Rare Isotope Physics

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June 13th, 2024

OUTLINE

1. Introduction
2. Shell model & clustering
3. Nuclear radioactivity
4. Nuclear reactions

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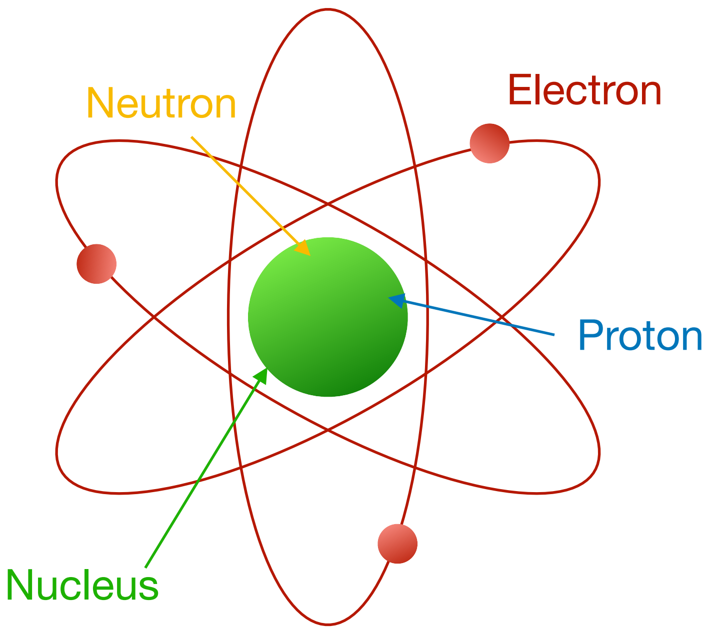
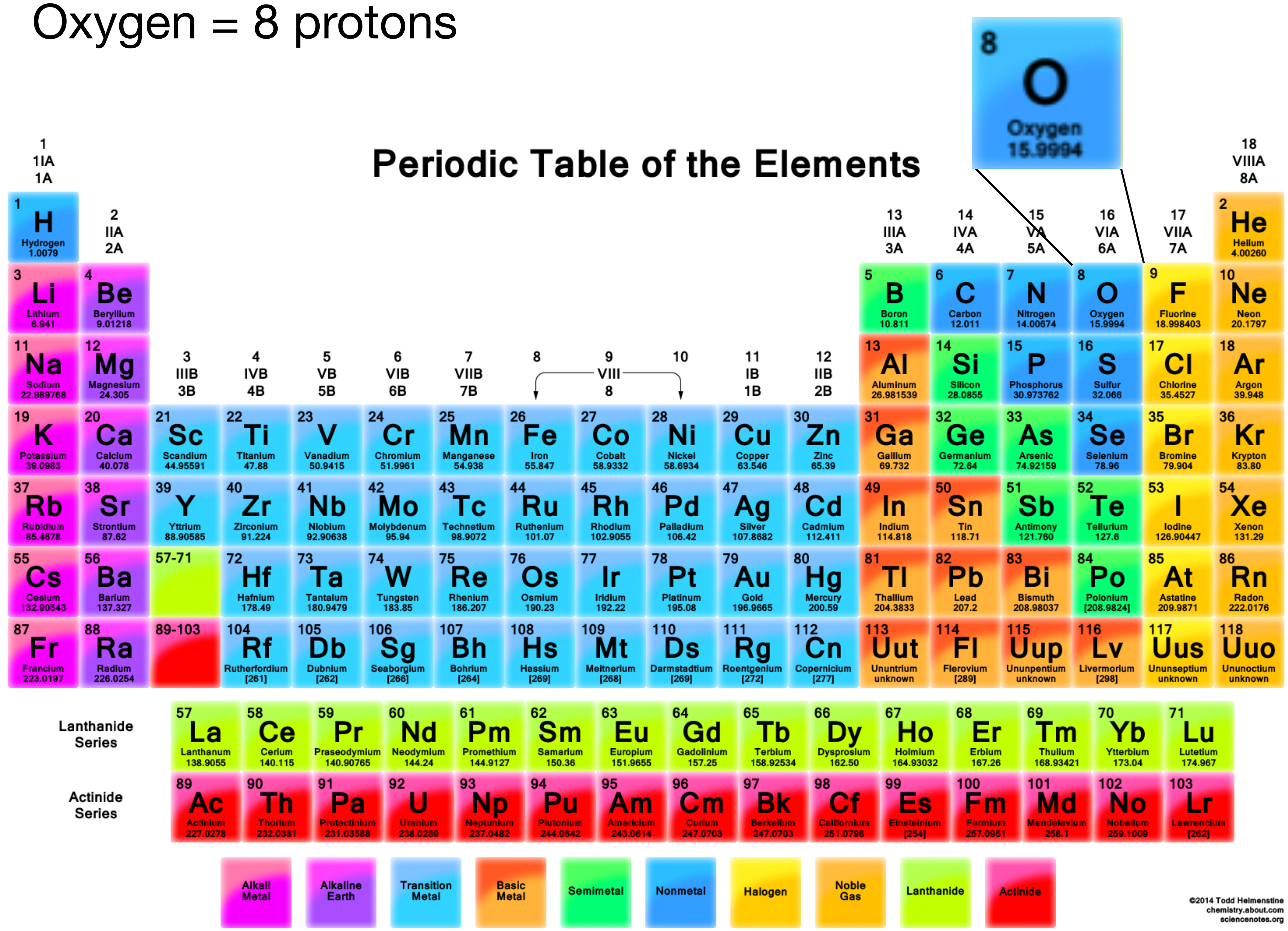
1. **Introduction**
2. **Shell model & clustering**
3. **Nuclear radioactivity**
4. **Nuclear reactions**

