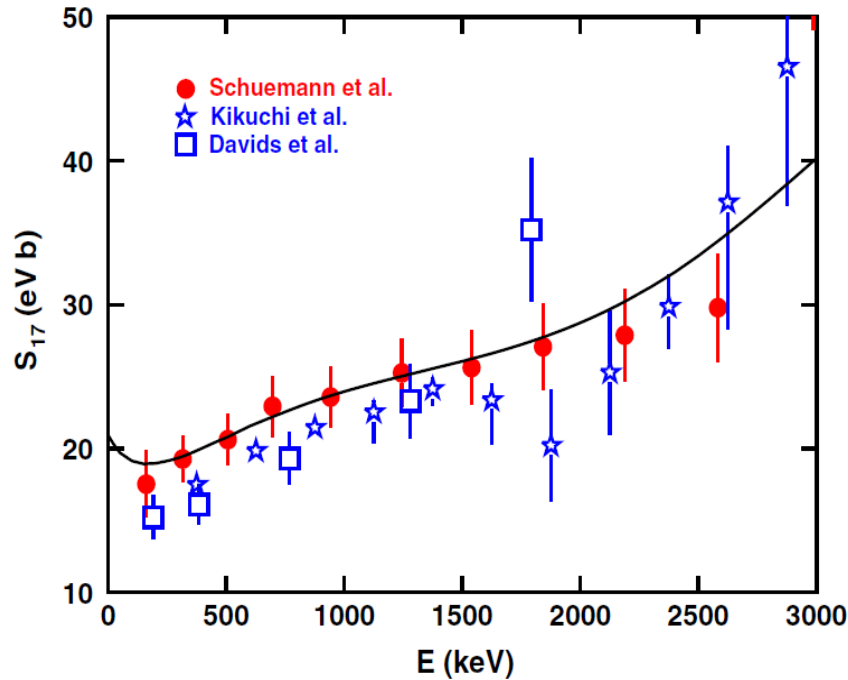


FIG. 8 (color online). S_{17} values from CD experiments. Full circles: latest analysis of the GSI CD experiment (Schümann *et al.*, 2006); open stars: Kikuchi *et al.* (1998) analyzed in first-order perturbation theory; open squares: Davids and Typel (2003). The error bars include statistical and estimated systematic errors. The curve is taken from the cluster-model theory of Descouvemont *et al.* (2004), normalized to $S_{17}(0) = 20.8$ eV b.

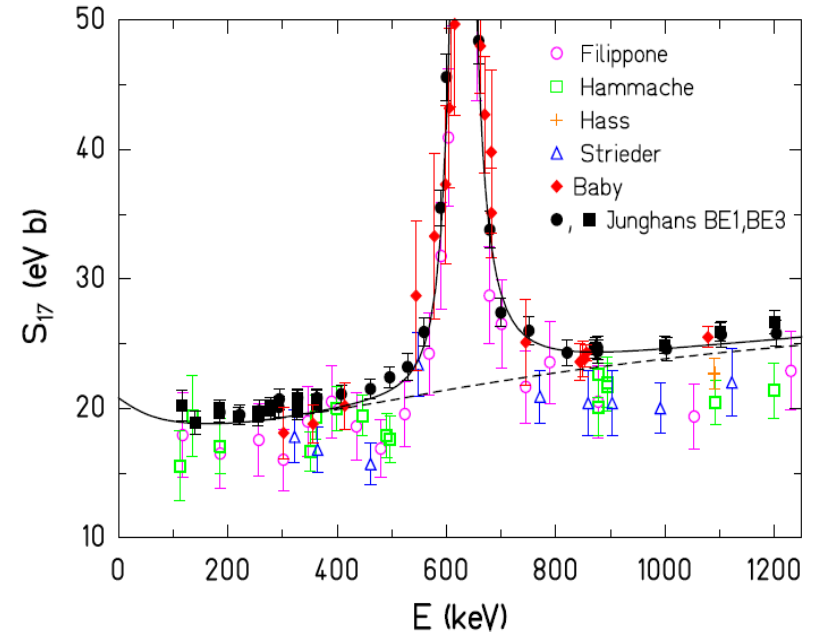
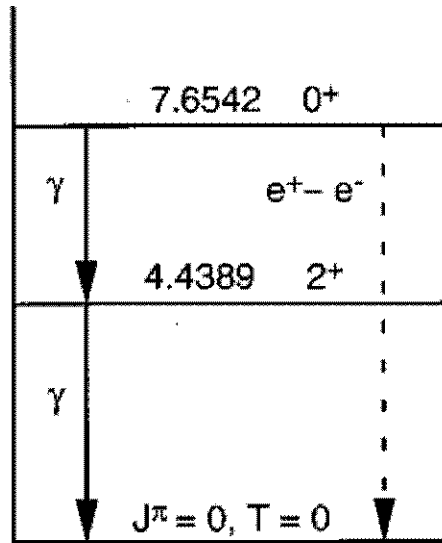


FIG. 9 (color online). $S_{17}(E)$ vs center-of-mass energy E , for $E \leq 1250$ keV. Data points are shown with total errors, including systematic errors. Dashed line: scaled Descouvemont (2004) curve with $S_{17}(0) = 20.8$ eV b; solid line: including a fitted 1^+ resonance shape.

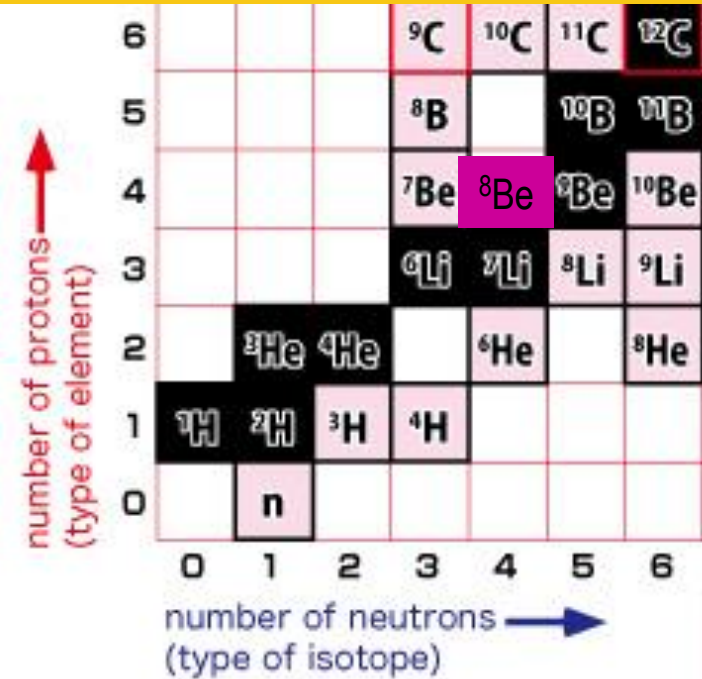
triple-alpha reaction and Hoyle state



$$\frac{7.2747}{3\alpha}$$



$$\frac{7.3666}{\alpha + {}^8\text{Be}}$$



Resonant capture reactions

heavier elements

big bang: neutrons, protons

solar-type stars: alphas, C, O

How about Ca?

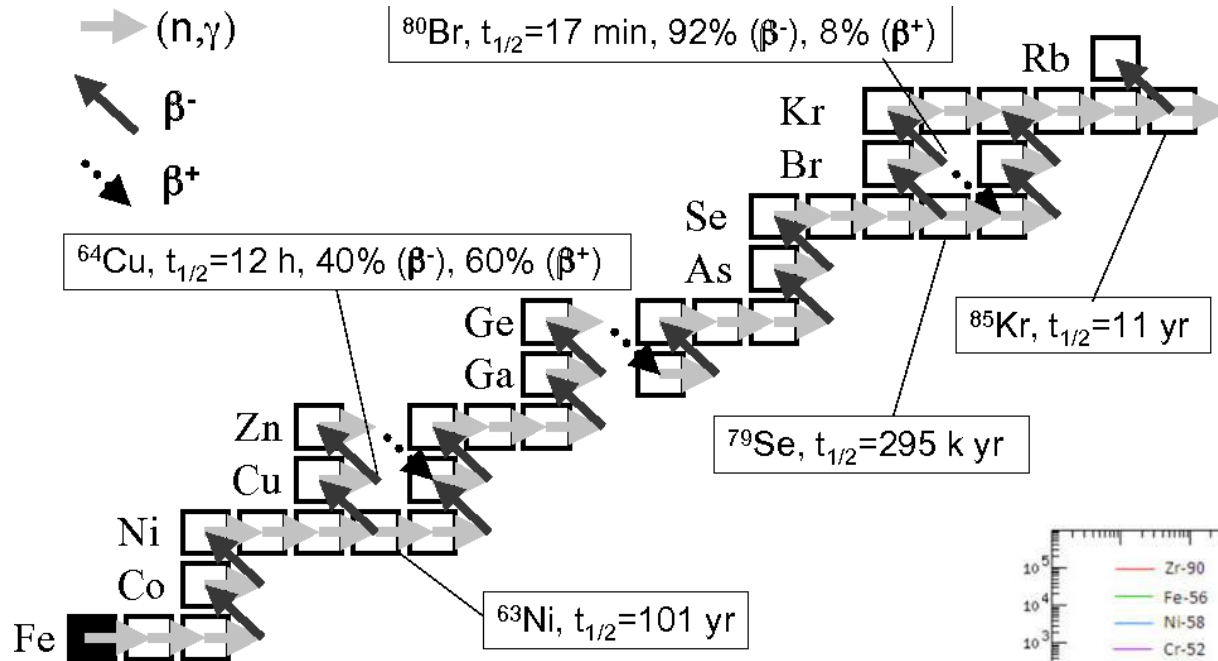
How about Iron?

How about Lead?

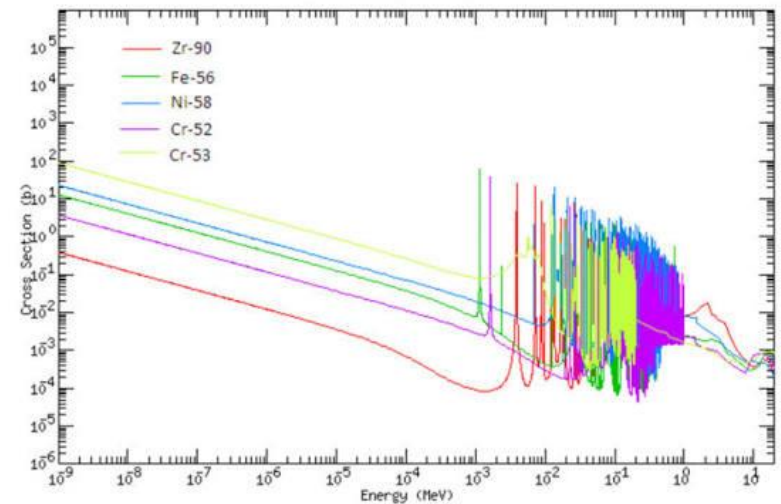
How about Uranium?



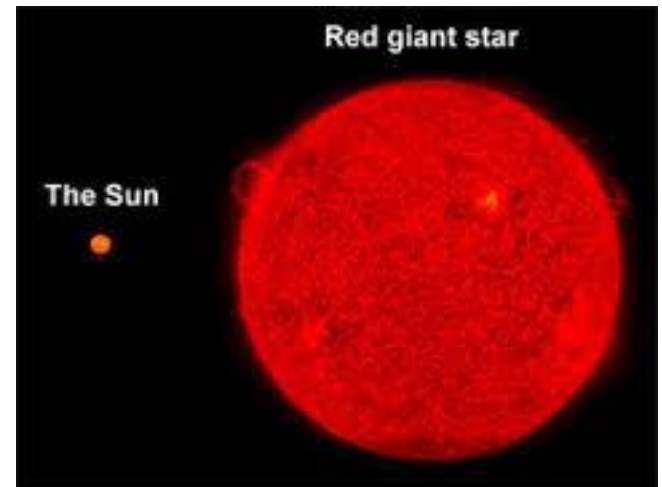
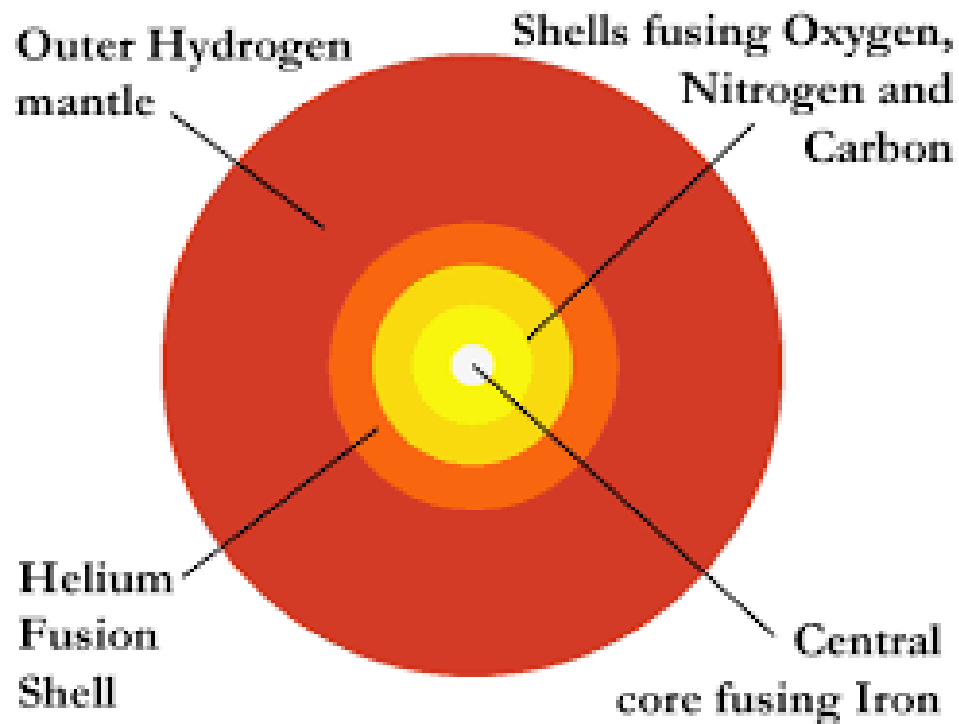
heavy elements and the s-process



neutron capture reactions

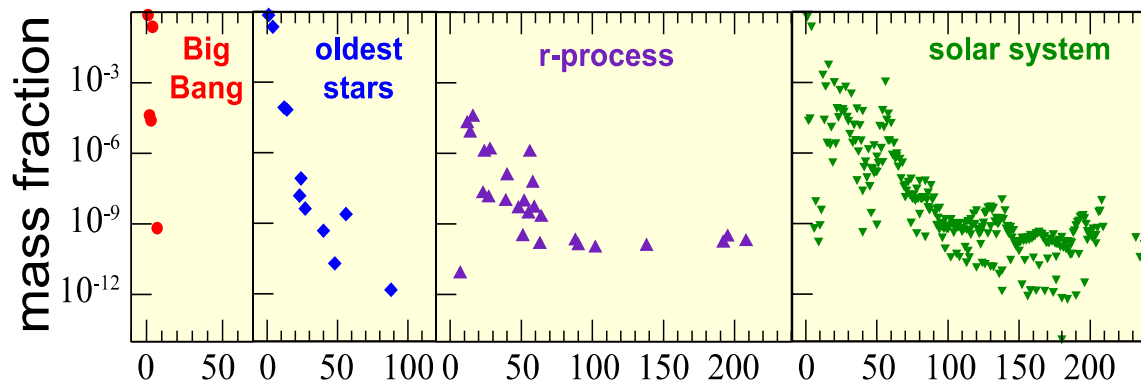


medium mass elements and red giants



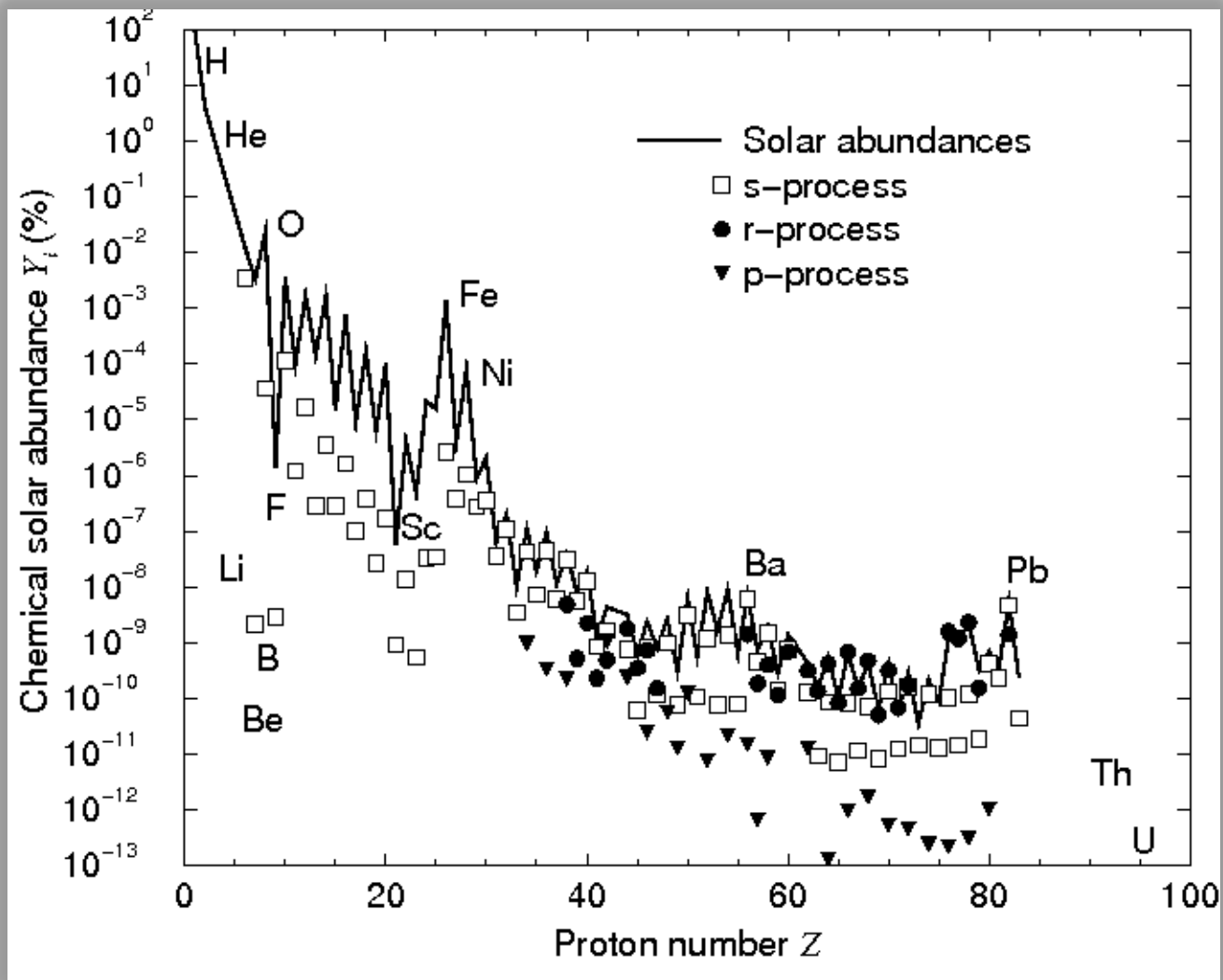
Big science questions

1) How did matter come into being and how does it evolve?