WHAT IS A NUCLEUS?



Atom

- Atom size : $10^{-10}\ m$ - Nucleus size : $10^{-15}\ m$
- Nuclei composed of protons & neutrons
- Element: defined by the atomic number
- Atomic number = number of protons in nucleus
- Oxygen = 8 protons



- Oxygen mass= 15.9994 a.m.u
- How many neutrons are there in Oxygen?

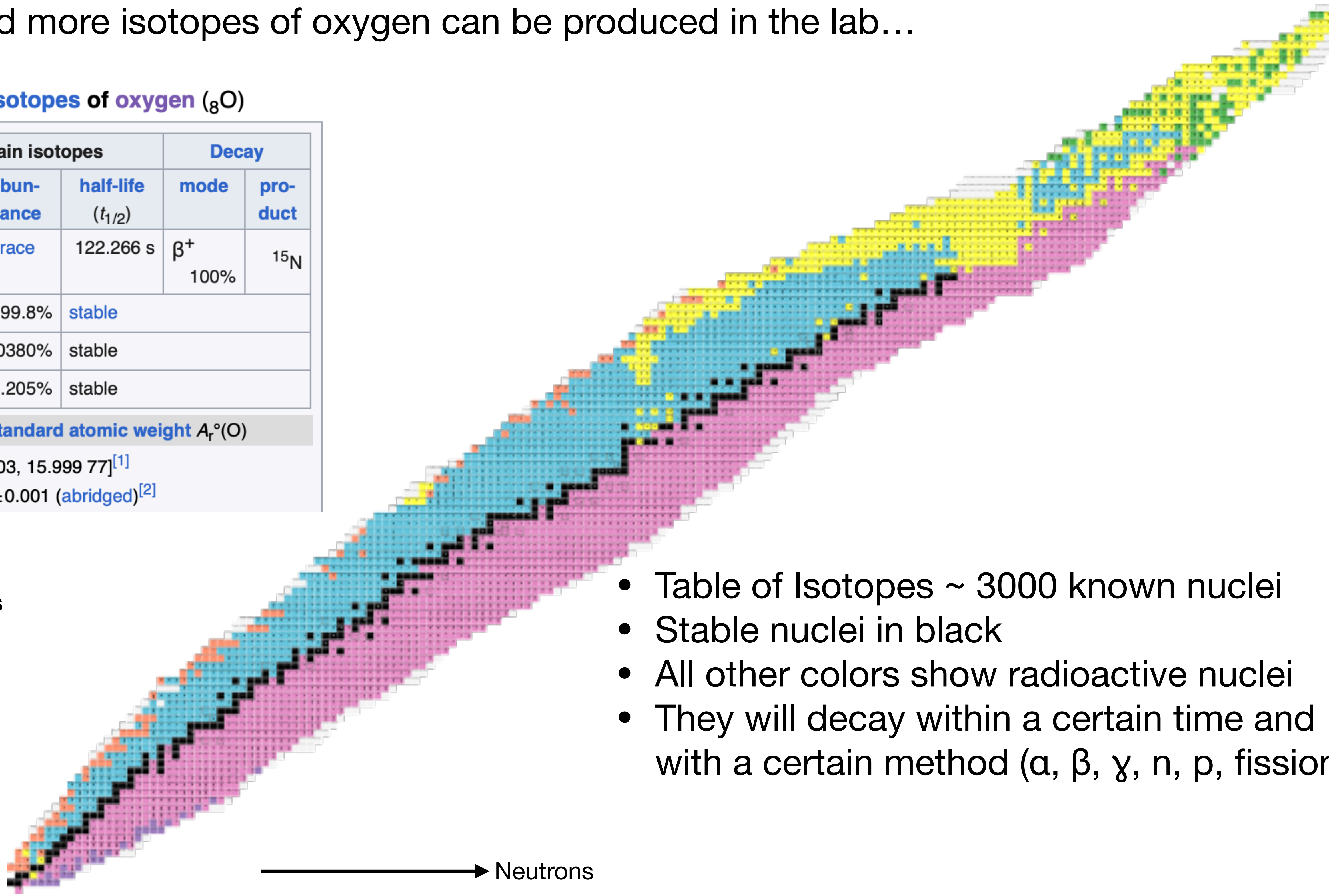
…

THE TABLE OF ISOTOPES

- Isotopes = Nuclei with the same number of protons
- Oxygen = 4 different isotopes present in nature: ^{15}O, ^{16}O, ^{17}O, ^{18}O
- And more isotopes of oxygen can be produced in the lab…

Isotopes of oxygen ($_8O$)

Main isotopes			Decay	
	abun-dance	half-life ($t_{1/2}$)	mode	pro-duct
^{15}O	trace	122.266 s	β^+ 100%	^{15}N
^{16}O	99.8%	stable		
^{17}O	0.0380%	stable		
^{18}O	0.205%	stable		
Standard atomic weight $A_r°(O)$				
[15.999 03, 15.999 77][1]				
15.999 ±0.001 (abridged)[2]				



Protons

Neutrons

- Table of Isotopes ~ 3000 known nuclei
- Stable nuclei in black
- All other colors show radioactive nuclei
- They will decay within a certain time and with a certain method (α, β, ɣ, n, p, fission)

ISOTOPES, ISOTONES, ISOBARS

Every nucleus is characterised by:

$${}^{A}_{Z}X_{N}$$

Z: Proton number (chemical element)

N: Neutron number

A=Z+N : Mass number

Isotopes: Nuclei with same Z

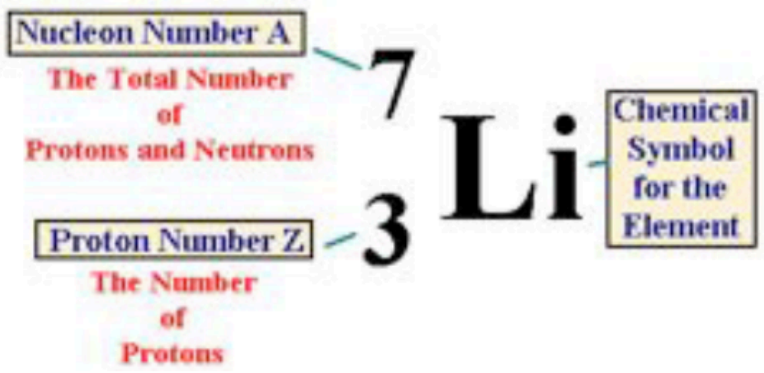
Isotones: Nuclei with same N

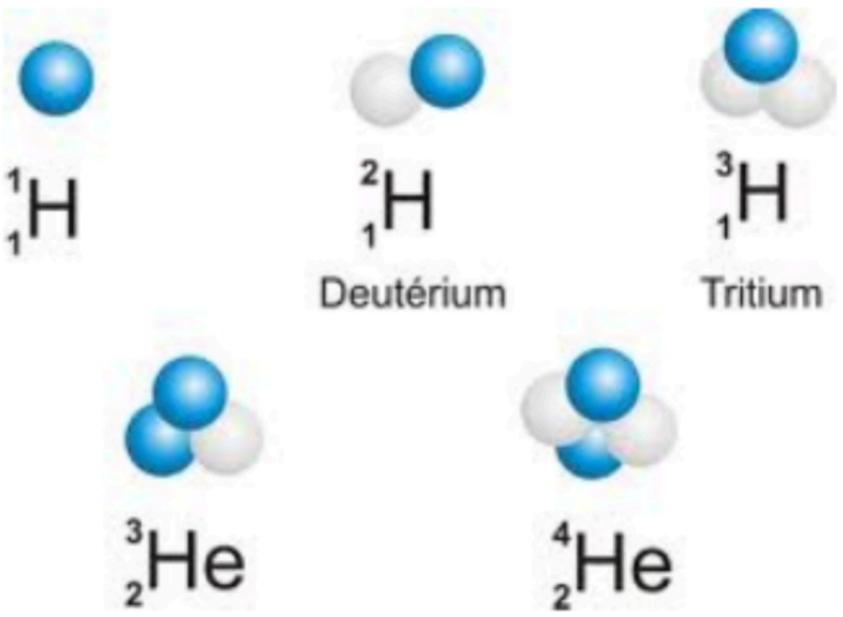
Isobars: Nuclei with same A

Charge of the nucleus **Ze** with e=1.602 10^{-19} C

Neutral atom has Z protons and Z electrons

Ion : missing or added electron(s) ($q=1^{+},2^{+},\ldots,Z^{+}$)