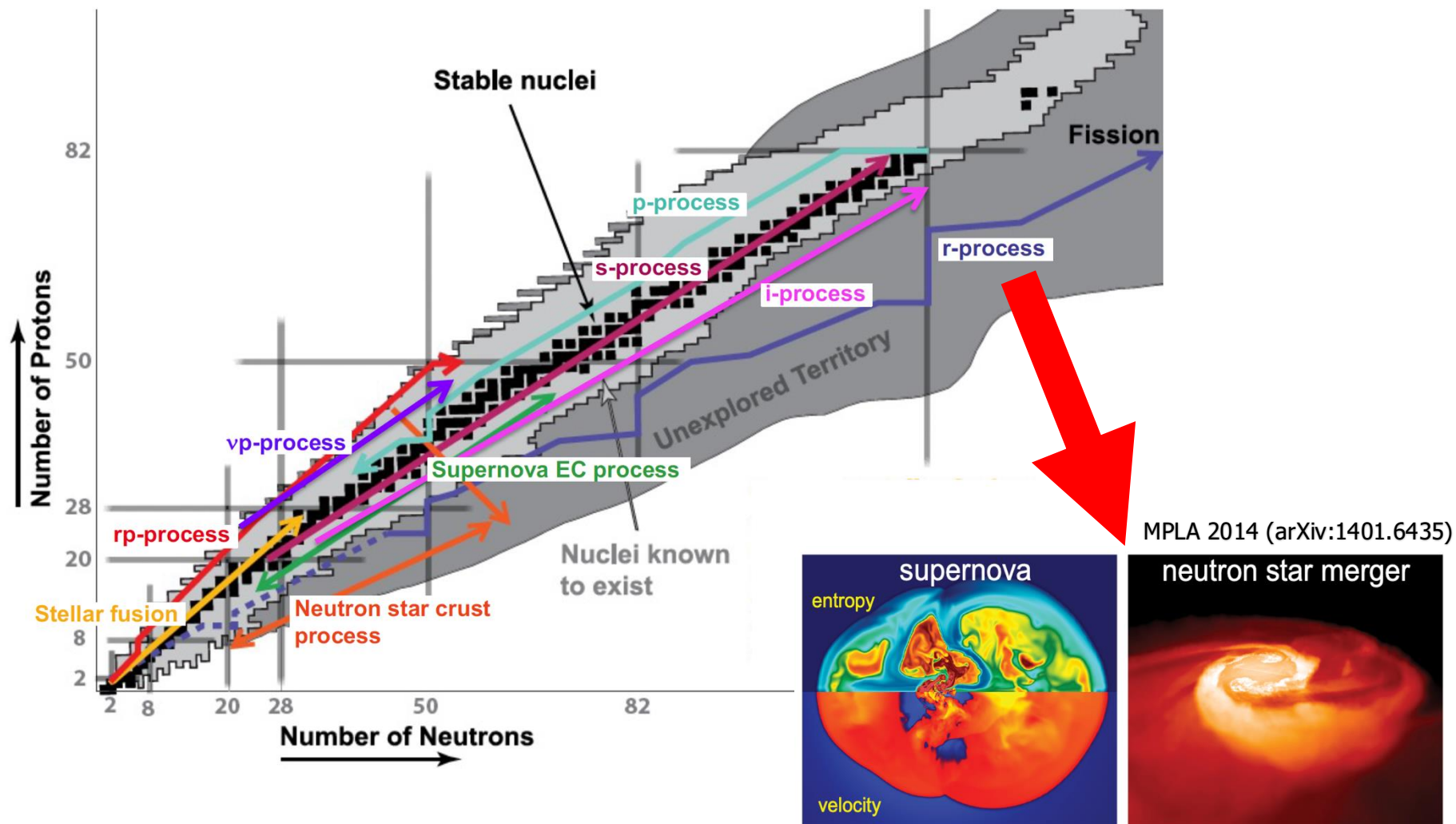


Understanding the observed sequence of abundance enrichment of nuclides continues to be an active area of research.

heavy elements: elemental abundancies



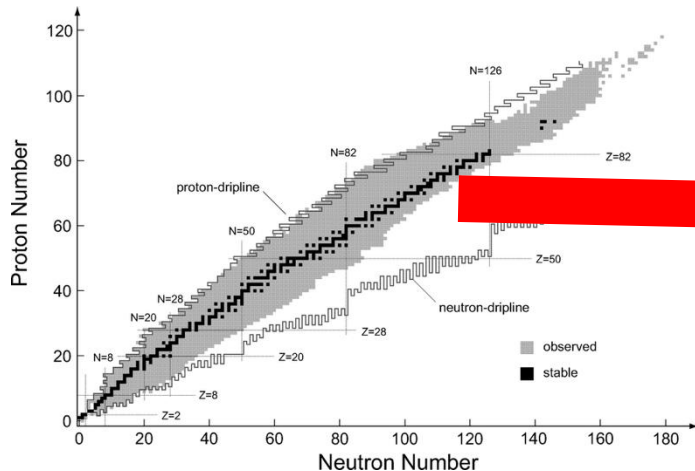
astrophysics on the nuclear chart



neutron stars – extrapolation to N very large

A teaspoon of a neutron star matter weighs as much as a mountain

Neutron stars:
Radius ~ 10 km
Mass ~ 1.4 Msun



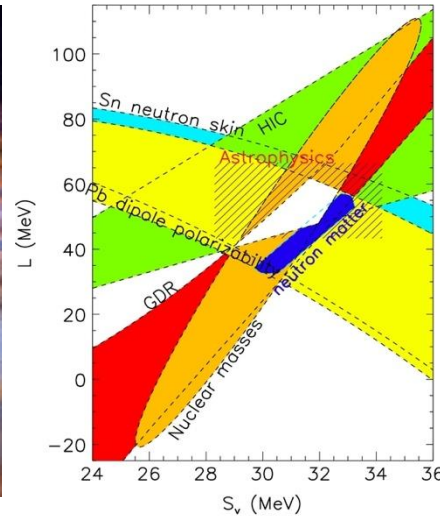
www.nasa.gov



neutron stars and equation of state



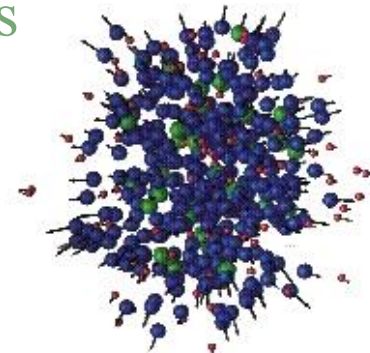
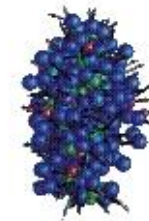
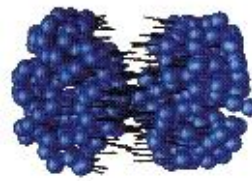
www.nasa.gov



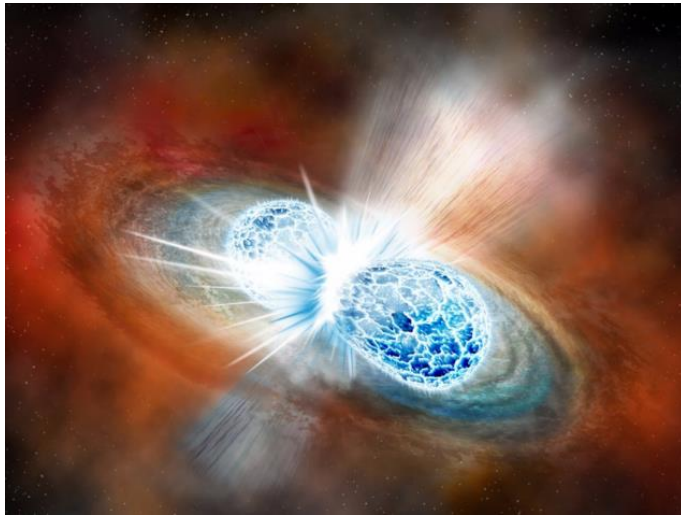
K. Hebeler et al. 2013 ApJ 773 11

need isospin, density and temperature dependence of nuclear matter

✧ Heavy Ion collisions

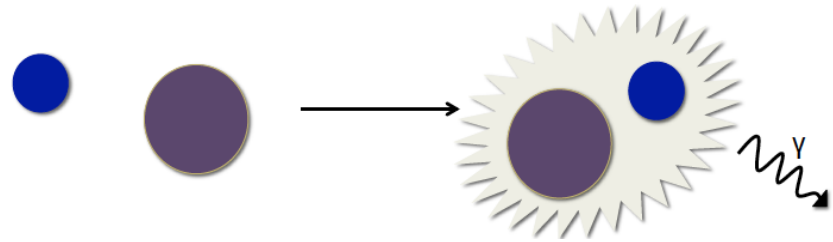


neutron capture for the r-process

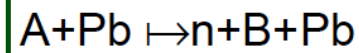


carnegiescience.edu/

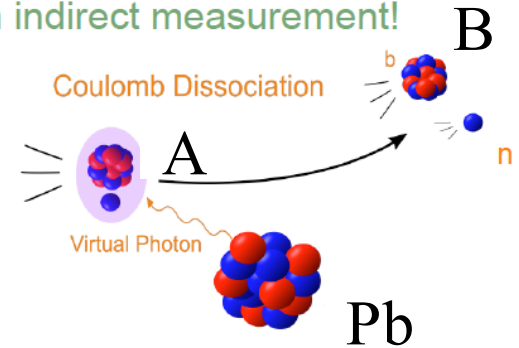
✧ (n,g) cross sections on unstable nuclei: **Currently Impossible!**



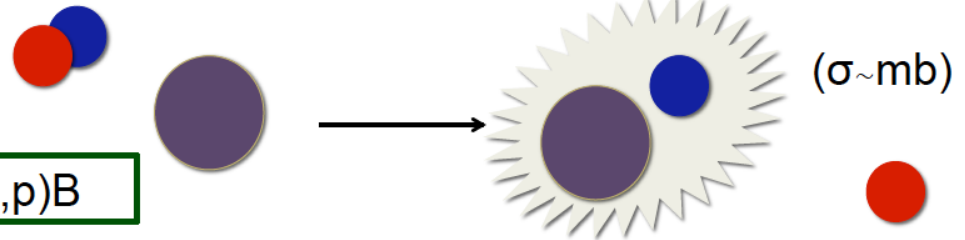
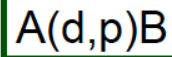
✧ Coulomb breakup offers an indirect measurement!



($\sigma \sim \text{mb}$)

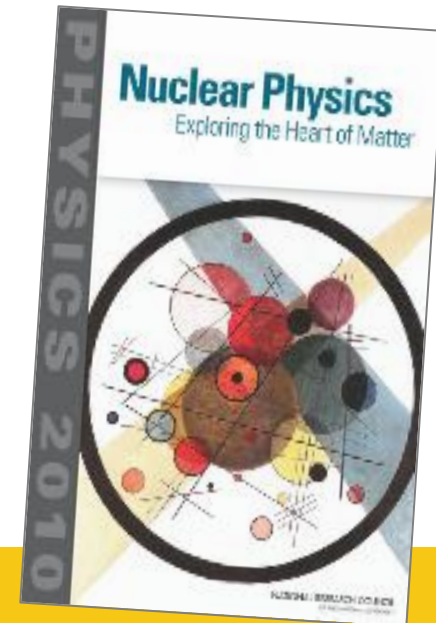


✧ transfer offers an indirect measurement!

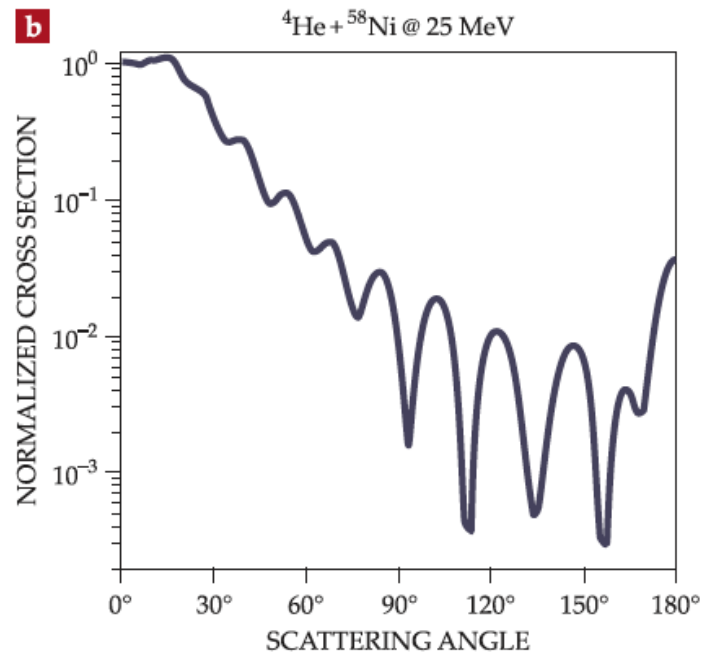
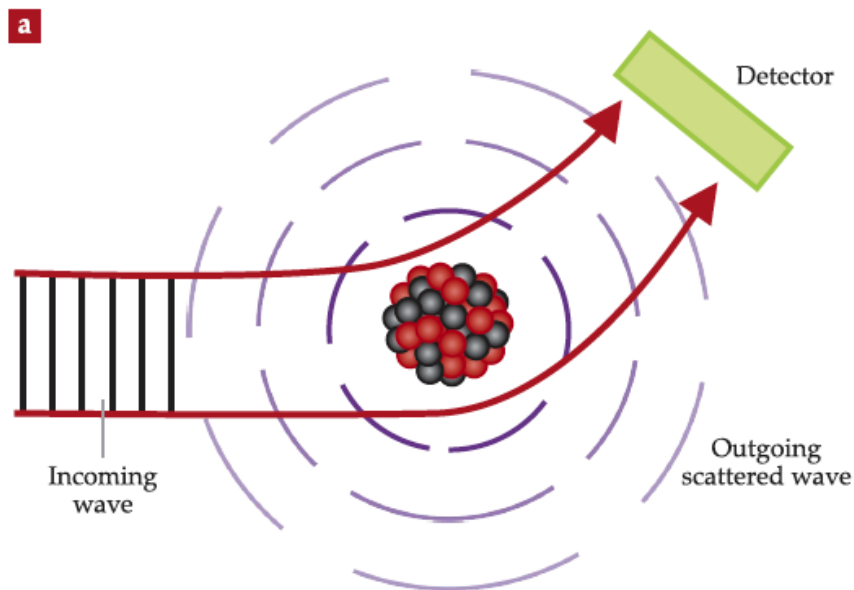


Big science questions

- 1) *How did matter come into being and how does it evolve?*
- 2) *How does subatomic matter organize itself and what phenomena emerge?*
- 3) *Are the fundamental interactions that are basic to the structure of matter fully understood? and*
- 4) *How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?*

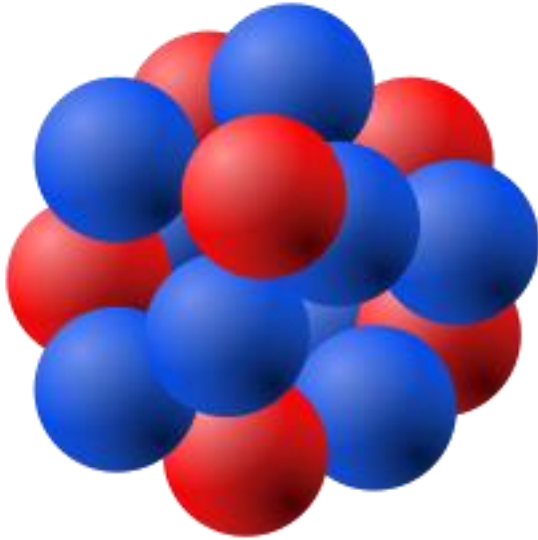


How to study the organization of nucleons in nuclei?



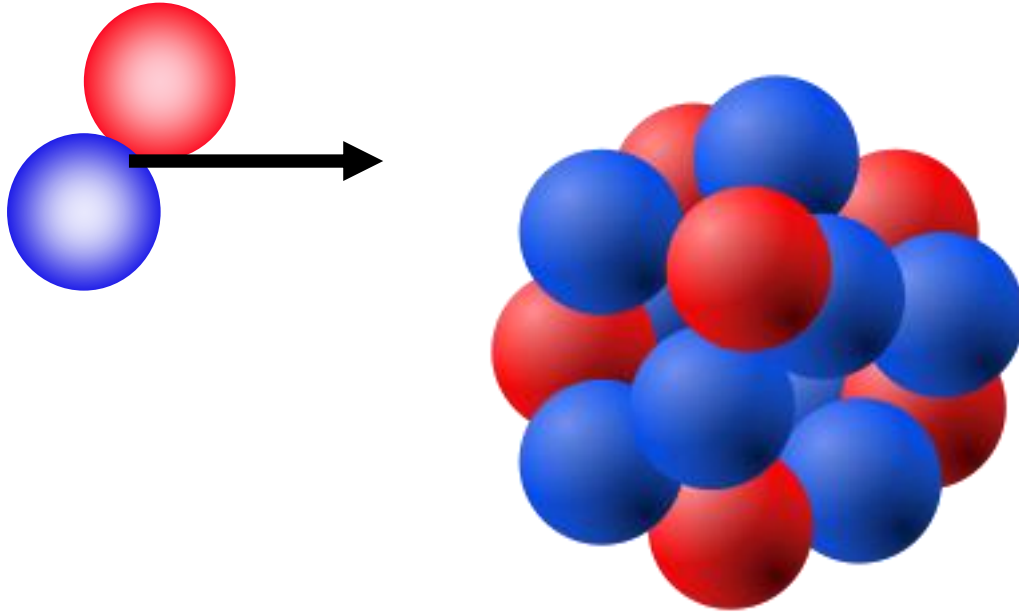
Reactions have been (and continue to be) the tool of choice to study nuclear structure

The atomic nucleus and single particle nature



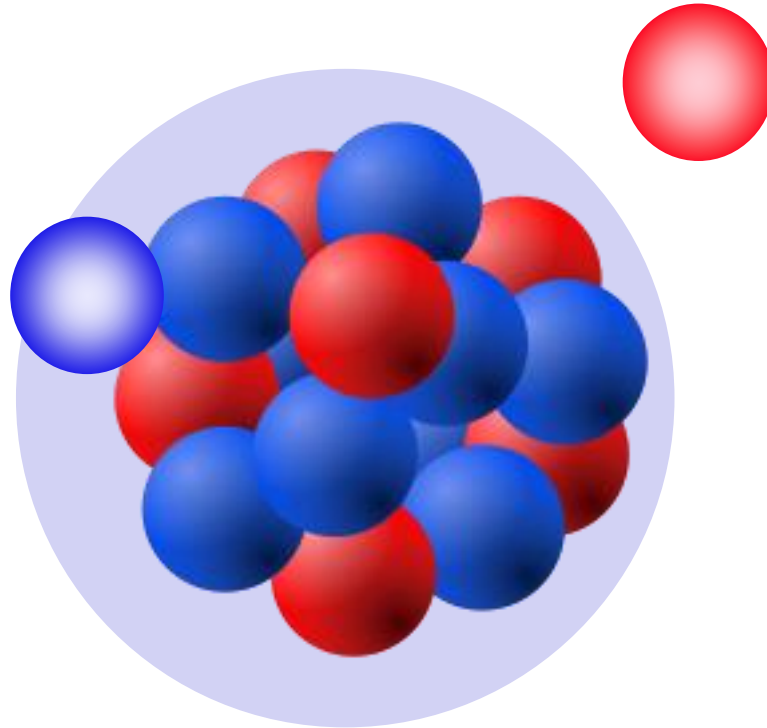
Picture in the sixties: Compact bundle of neutrons and protons; filling in orbitals similarly to electrons in the atom

The atomic nucleus and single particle nature



Single nucleons transfer reactions provide the tool of choice to study single-particle structure in nuclei.

The atomic nucleus and single particle nature



Single nucleons transfer reactions provide the tool of choice to study single-particle structure in nuclei.

Example: $^{40}\text{Ca}(d,p)^{41}\text{Ca}$

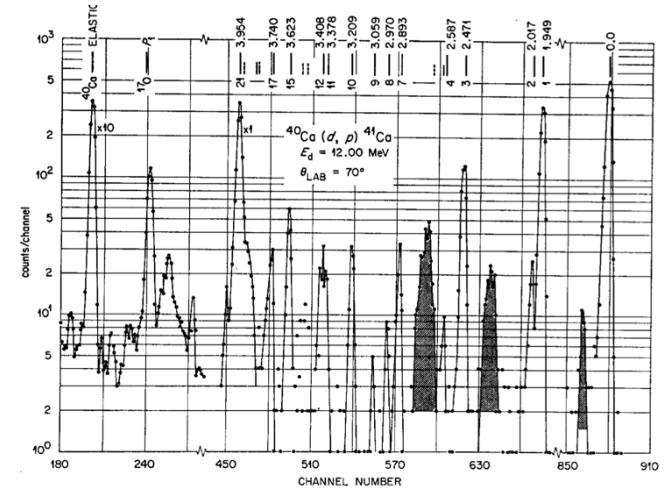
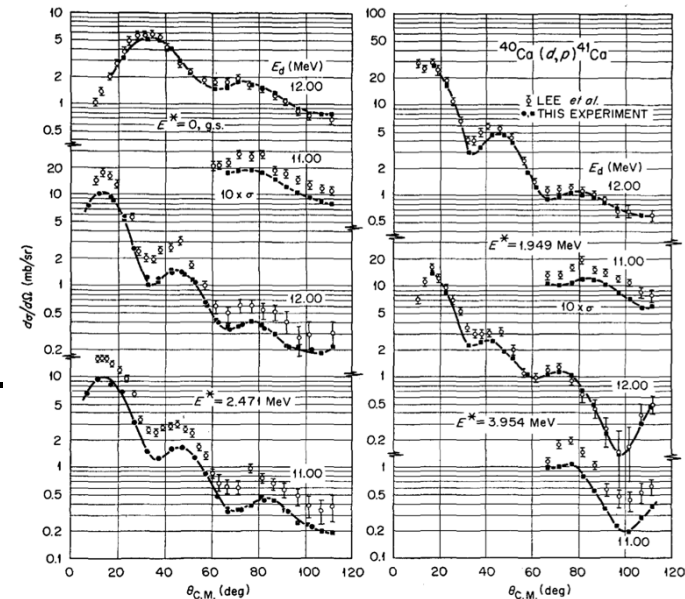
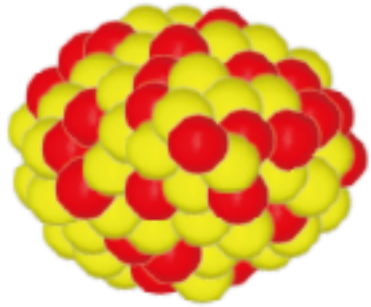


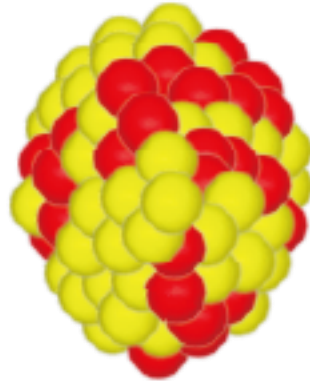
Fig. 1. Typical spectrum at 70° for 12 MeV deuterons.