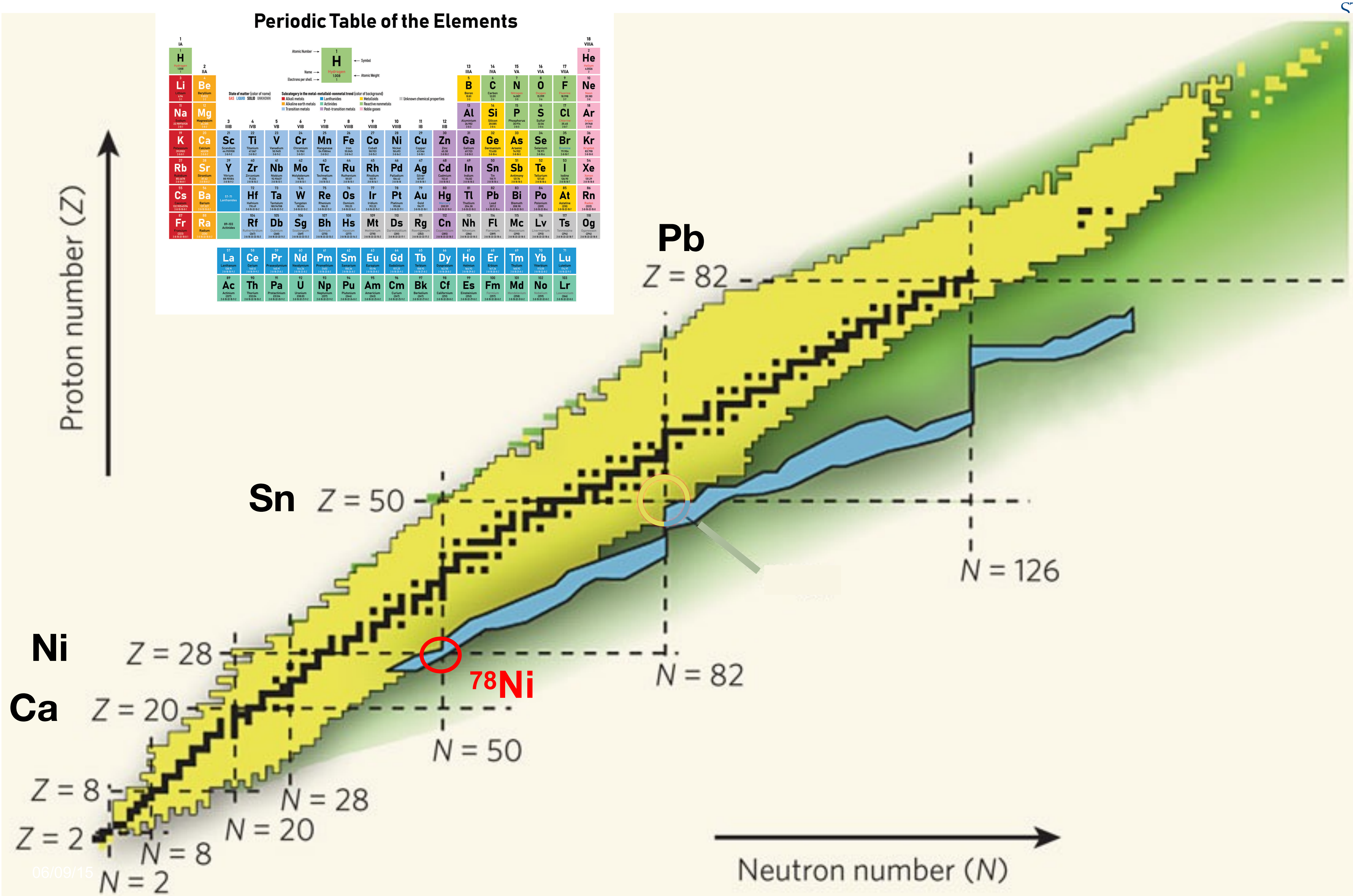


- https://www.nndc.bnl.gov/nudat3/

MICHIGAN STATE UNIVERSITY

NUCLEAR CHART

MORGAN STATE UNIVERSITY



- Stable nuclei (in black) form the “valley of stability”
- Radioactive nuclei known (in yellow) and all other possible unknown (in green)

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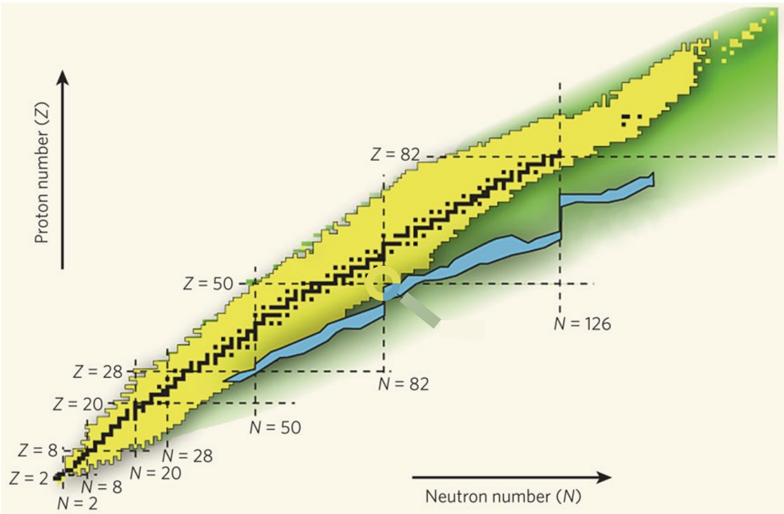
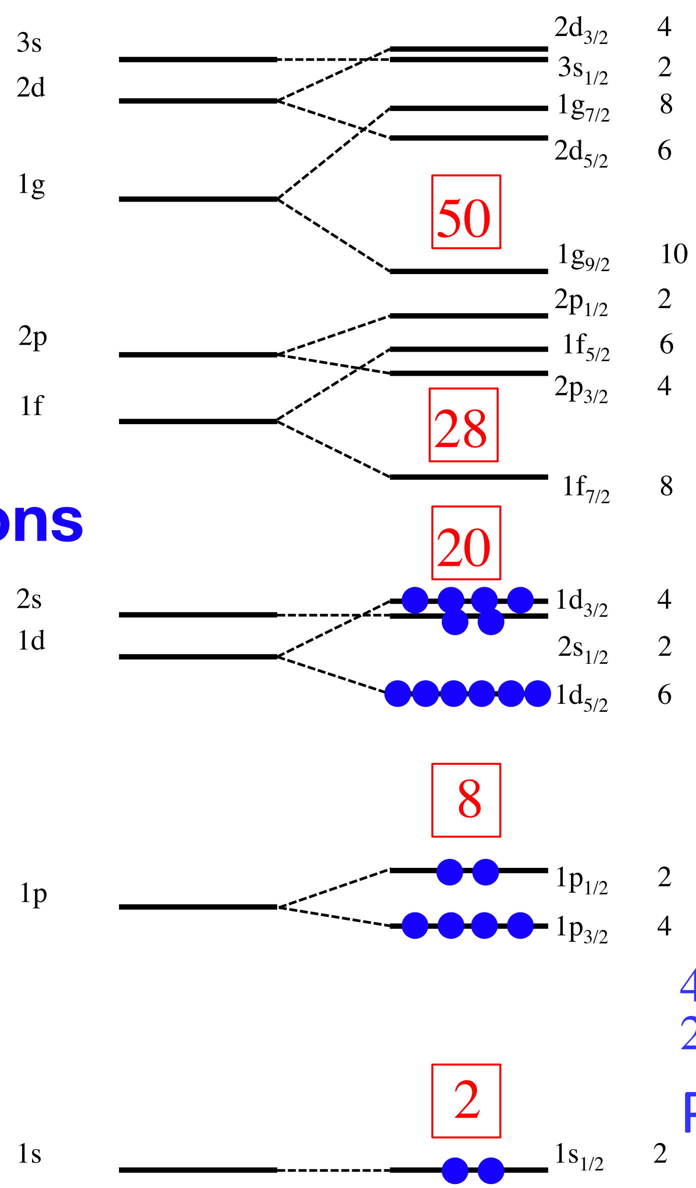
MAGIC NUCLEI & EXOTIC NUCLEI



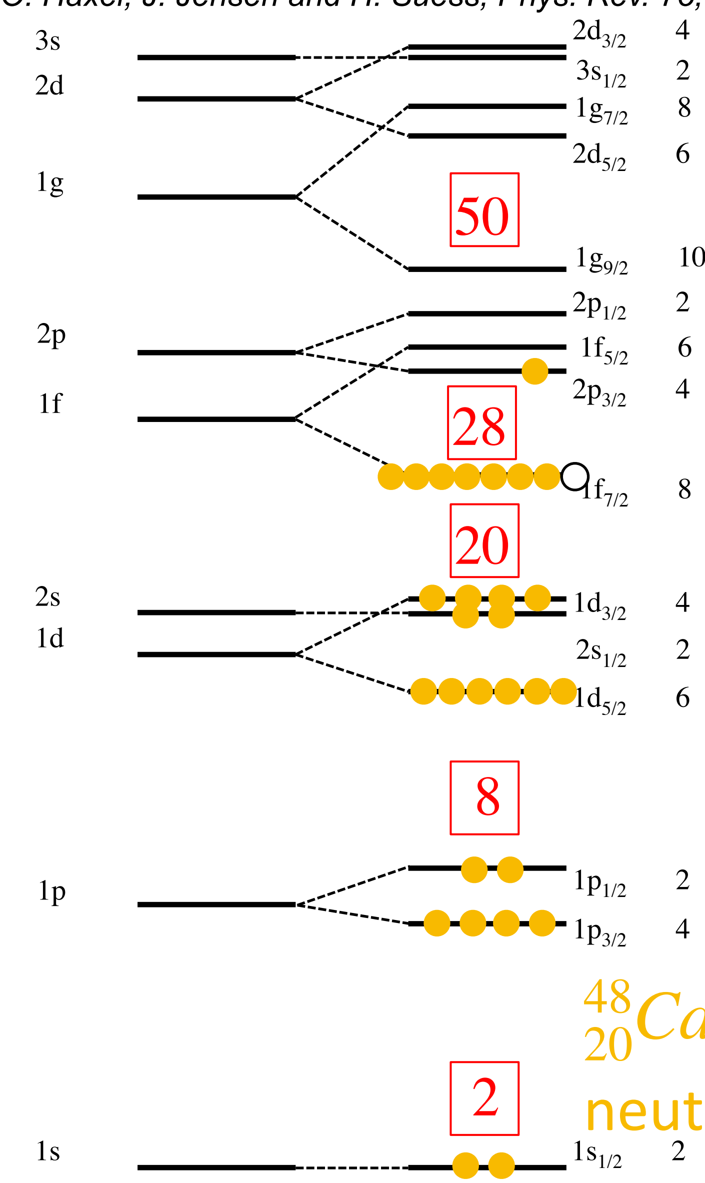
- Magic numbers= 2, 8, 20, 28, 50, 82…
- Corresponds to closed (or full) shells in our nuclear shell model
- Magic number signature= high first excited state
- Example: ^{48}Ca, doubly magic