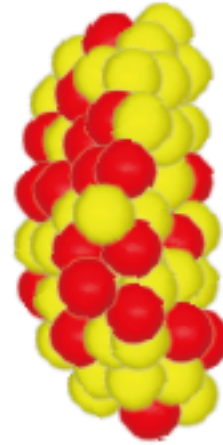
The atomic nucleus and its collective nature



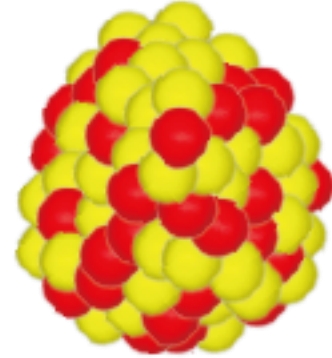
Tangerine ?



Lemon ?



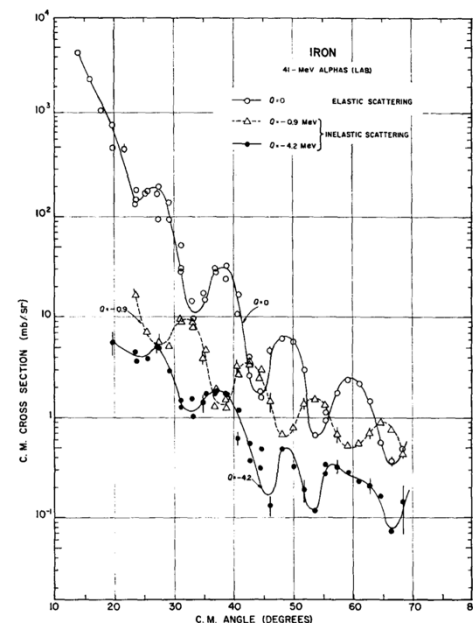
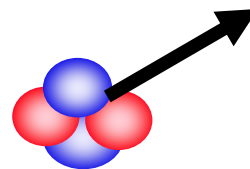
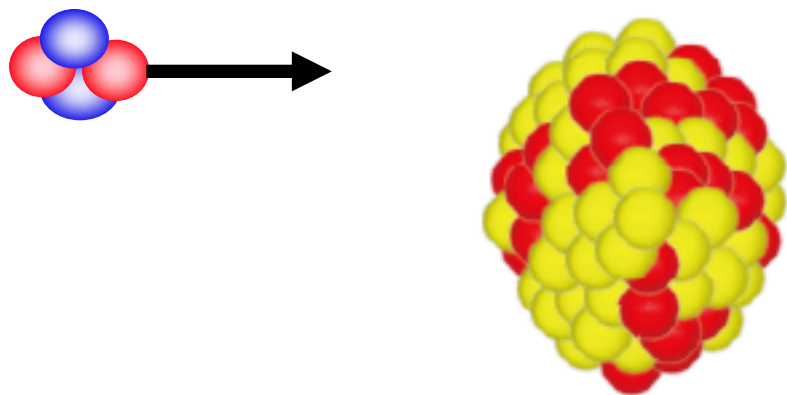
Banana ?



Pear ?

Collective effects
Vibrational modes with different shapes
Rigid enough that it can be deformed

The atomic nucleus and its collective nature

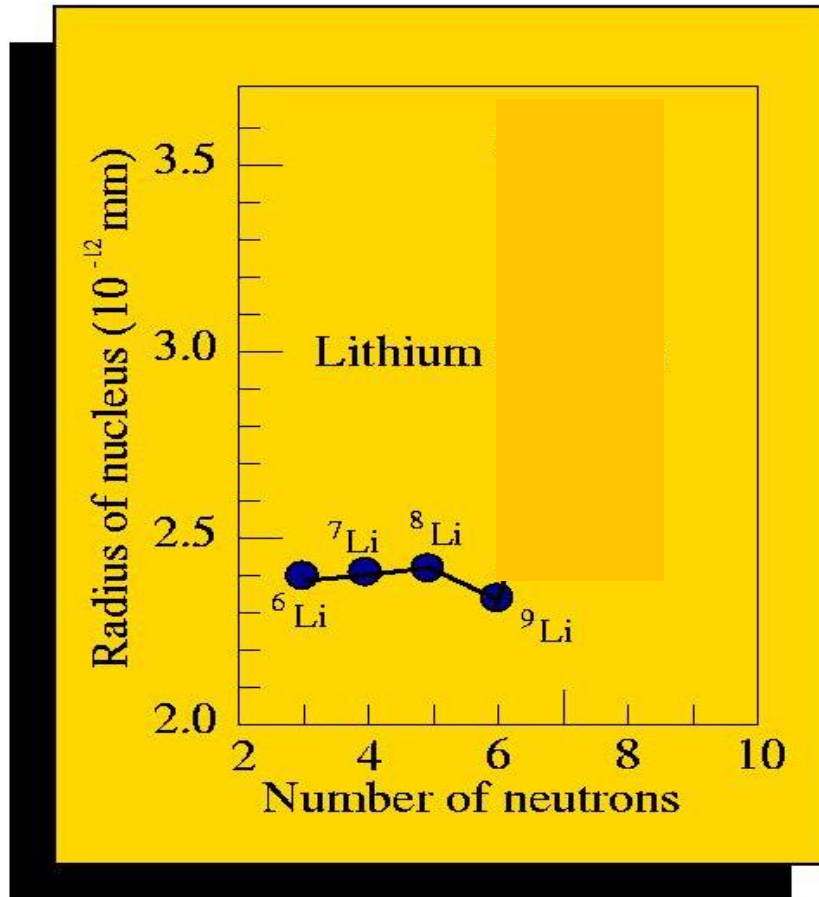
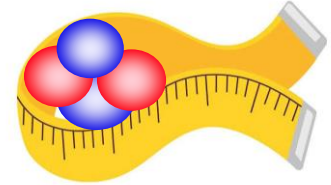


Inelastic scattering allows us to understand collective phenomena

Nucleus	R_0 (10^{-13} cm)	θ_n	β_2
Ti ⁴⁸	6.51		≈ 0.15
Fe	6.88	32°	0.11
Ni	6.83	22°	0.15
Zn	7.08	22°	0.19
Zn ⁶⁴	7.10	22°	0.19
Sr	7.44		≈ 0.08

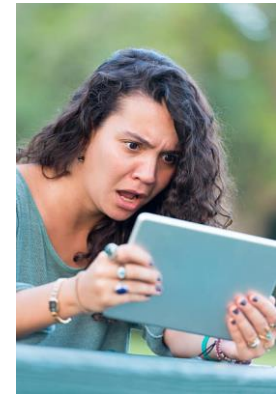
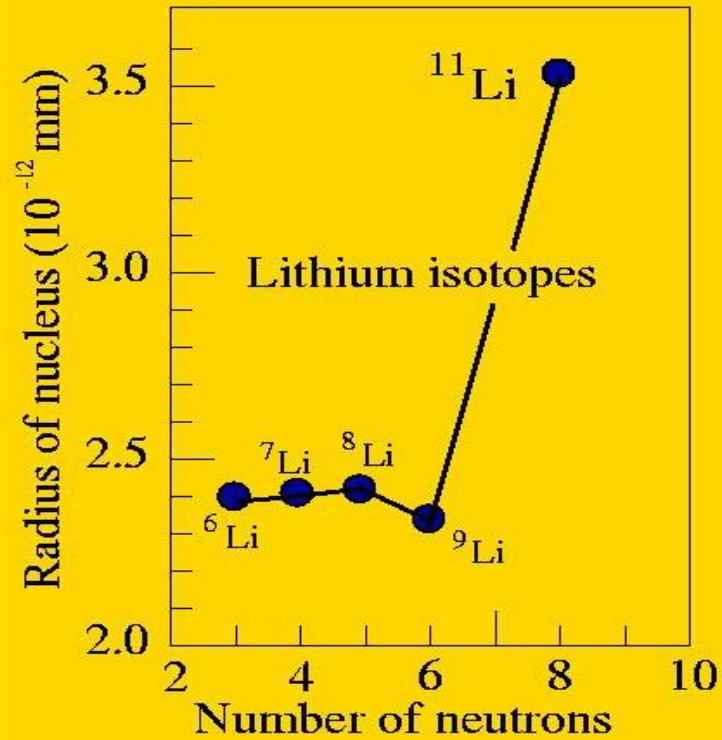
example: (α, α') @40 MeV

The atomic nucleus: its size



Adding more neutrons barely changes the radius,
Consistent with the compact bundle of nucleons picture

The atomic nucleus: its size



What???

The atomic nucleus: its size

VOLUME 55, NUMBER 24

PHYSICAL REVIEW LETTERS

9 DECEMBER 1985

Measurements of Interaction Cross Sections and Nuclear Radii in the Light p -Shell Region

I. Tanihata,^(a) H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yoshikawa

Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

K. Sugimoto,^(b) O. Yamakawa, and T. Kobayashi

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

N. Takahashi

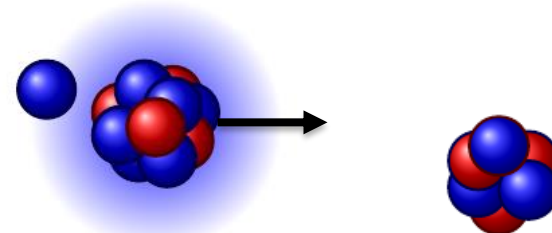
College of General Education, Osaka University, Toyonaka, Osaka 560, Japan

(Received 11 July 1985; revised manuscript received 17 September 1985)

Interaction cross sections (σ_I) for all known Li isotopes (${}^6\text{Li}$ – ${}^{11}\text{Li}$) and ${}^7\text{Be}$, ${}^9\text{Be}$, and ${}^{10}\text{Be}$ on targets Be, C, and Al have been measured at 790 MeV/nucleon. Root mean square radii of these isotopes as well as He isotopes have been deduced from the σ_I by a Glauber-type calculation. Appreciable differences of radii among isobars (${}^6\text{He}$ – ${}^6\text{Li}$, ${}^8\text{He}$ – ${}^8\text{Li}$, and ${}^9\text{Li}$ – ${}^9\text{Be}$) have been observed for the first time. The nucleus ${}^{11}\text{Li}$ showed a remarkably large radius suggesting a large deformation or a long tail in the matter distribution.

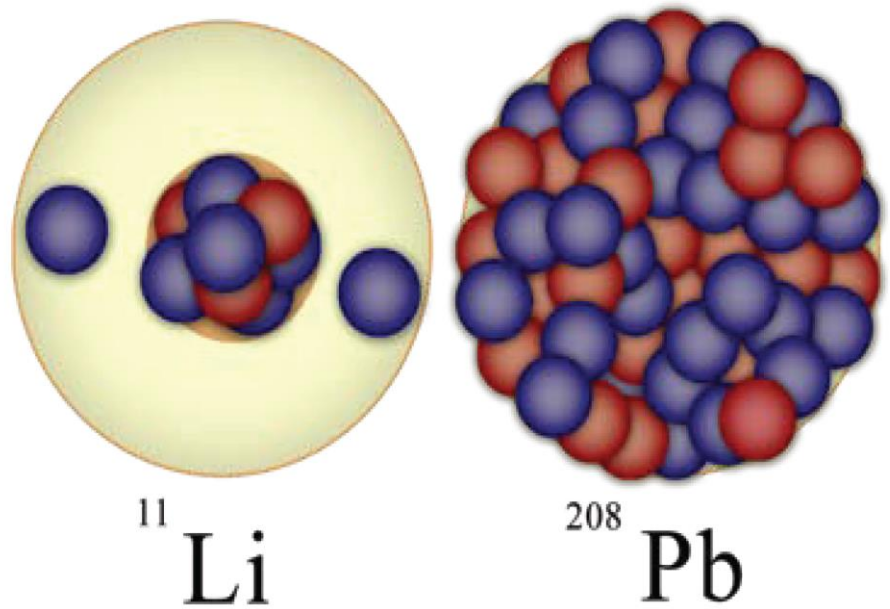
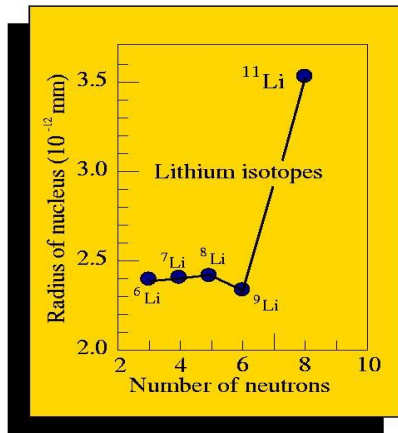
TABLE I. Interaction cross sections (σ_I) in millibarns.

Beam	Be	Target C	Al
${}^6\text{Li}$	651 ± 6	688 ± 10	1010 ± 11
${}^7\text{Li}$	686 ± 4	736 ± 6	1071 ± 7
${}^8\text{Li}$	727 ± 6	768 ± 9	1147 ± 14
${}^9\text{Li}$	739 ± 5	796 ± 6	1135 ± 7
${}^{11}\text{Li}$		1040 ± 60	
${}^7\text{Be}$	682 ± 6	738 ± 9	1050 ± 17
${}^9\text{Be}$	755 ± 6	806 ± 9	1174 ± 11
${}^{10}\text{Be}$	755 ± 7	813 ± 10	1153 ± 16



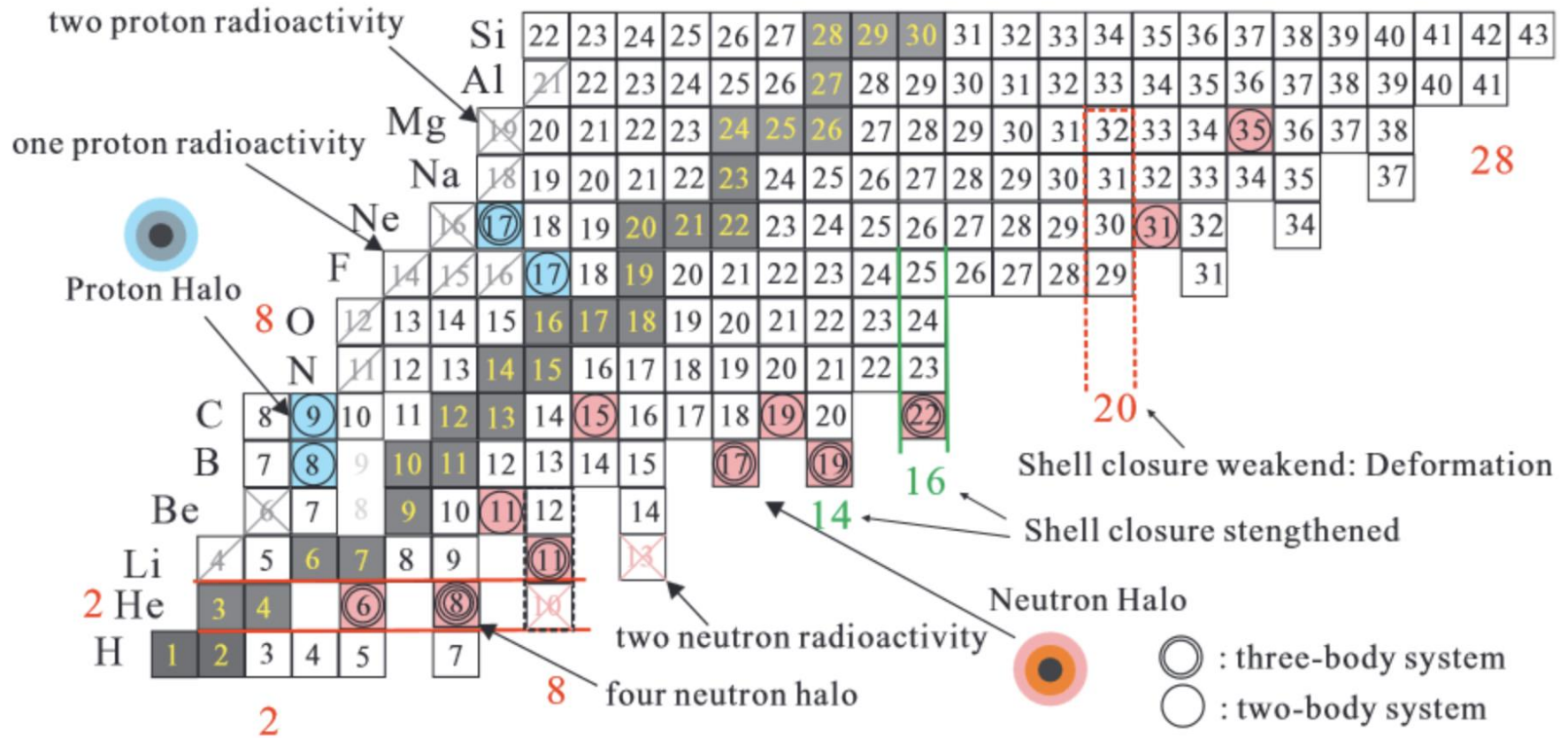
$$\sigma_I(p, t) = \pi [R_I(p) + R_I(t)]^2$$

The atomic nucleus: nuclei with halos

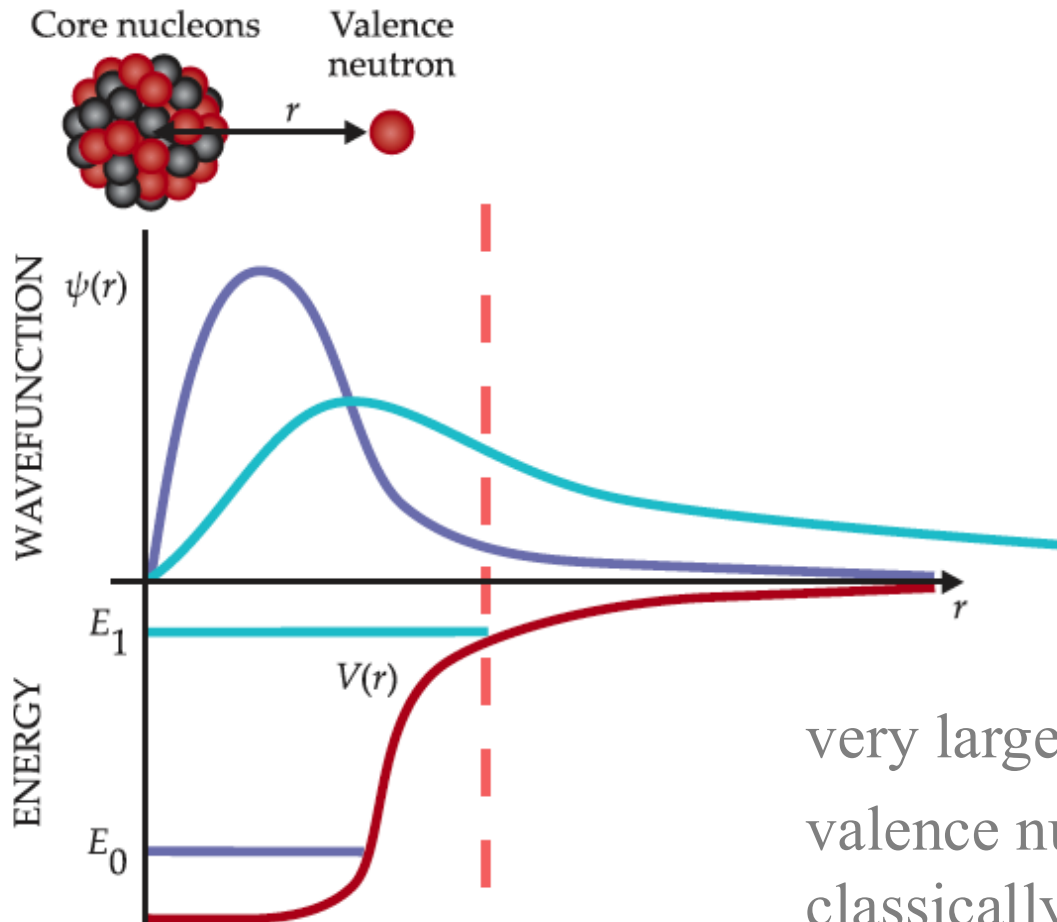


The valence neutron orbitals have the same radius as Pb!

The atomic nucleus: nuclei with halos

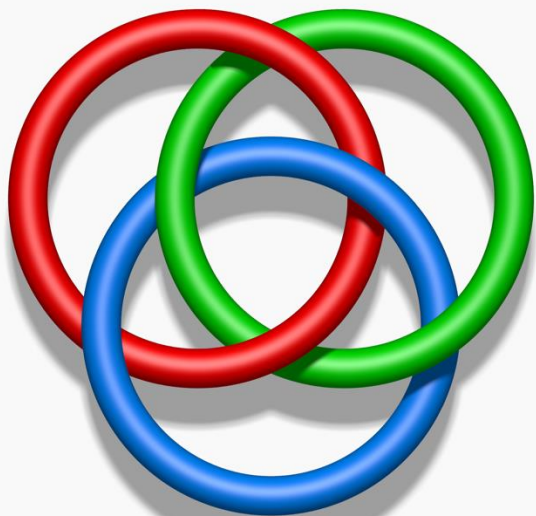


Understanding structure at particle thresholds



very large spatial extension;
valence nucleons live in the
classically forbidden region.

weakly bound systems: halo nuclei

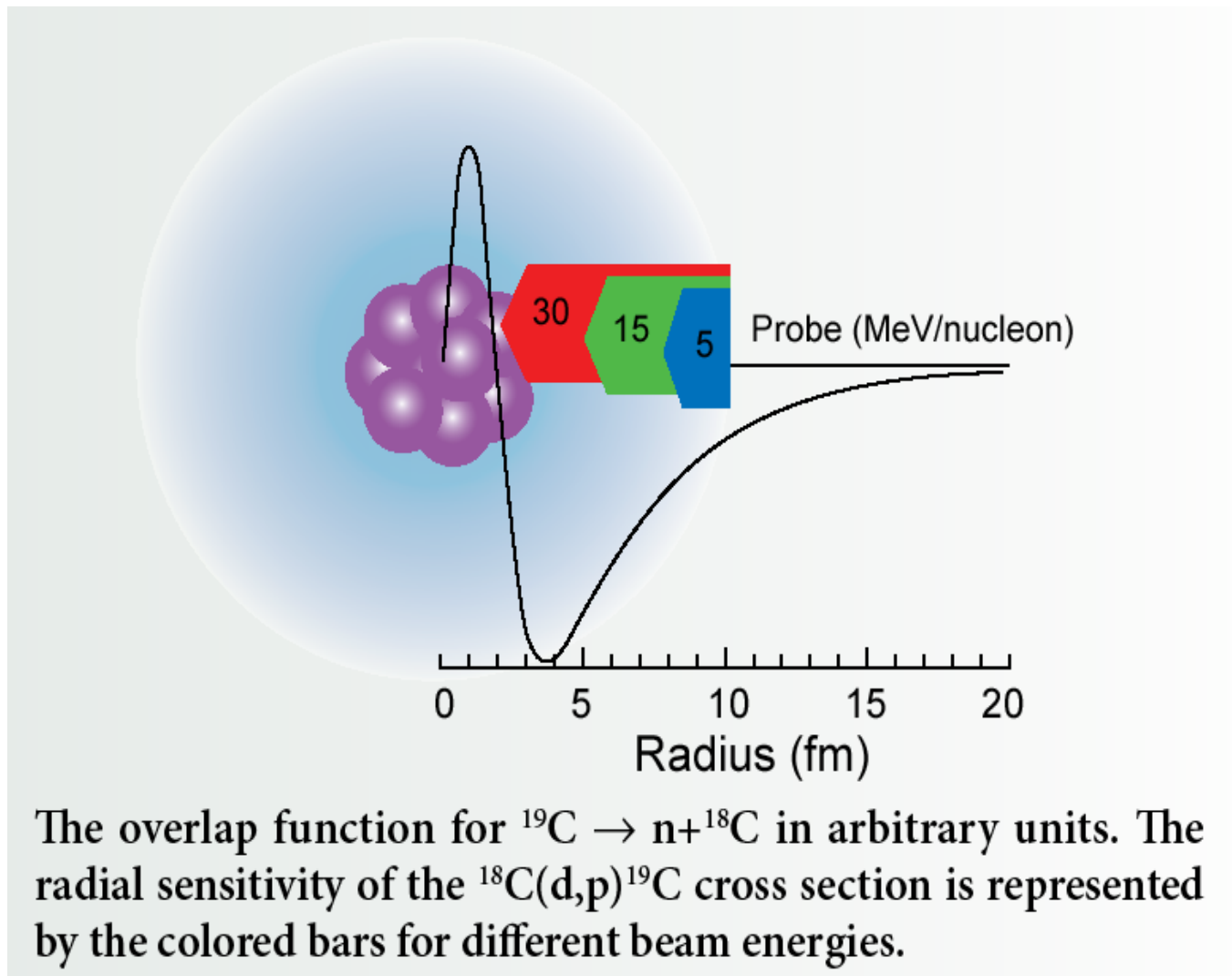


lasts a few milliseconds!
Can't make targets!

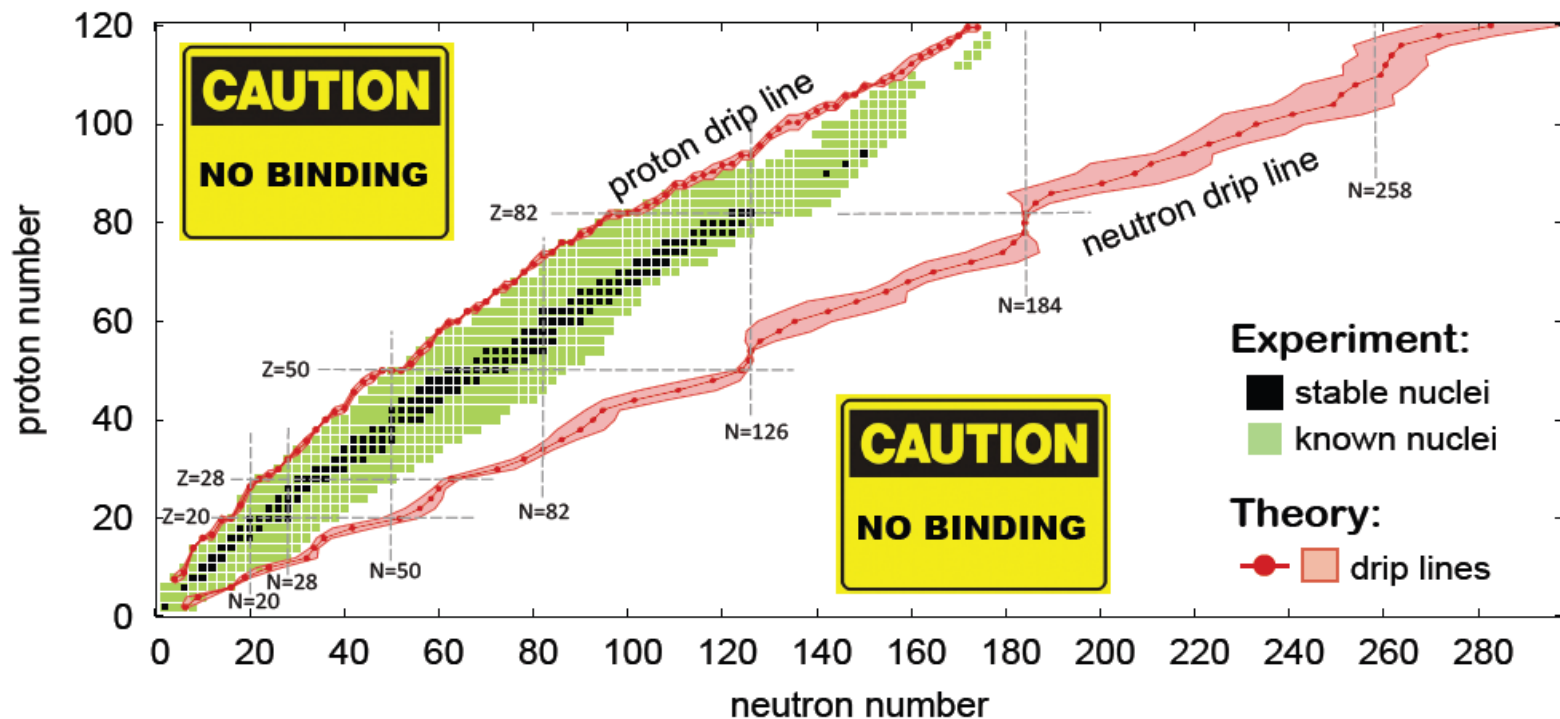
^{11}Li

What's so cool about $2n$ halo nuclei?
Borromean systems

Reactions as tomography of the nucleus



Limits of stability in the superheavies – terra incognita



Producing superheavies – fusion reactions

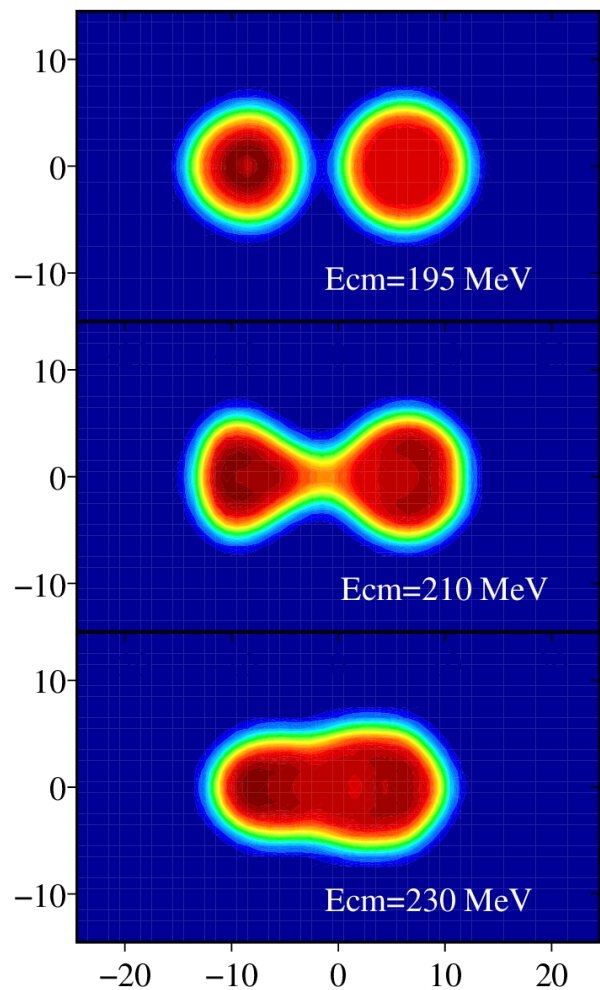


FIG. 1. (Color online) TDHF calculations for $^{132}\text{Sn} + ^{96}\text{Zr}$. Contour plots of the mass density at the distance of closest approach in a central collision, calculated at three different $E_{c.m.}$ energies.

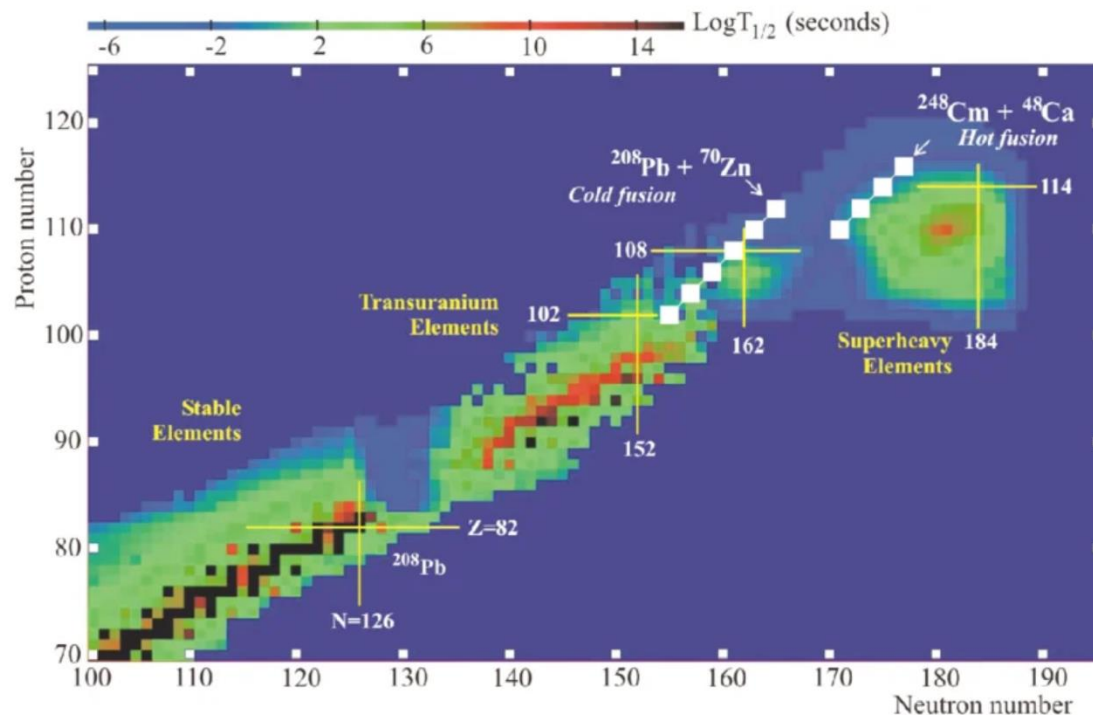
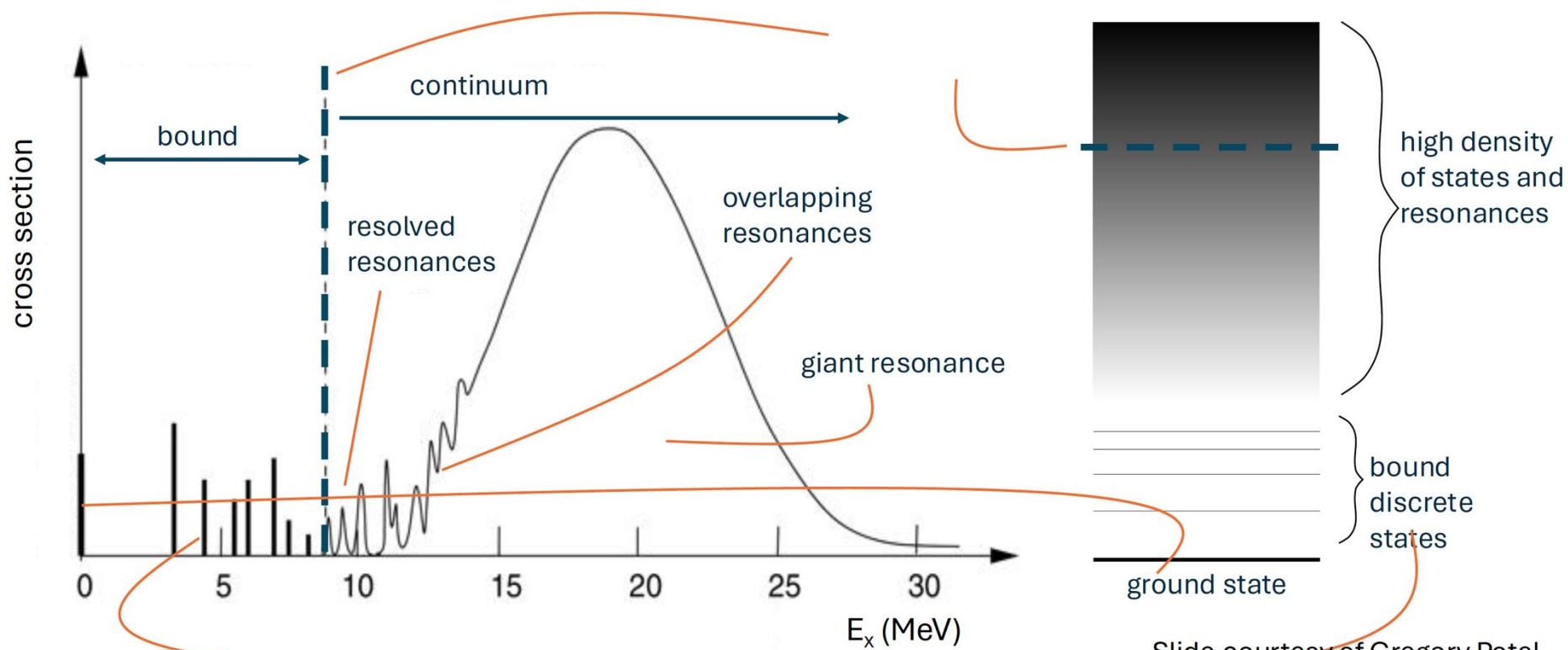


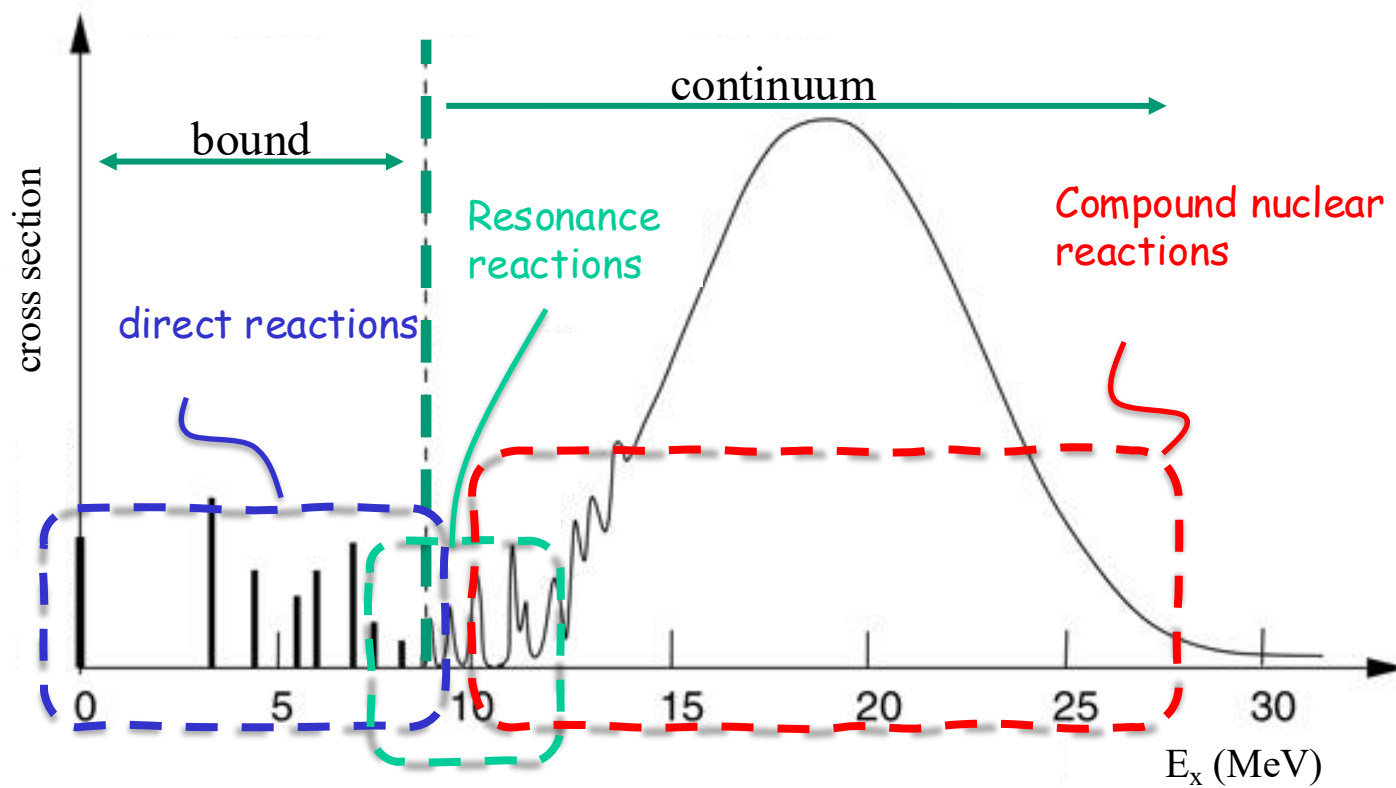
Chart of the nuclides; the domain of the heavy and superheavy elements. White squares show the chains of the sequential α -decay of nuclei of element 112 produced in the cold-fusion reaction $^{208}\text{Pb} + ^{70}\text{Zn} \rightarrow ^{277}112 + n$ and element 116—in the hot fusion reaction $^{248}\text{Cm} + ^{48}\text{Ca} \rightarrow ^{293}116 + 3n$. Eight extra neutrons should increase the half-life of $^{277}112$ by 4 or 5 orders of magnitude.