M. Goeppert-Mayer, Phys. Rev. 75, 1969 (1949).
O. Haxel, J. Jensen and H. Suess, Phys. Rev. 75, 1766 (1949).

20 protons



$^{48}_{20}Ca_{28}$
Protons



28 neutrons

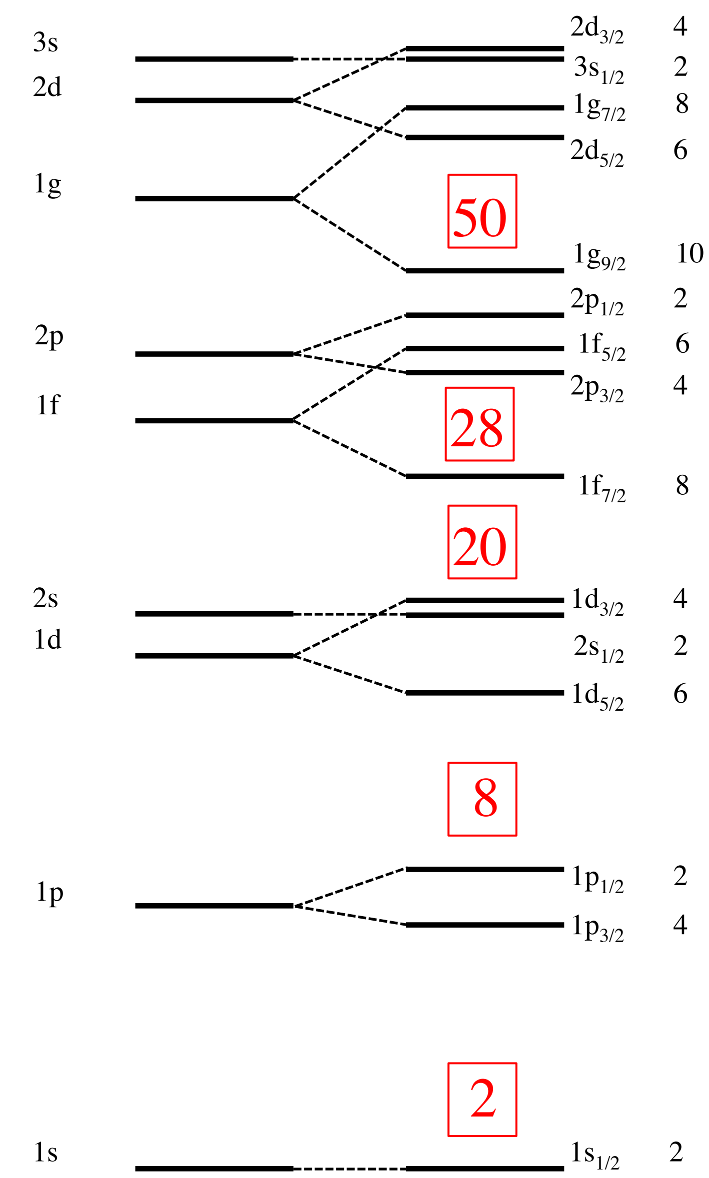
$^{48}_{20}Ca_{28}$
neutrons

SHELL MODEL NOTATIONS

- Quantum numbers to define possible states:
  - Principal quantum number n
  - Orbital angular momentum ℓ ($\ell = 0,1,2,3,4$ are s, p, d, f, g orbitals)
  - Spin s (here +1/2 or -1/2, as both protons and neutrons are fermions)
  - Total angular momentum j, here $j = \ell + s$ or $\ell - s$