Basic concepts in reactions

Classification of reactions



Classification of reactions



classification of reactions

Direct reactions

transfer momentum is small compared to initial momentum

typically peripheral

short timescale (10^{-22} s)

$E > 10$ MeV

mostly one step

final states keep memory of initial states

Compound reactions

longer timescale

many steps in the reaction

all nucleons share the beam energy

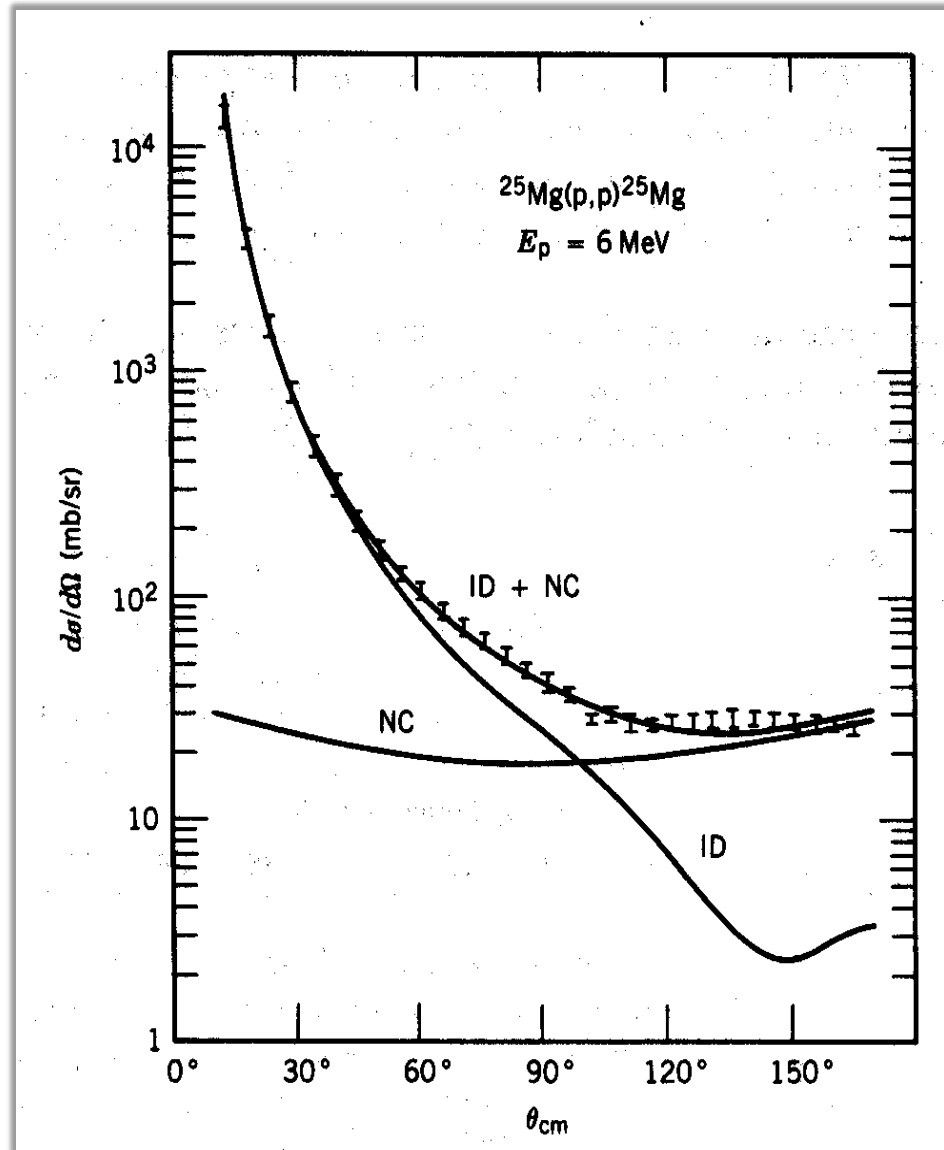
loss of memory from the initial state

low energy reactions

angular distribution: compound vs direct

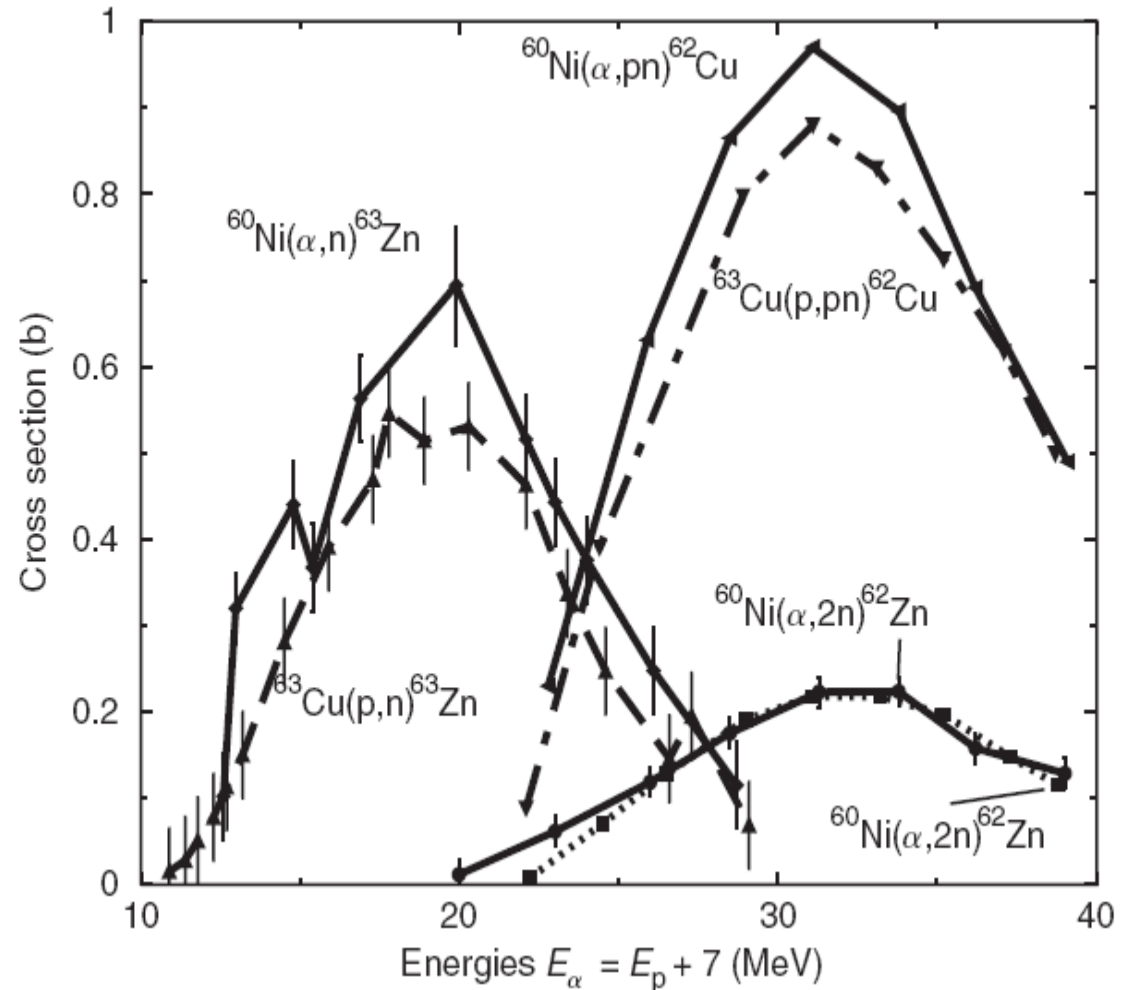
Direct reactions (ID):
Forward peaked (large b)

Compound reactions
(NC):
Distribution is generally isotropic (except for heavy ion collision where L transfer is large)

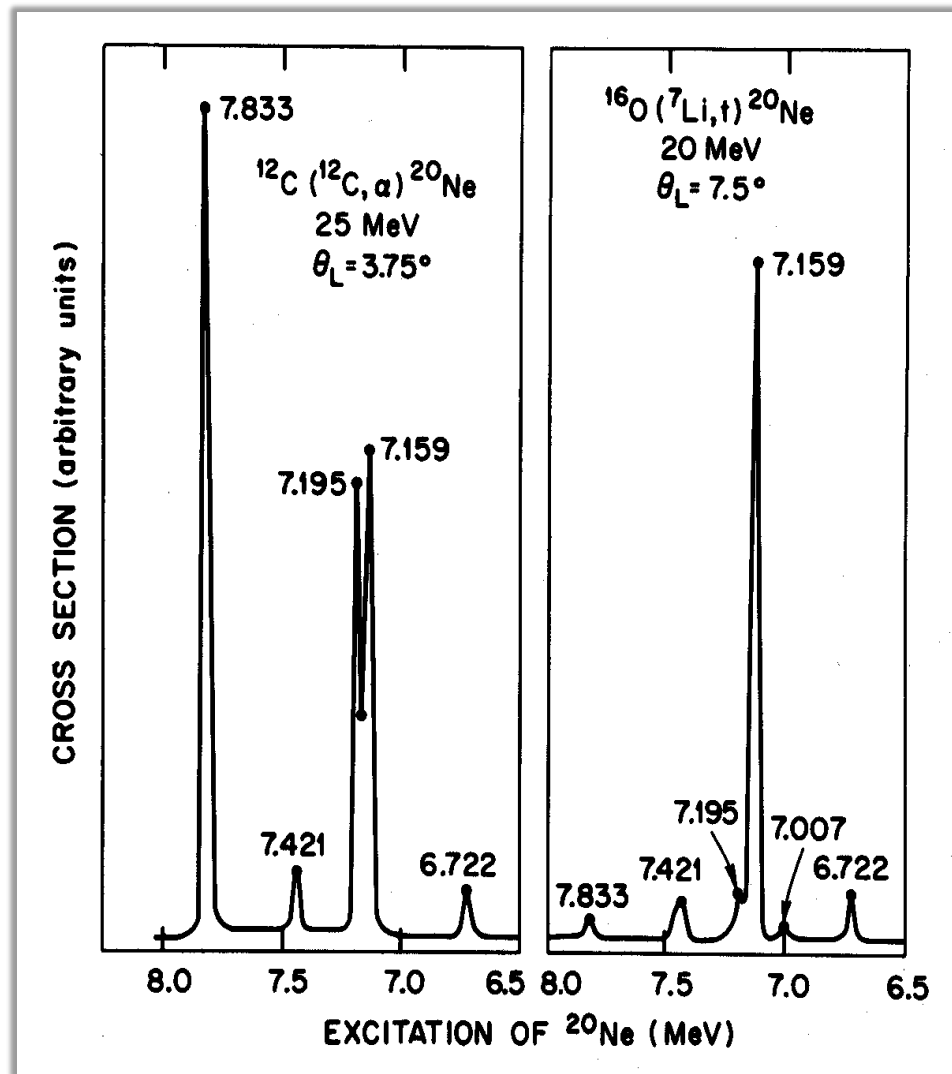


compound reactions

the decay of the compound state does not depend on the initial state.



selectivity of direct reactions



classification of reactions

Direct reactions

transfer momentum is small compared to initial momentum

typically peripheral

short timescale (10^{-22} s)

$E > 10$ MeV

mostly one step

final states keep memory of initial states

Resonance reactions

reactions that go through a resonance (peak in the cross section)

intermediate step in the reaction

longer time scale

Compound reactions

longer timescale

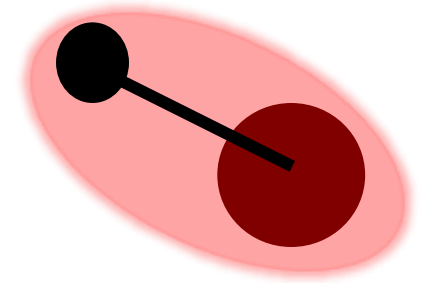
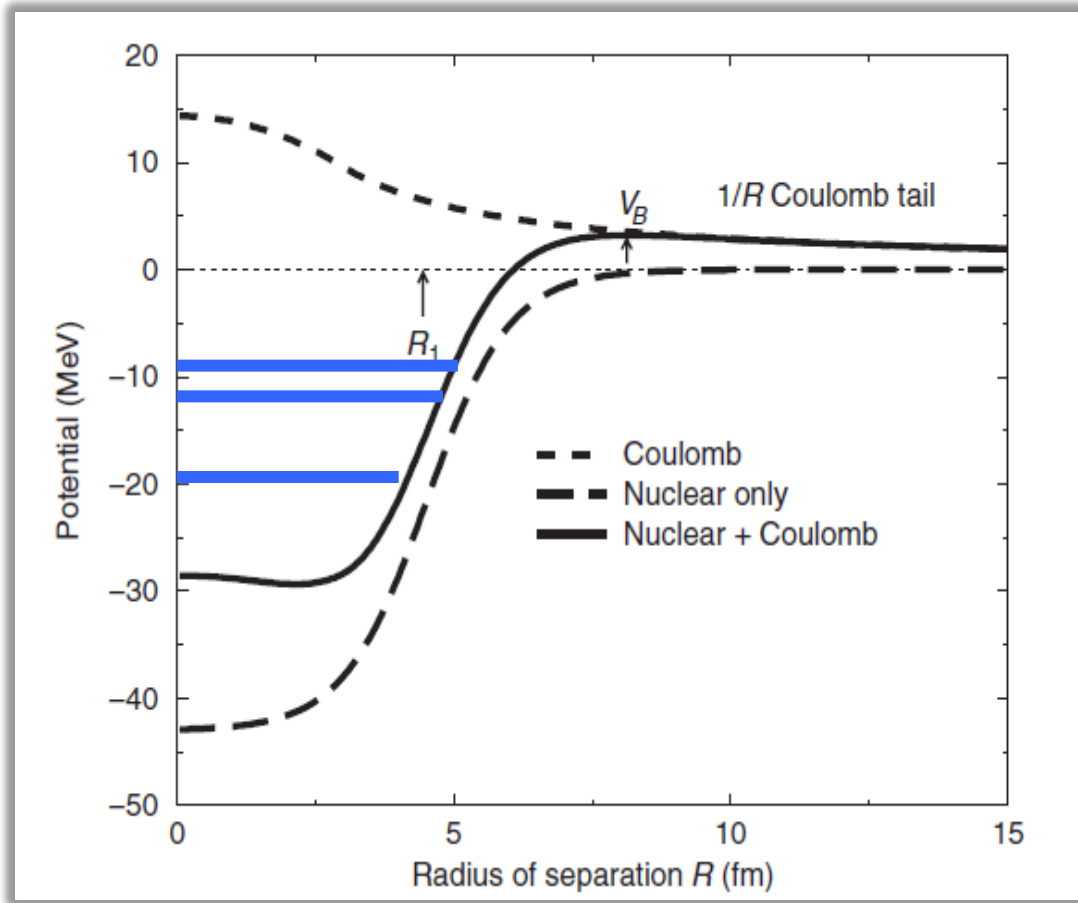
many steps in the reaction

all nucleons share the beam energy

loss of memory from the initial state

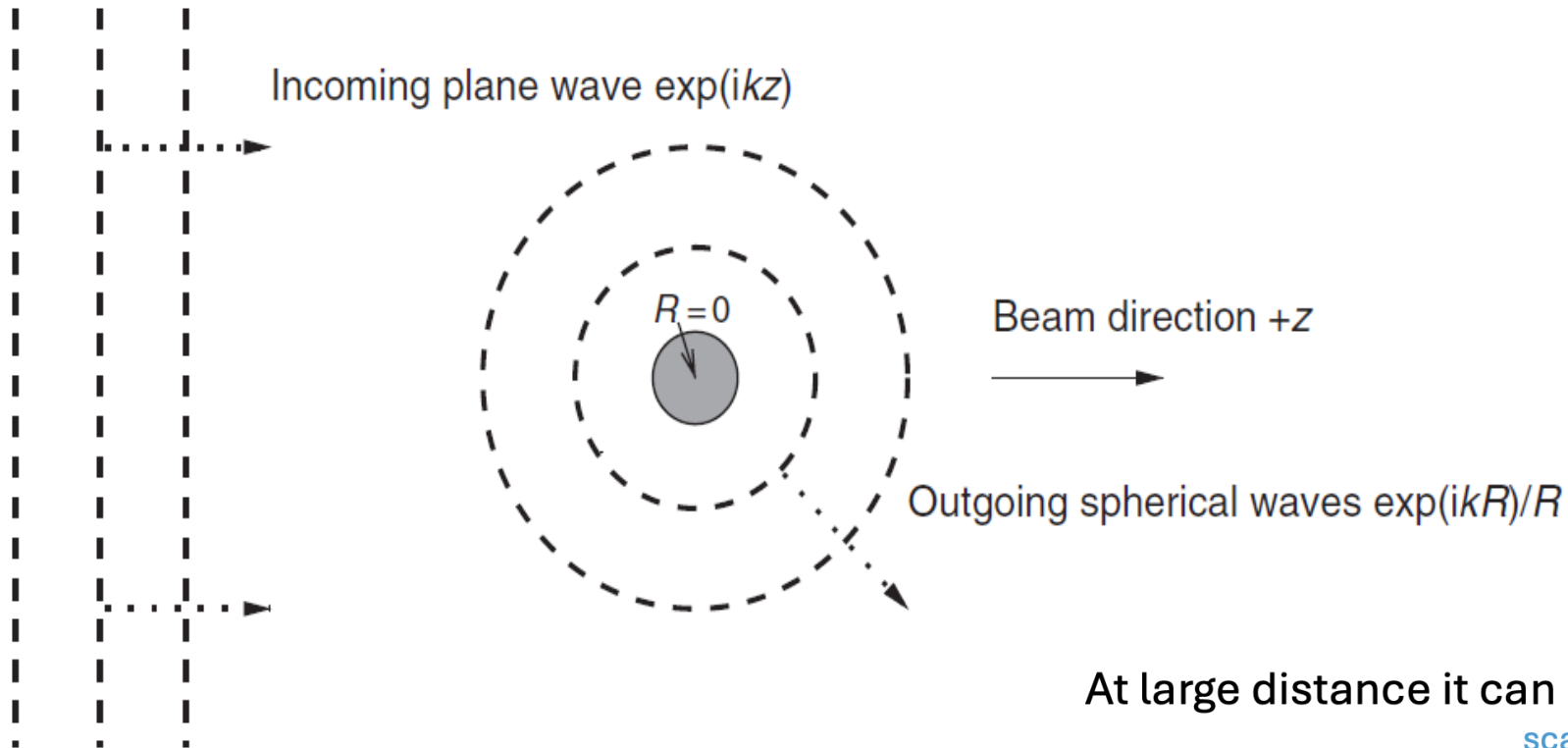
low energy reactions

interactions and nuclei



Reactions focus on $E > 0$

picture for elastic scattering



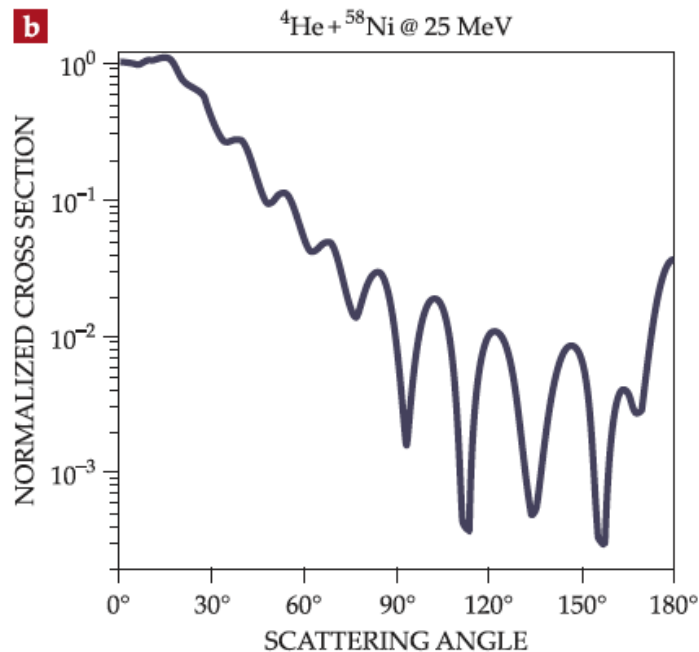
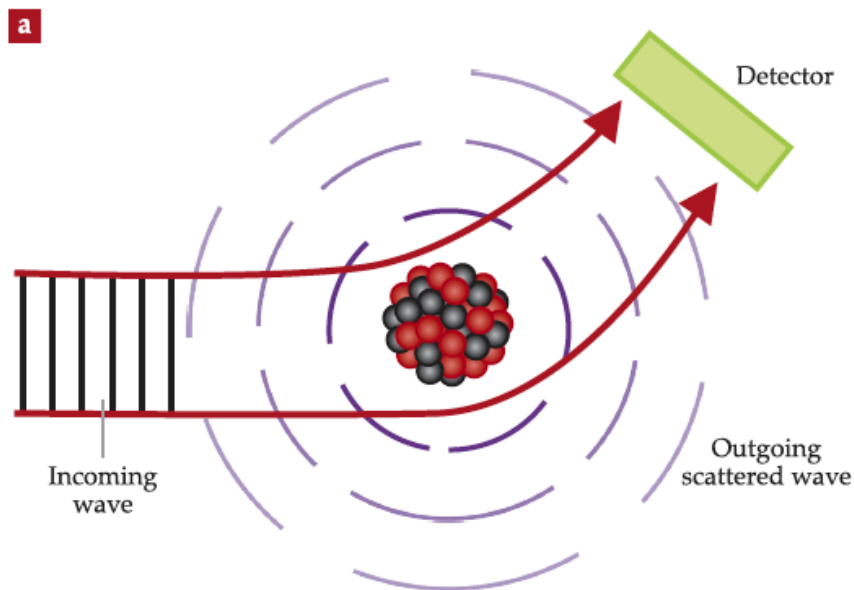
At large distance it can be shown

$$\psi^{\text{asym}} = \psi^{\text{beam}} + \psi^{\text{scat}} = e^{ikz} + f(\theta) \frac{e^{ikr}}{r}$$

Solution for $V=0$ scattering amplitude
deflection angle

$$\mathbf{j} = \mathbf{v} |\psi|^2$$

picture for elastic scattering: superpositions of waves



Interference pattern tells us about the the projectile/target and their interaction

cross section

Definition of cross section:

the area within which a projectile and a target will interact and give rise to a specific product.

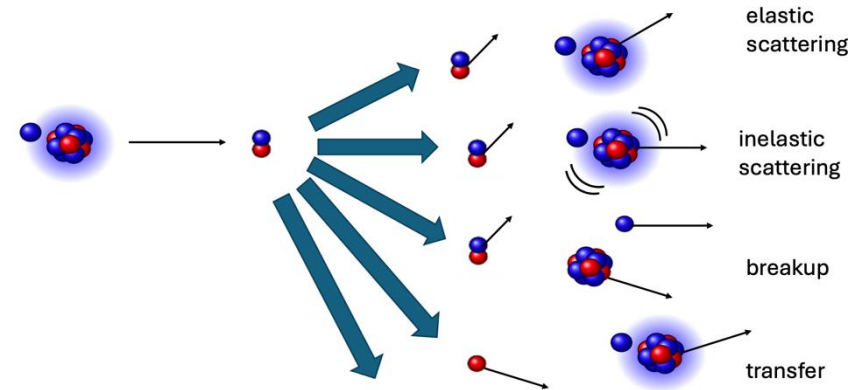
Units 1b (barn) = 10 fm x 10 fm

Number of particles per unit time scattered into an element of solid angle divided by the incident flux $\frac{d\sigma(\theta)}{d\Omega}$

nuclear reactions and q-value

- projectile (A)
- target (B)
- residual nuclei (C+D)
- q-value of a reaction:

$$Q = (m_A + m_B - m_C - m_D)c^2$$



Notations for the reaction

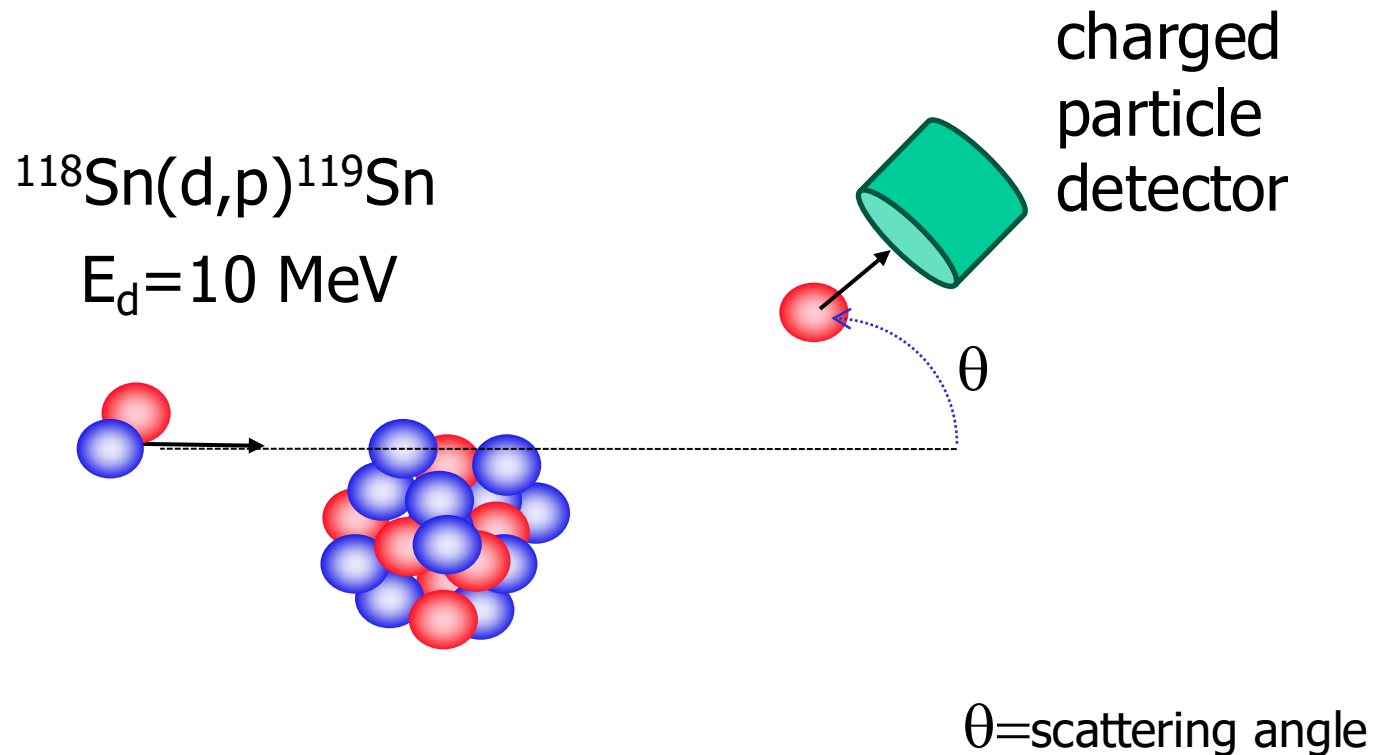
B(A,C)D

A+B \Rightarrow C+D

Studying stable isotopes

Direct kinematics:

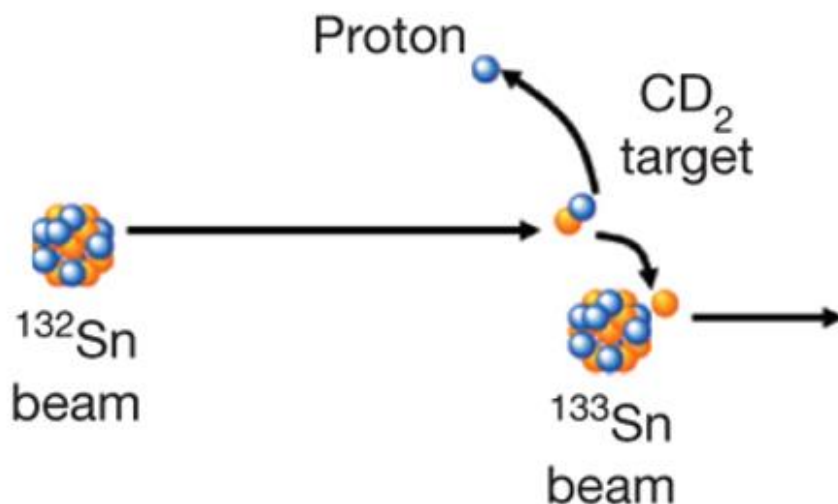
projectile (light isotope) serves as a probe
target (heavy isotope) is the object of study



Studying unstable isotopes

In inverse kinematics:

projectile (heavy isotope) is the object of study
target (light isotope) serves as a probe



$$E_{\text{lab}} = 5 \text{ MeV.A}$$

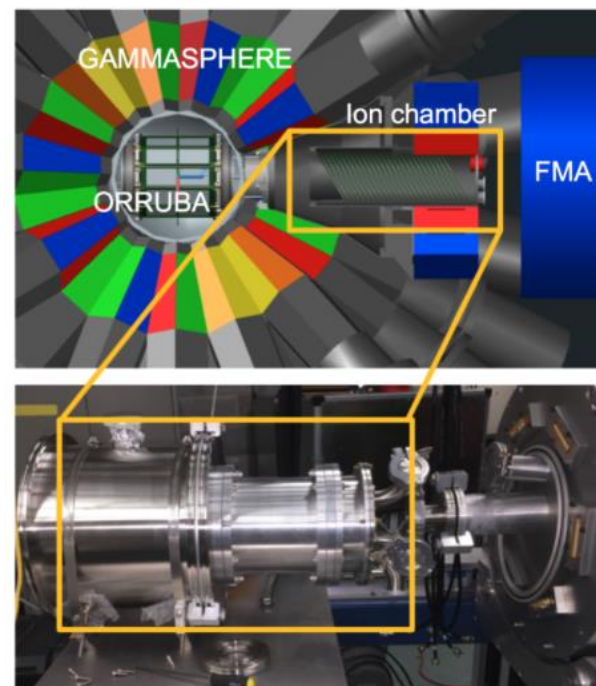
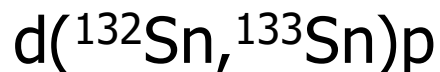


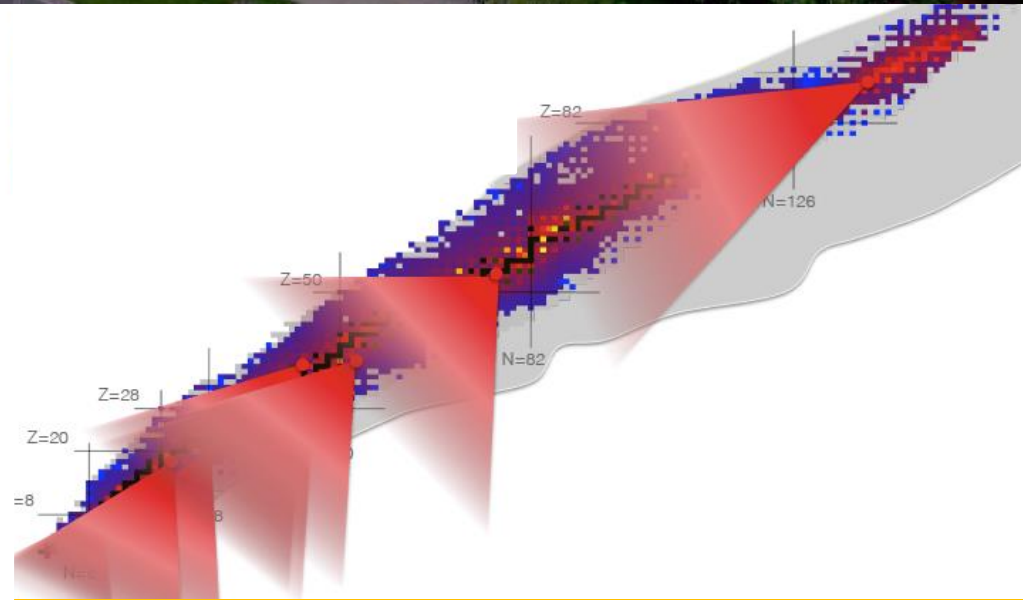
Diagram of the GODDESS detector system showing the ORRUBA silicon strip detector system mounted inside GAMMASPHERE as well as the new fast ionization chamber

Production of exotic nuclei and FRIB

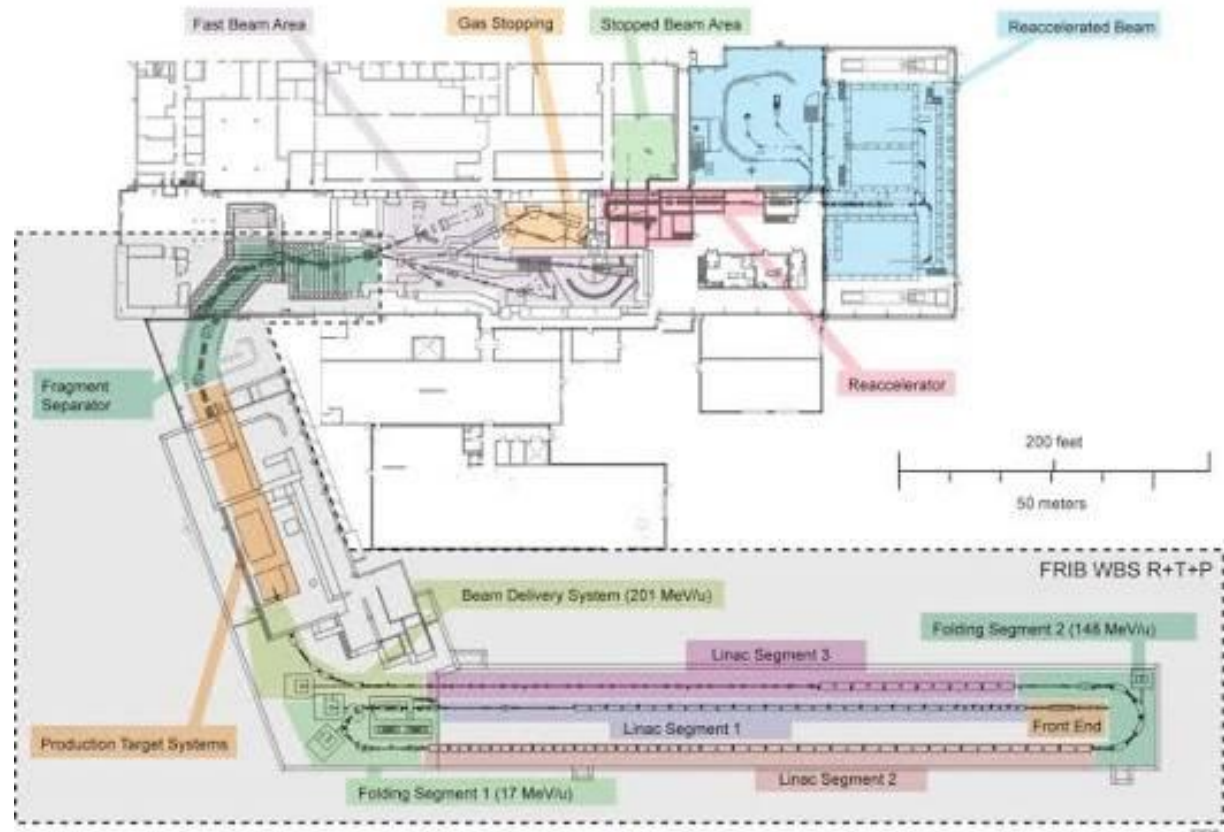
Nuclei produced through fragmentation reactions



nearly 80% of all isotopes
may be produced at FRIB



Nuclei produced through fragmentation reactions



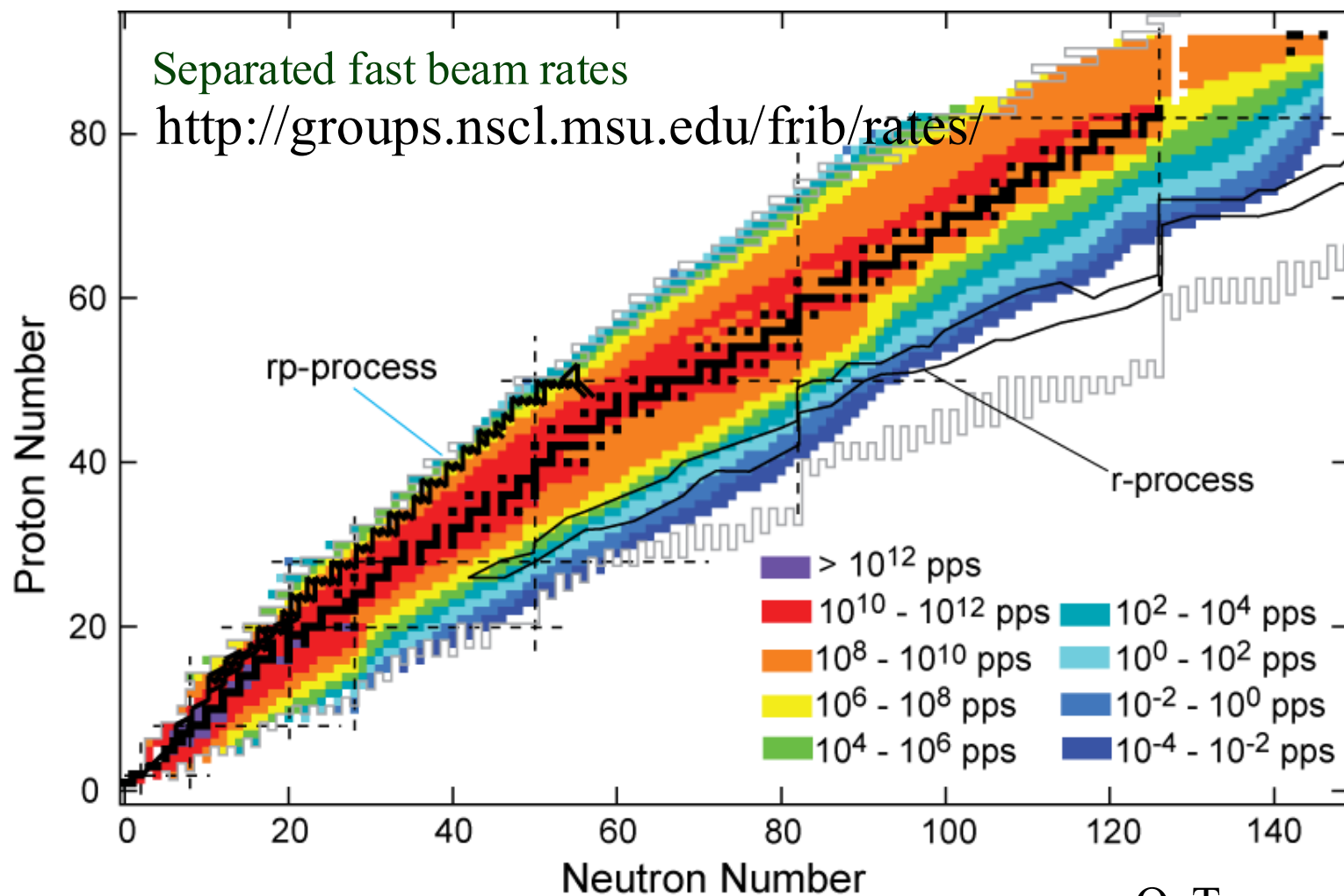
1. Stable heavy-ion beam accelerated in linac segments
2. Collides with the production target, producing a hot mess
3. Fragment separator selects the isotope of interest
4. Driven into the experimental vault

Features of FRIB

- Heavy ion, superconducting linear accelerator with 400 kW beam power at 200 MeV/u
- 400 kW corresponds to a ^{136}Xe beam of 8×10^{13} ion/s and a sensitivity to production cross sections as low as **2×10^{-6} pb.**
- ^{238}U intensity of 5×10^{13} ion/s
- FRIB laboratory will have beams of rare isotopes at a wide range of energies
 - Stopped beams for trapping, laser spectroscopy, etc.
 - Reaccelerated beams to 15 MeV/u (goal) with 15 – 22 MeV/u depending on A/Q)
 - Fast beams up to 250 MeV/u (used in-flight with no slowing)
- Limited multi-user capability through harvesting