A nuclear shell is uniquely defined by : $n\ell_j$

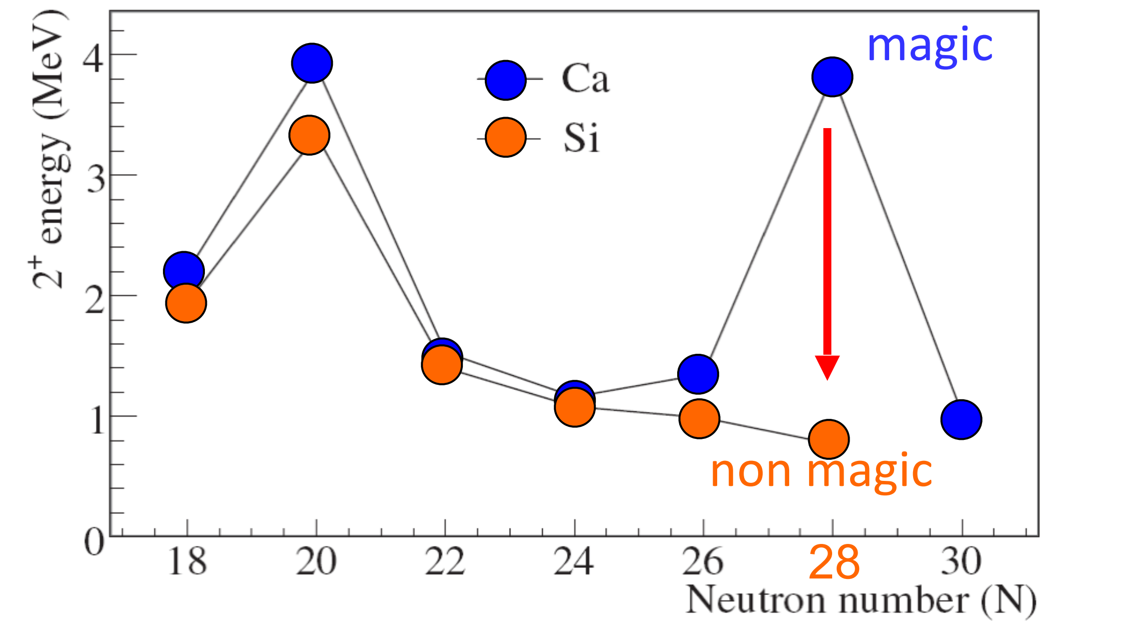
The spin-orbit coupling is splitting the state with the same orbital angular momentum (electron shells) into TWO states now, using the total angular momentum as well



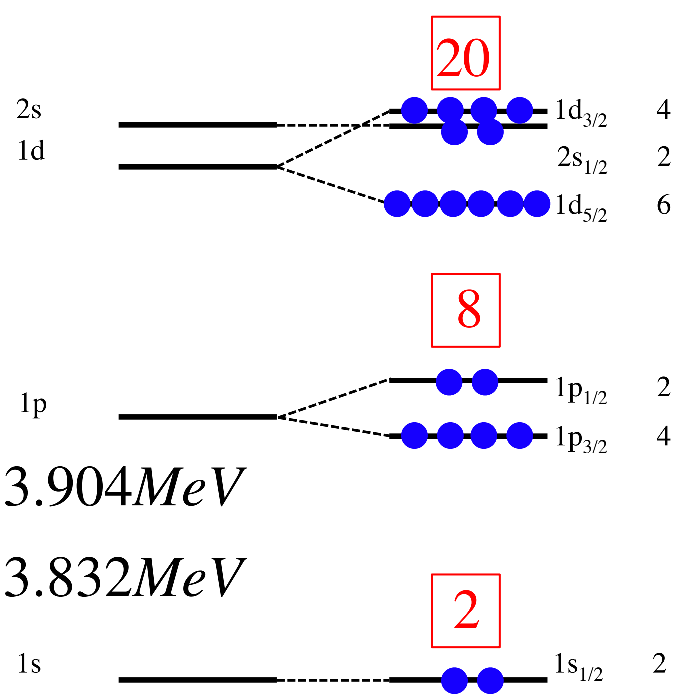
MAGIC NUCLEI & EXOTIC NUCLEI

- Magic numbers= 2, 8, 20, 28, 50, 82…
- As we go to exotic nuclei, magic numbers are changing !
- Example: Ca (Z=20) vs Si (Z=14) for N=28