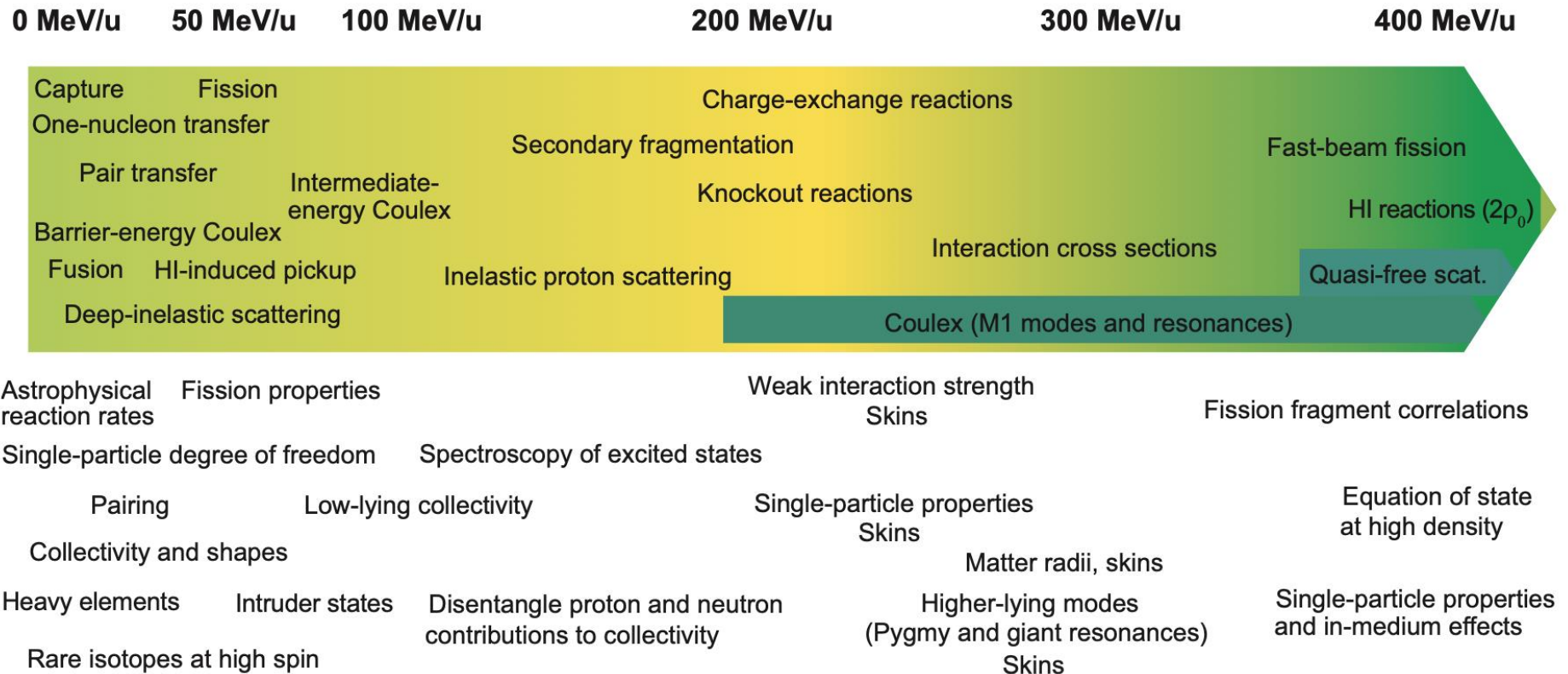


FRIB production in particle per second



O. Tarasov LISE++

Types of studies as a function of beam energy



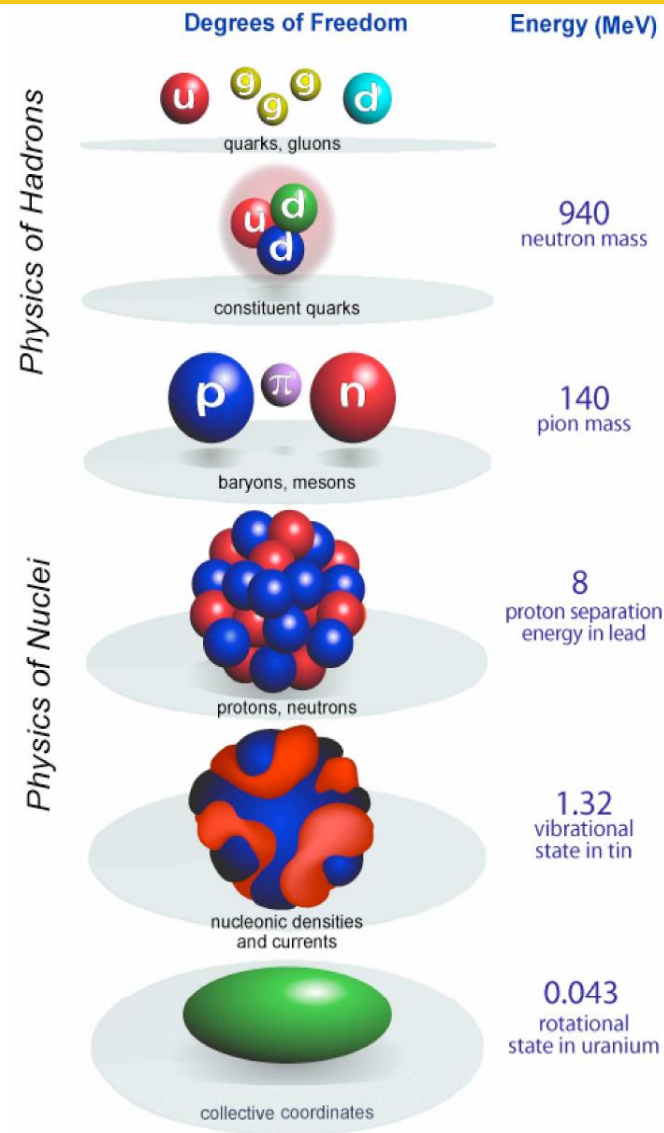
Questions

Activity Time

1. What are the neutron separation energies for ^{12}C and ^{22}C ? ^{16}O and ^{23}O ? What are the lifetimes?
2. Calculate the Q-value for $^{48}\text{Ca}(d,p)^{49}\text{Ca}(\text{gs})$ and $^{132}\text{Sn}(d,p)^{133}\text{Sn}(\text{gs})$ and discuss the differences in the final state.

backup

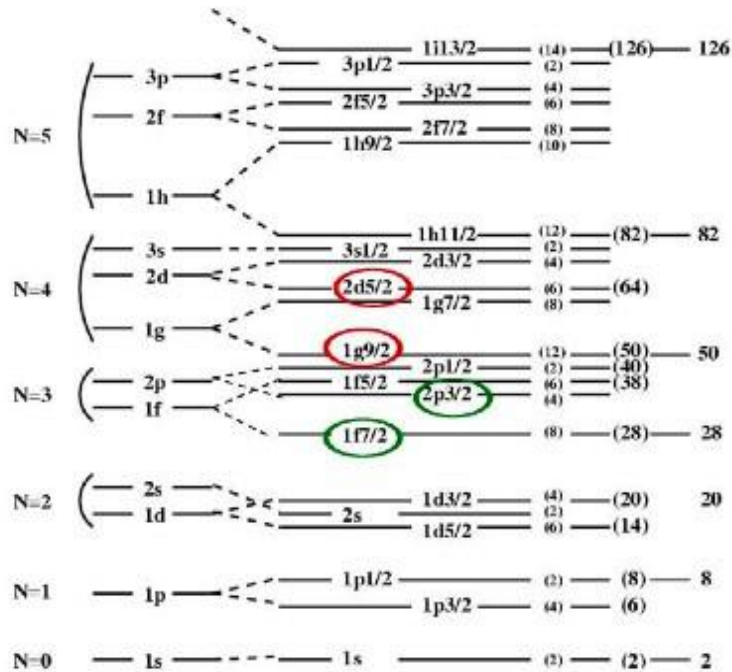
relevant scales for nuclei



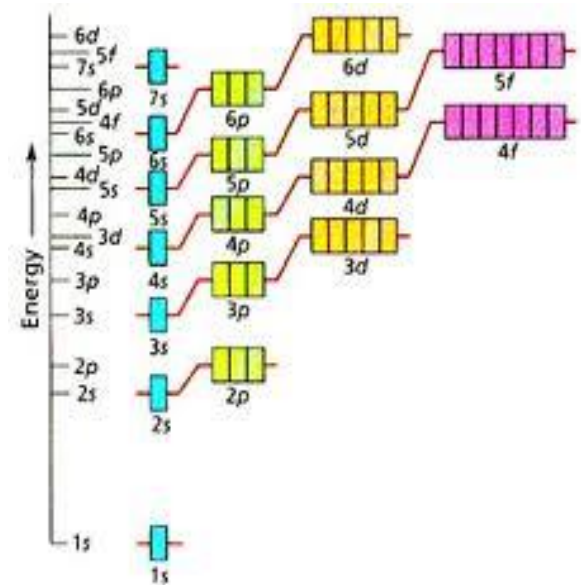
understanding nuclei



nuclear shell model



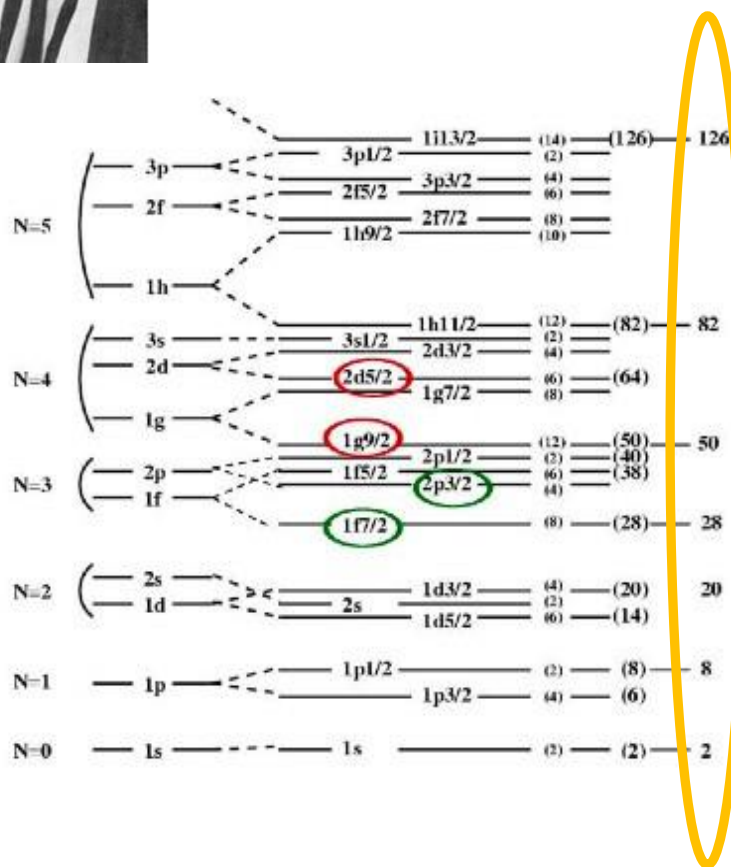
electronic shells



understanding nuclei



nuclear shell model



magic numbers

^{208}Pb

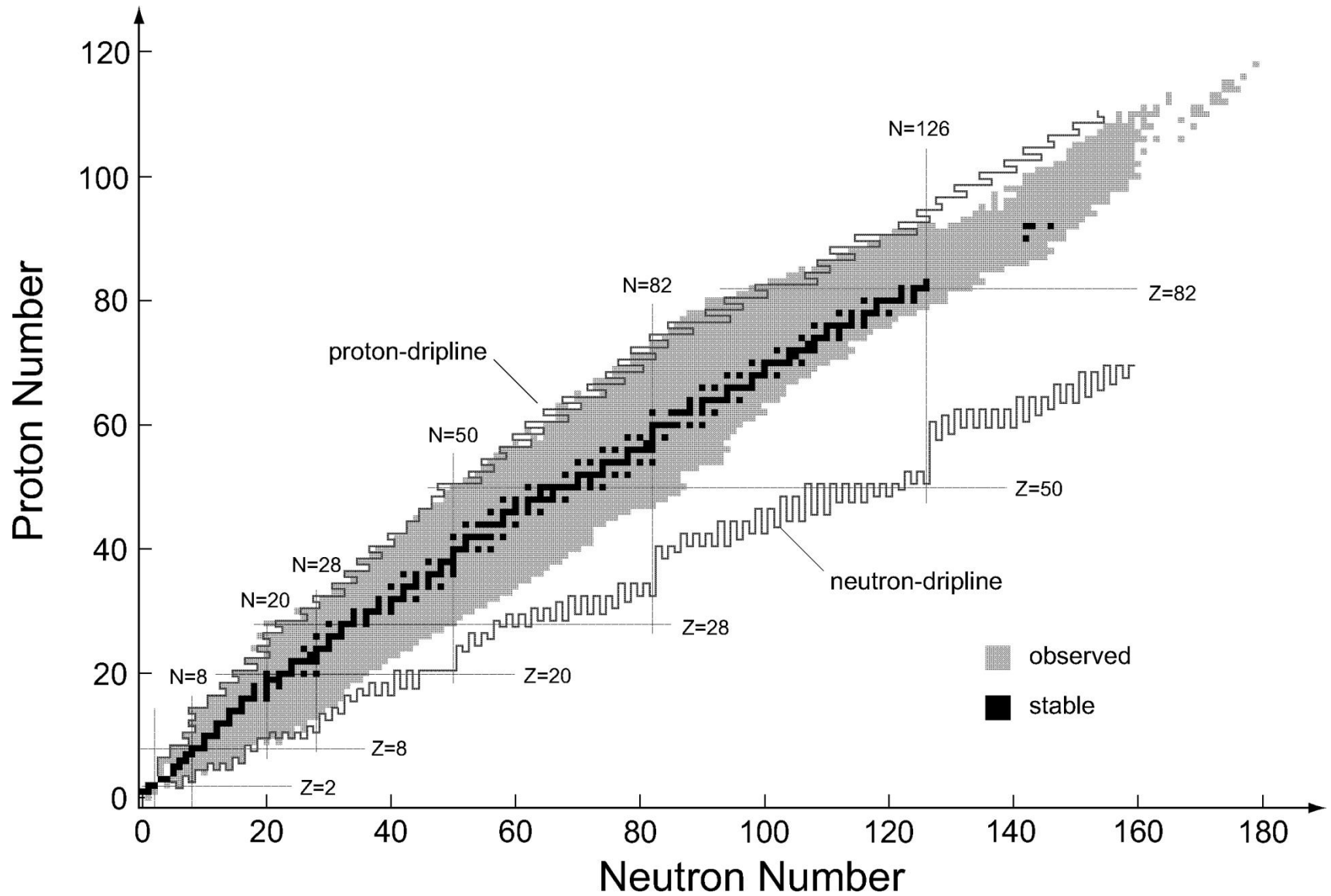
^{100}Sn , ^{132}Sn

^{56}Ni , ^{78}Ni

^{40}Ca , ^{48}Ca

^{16}O

properties of nuclei: chart of nuclei



Traditional shell model: single particle basis

From Thomas Papenbrock's lecture slides

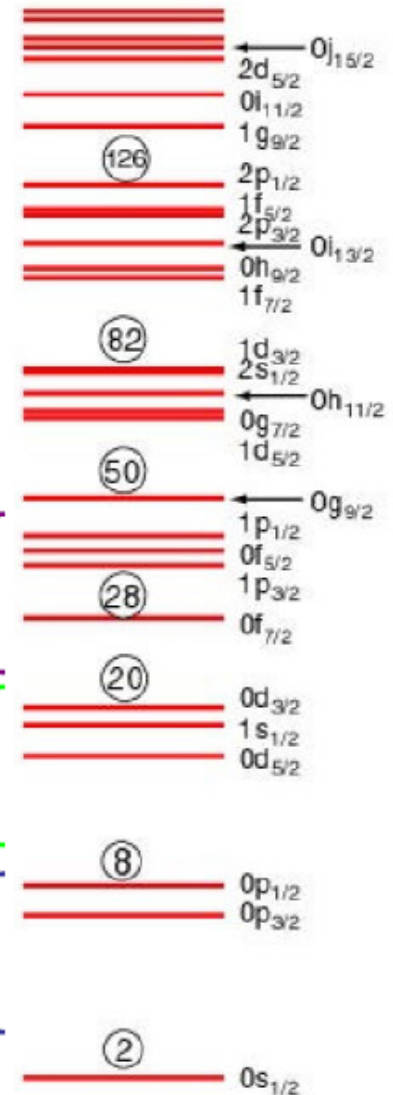
Main idea: Use shell gaps as a truncation of the model space.

- Nucleus $(N, Z) =$ Double magic nucleus (N^*, Z^*)
+ valence nucleons $(N - N^*, Z - Z^*)$

- Restrict excitation of valence nucleons to one oscillator shell.
 - Problematic: Intruder states and core excitations not contained in model space.

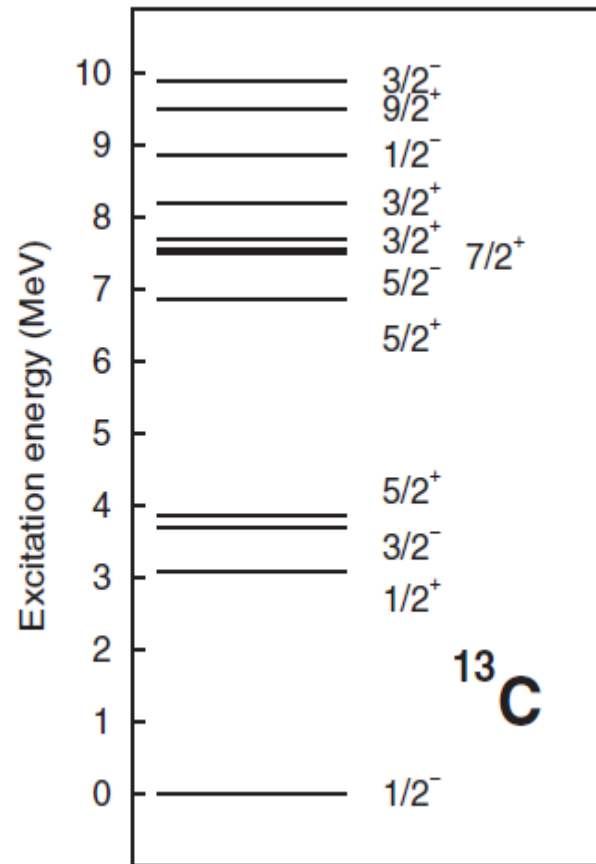
• Examples:

- pf-shell nuclei: ^{40}Ca is doubly magic
- sd-shell nuclei: ^{16}O is doubly magic
- p-shell nuclei: ^4He is doubly magic



Based on these ideas, what is the expected spectrum for ^{13}C ?

nuclear states: example



nuclear bulk properties: liquid-drop model

$$E_B = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A^{1/3}} - a_C \frac{Z(Z-1)}{A^{1/3}} + \delta(A, Z)$$

Volume
term

Surface
term

Asymmetry
term

Coulomb
term

Pairing
term

For pairing term:

$$\delta(A, Z) = \begin{cases} +\delta_o & A, Z \text{ even} \\ 0 & A \text{ odd} \\ -\delta_o & A, Z \text{ odd} \end{cases}$$

where

$$\delta_o = \frac{a_P}{A^{1/2}}$$

Coefficients:

$$a_V = 15.85 \text{ MeV}$$

$$a_S = 18.34 \text{ MeV}$$

$$a_A = 23.21 \text{ MeV}$$

$$a_C = 0.714 \text{ MeV}$$

$$a_P = 12.00 \text{ MeV}$$

nuclear stability

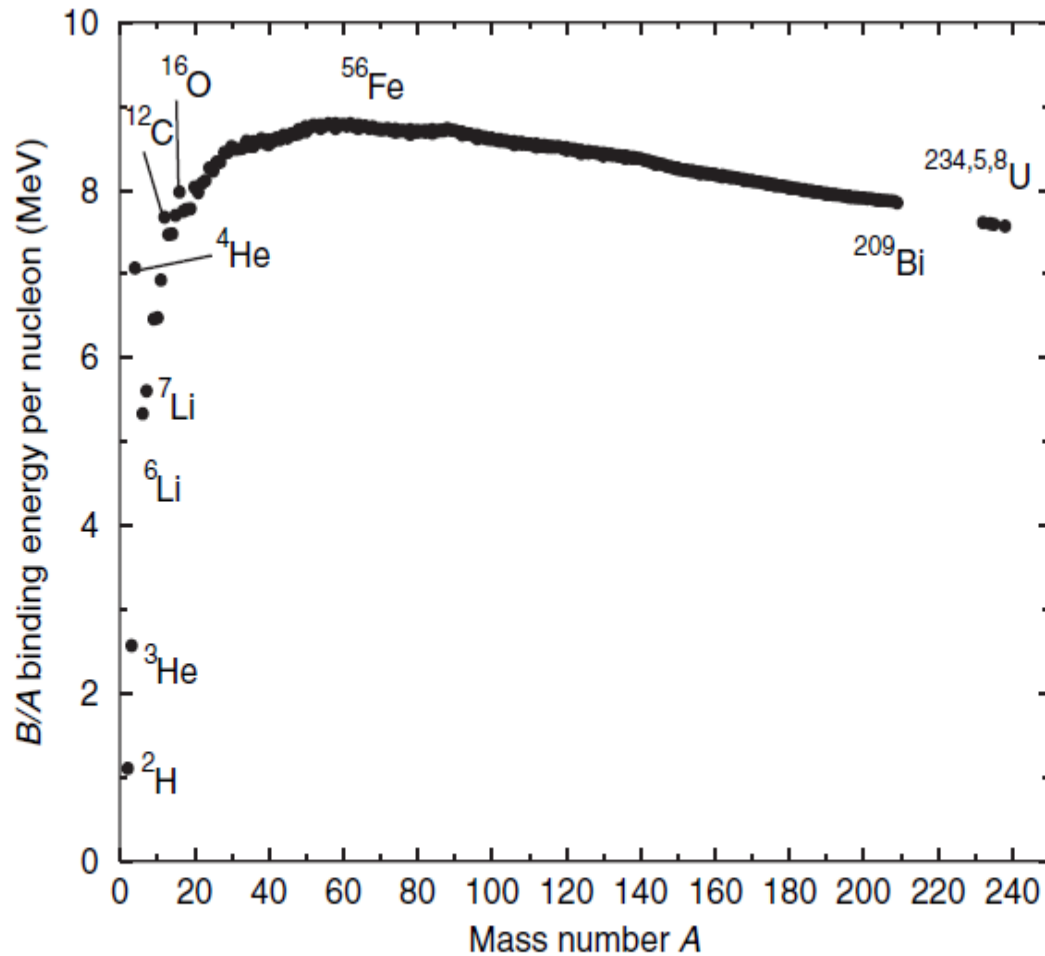
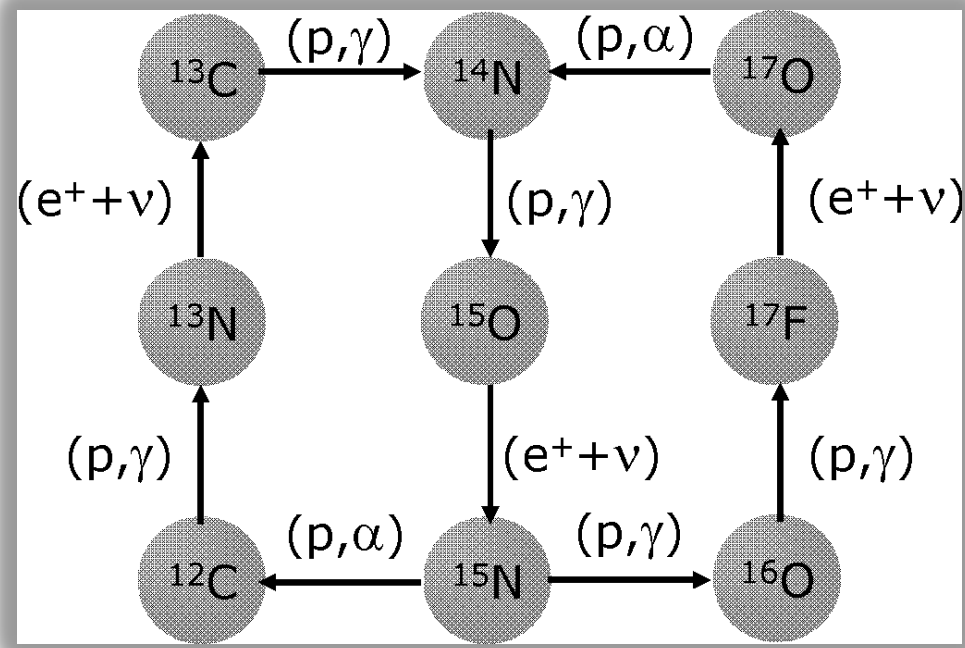
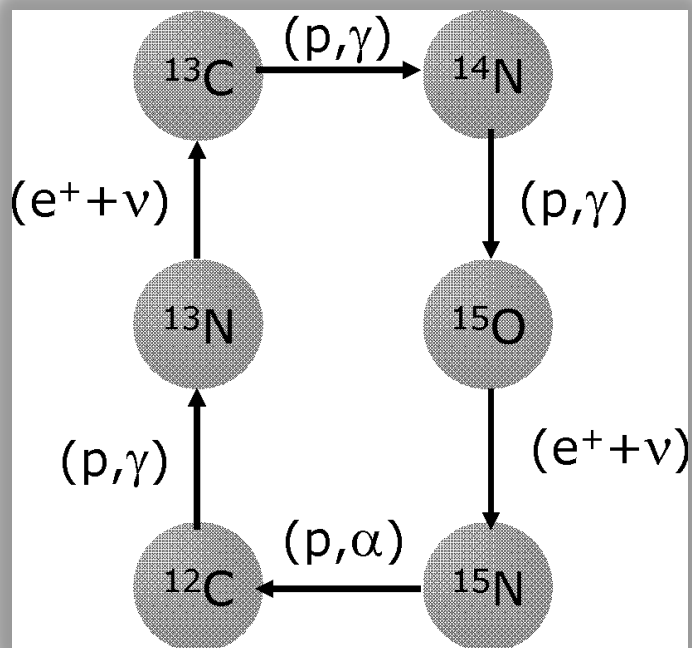


Fig. 1.1. Binding energies per nucleon, $B(A, Z)/A$, for all naturally occurring long-lived isotopes of A nucleons.

CNO cycles



Big science questions

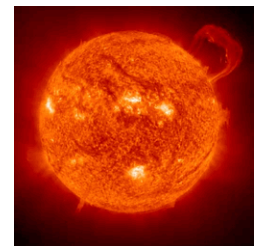
1) How did matter come into being and how does it evolve?

Strong interplay of various subfields:

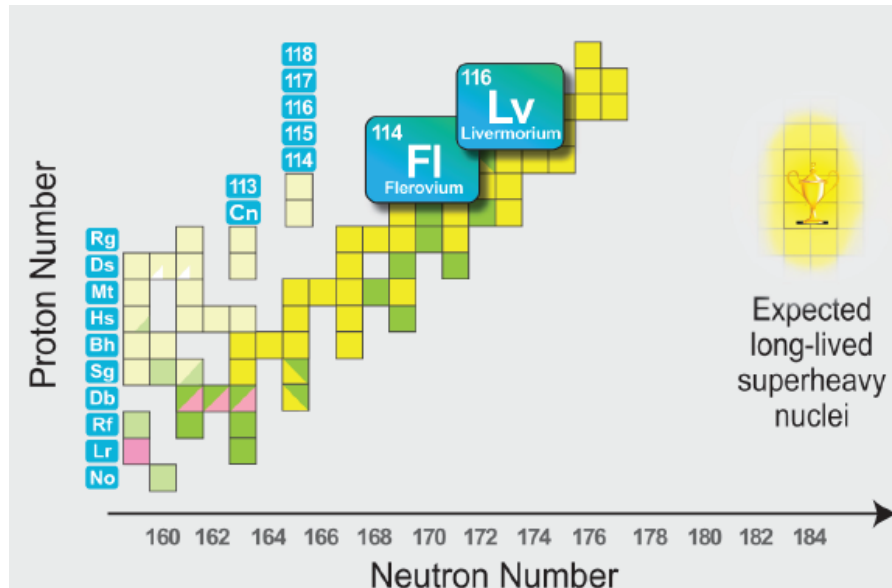
- Nuclear Data (experiments)
- Nuclear theory input complements those data
- Observations (astronomy) that provide additional constraints
- Astrophysics simulations

Big science questions: origin of the elements

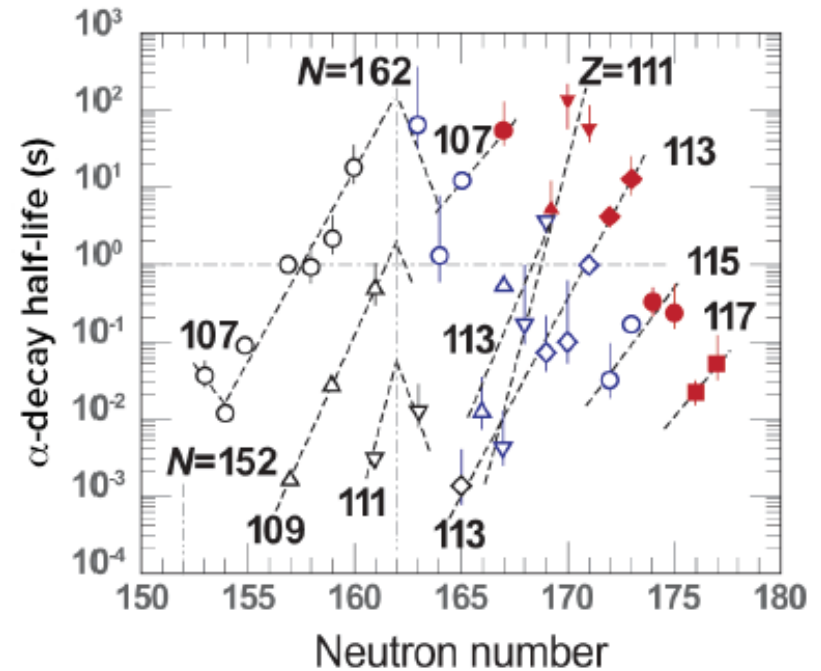
- The stability of matter is closely related to its origin.
- Our field explores the likely series of nuclear reactions and decays that have led to the synthesis of the elements and their isotopes.
- Experimentally the study of the origin of matter has two parts
 - nuclear astrophysics with intense stable beams studies the reactions of stable isotopes in stars – role for stable beam facilities and an underground accelerator
 - the key role unstable isotopes play in astrophysical processes (radioactive beam facilities)



Superheavies

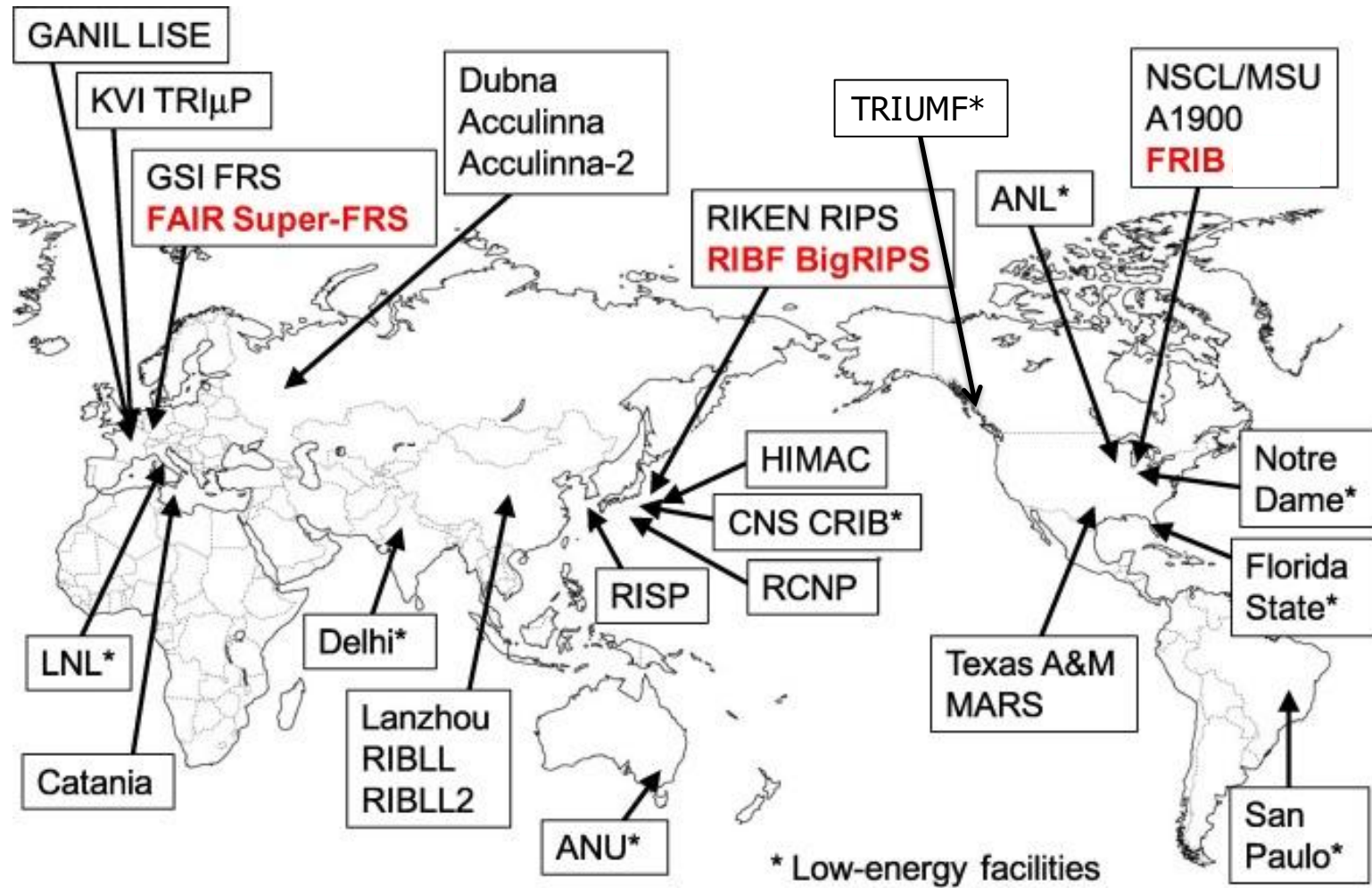


- Elements 113 and 115 were confirmed
- Flerovium ($Z=114$) and Livermorium ($Z=116$) joined the periodic table
- New chemical element 117 was discovered and experimentally confirmed



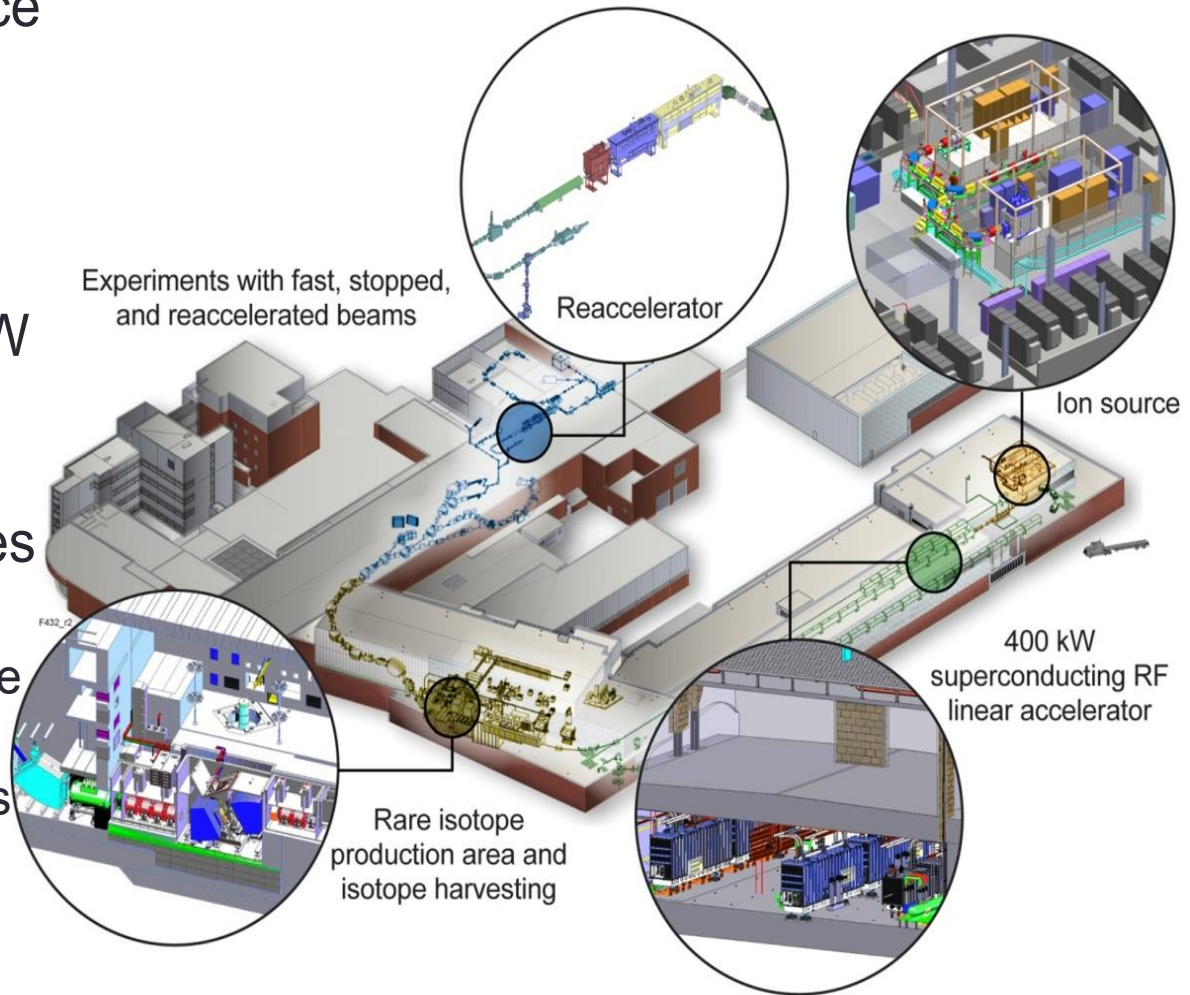
- Recently discovered nuclei (red and blue) show a trend of longer half-lives as the neutron number increases

rare isotope beams facilities worldwide

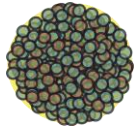


Facility for Rare Isotope Beams (FRIB)

- Funded by DOE Office of Science Office of Nuclear Physics. T. Glasmacher, Project Director
- Key Feature is 400kW beam power (5×10^{13} $^{238}\text{U/s}$)
- Separation of isotopes in-flight
 - Fast development time for any isotope
 - Suited for all elements and short half-lives
 - Fast, stopped, and reaccelerated beams

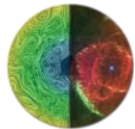


FRIB Scientific Program



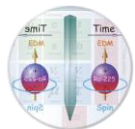
Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Many-body quantum problem: intellectual overlap to mesoscopic science, quantum dots, atomic clusters, etc.
- The limits of stability of elements and isotopes



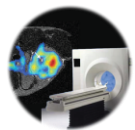
Astrophysical processes

- Stellar archeology
- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts ...
- Properties of neutron stars



Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei

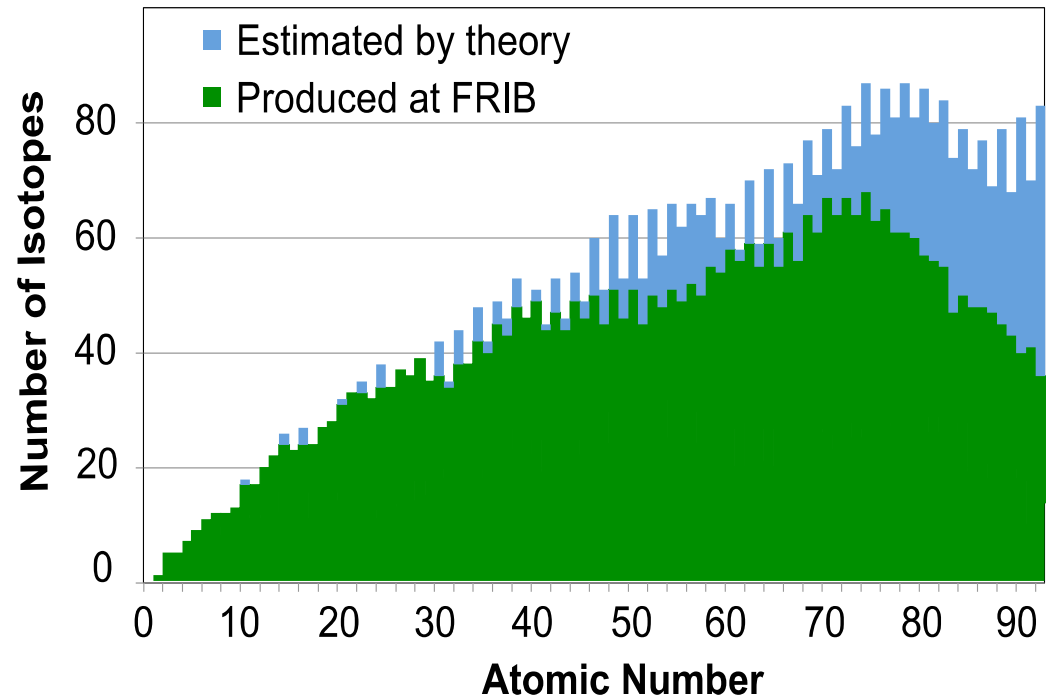
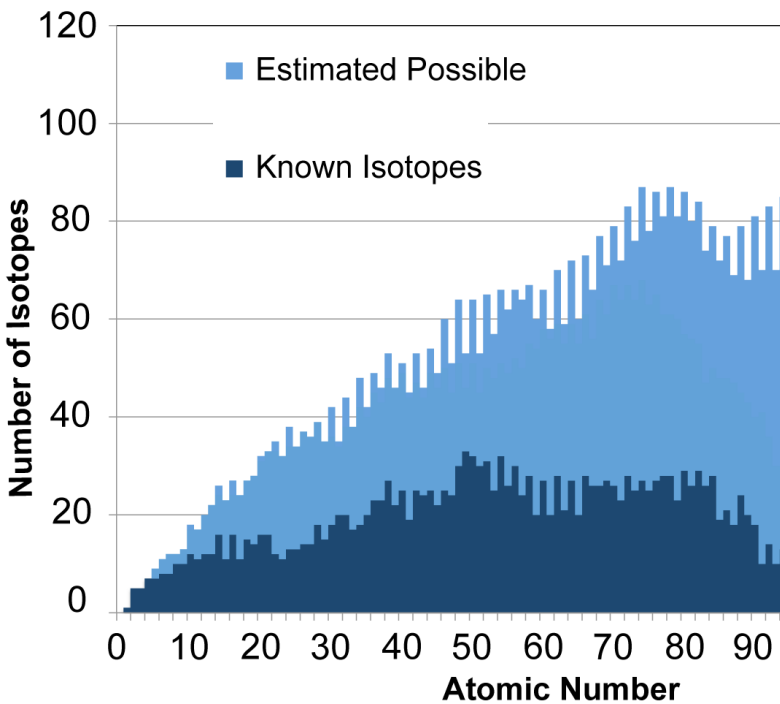


Societal applications and benefits

- Biology, environment, energy, material sciences, national security



Our nucleus factory



Nearly 80% of all isotopes up to Uranium may be produced at FRIB