Magic number signature



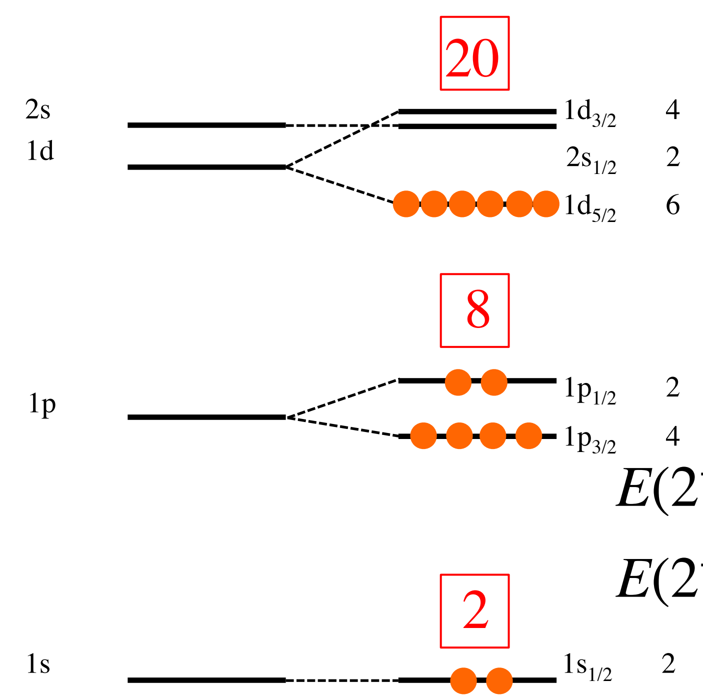
Shell structure for protons



$^{48}_{20}Ca_{28}$

$$E(2^+, {}^{40}_{20}Ca_{20}) = 3.904 MeV$$

$$E(2^+, {}^{48}_{20}Ca_{28}) = 3.832 MeV$$

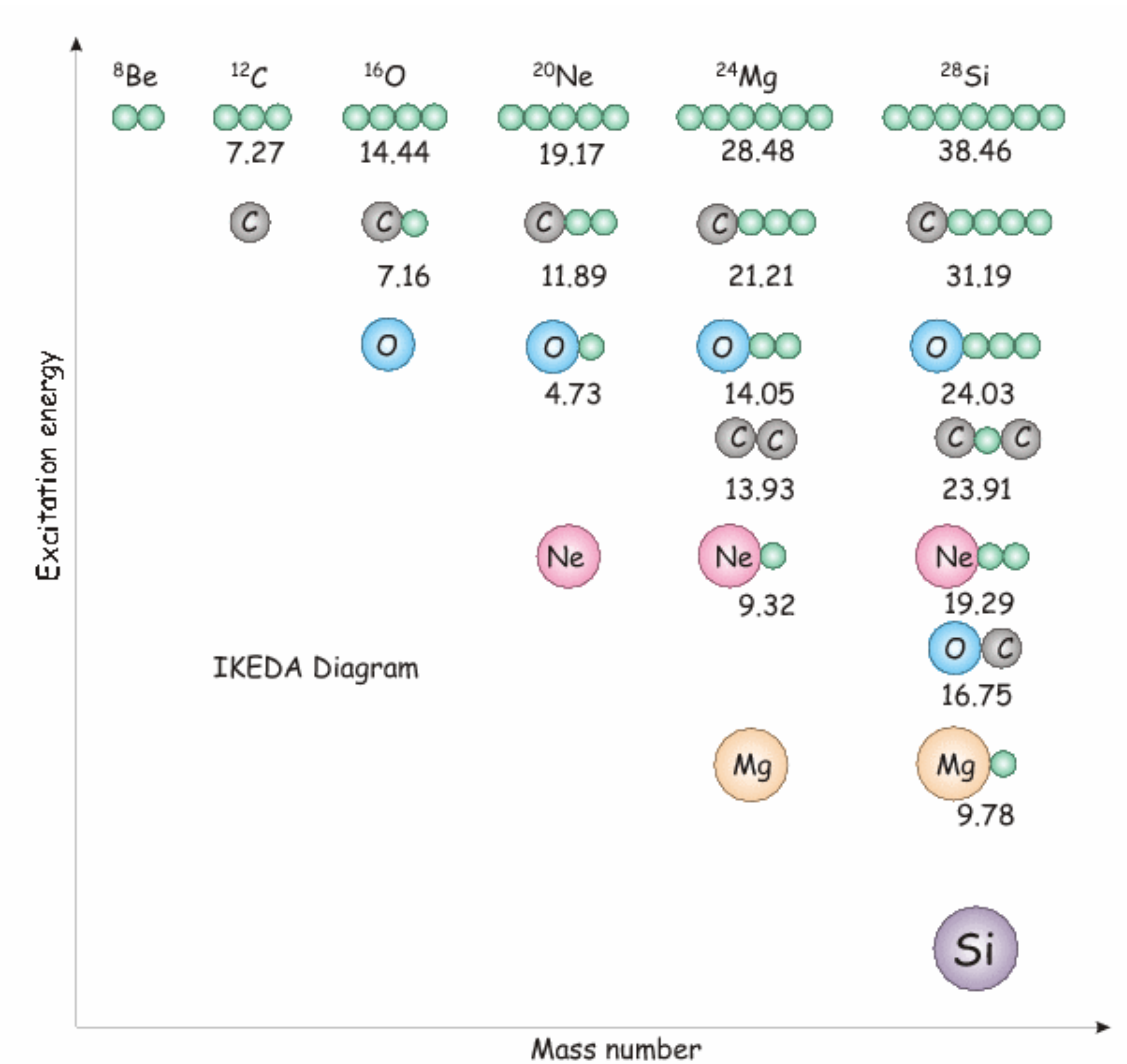


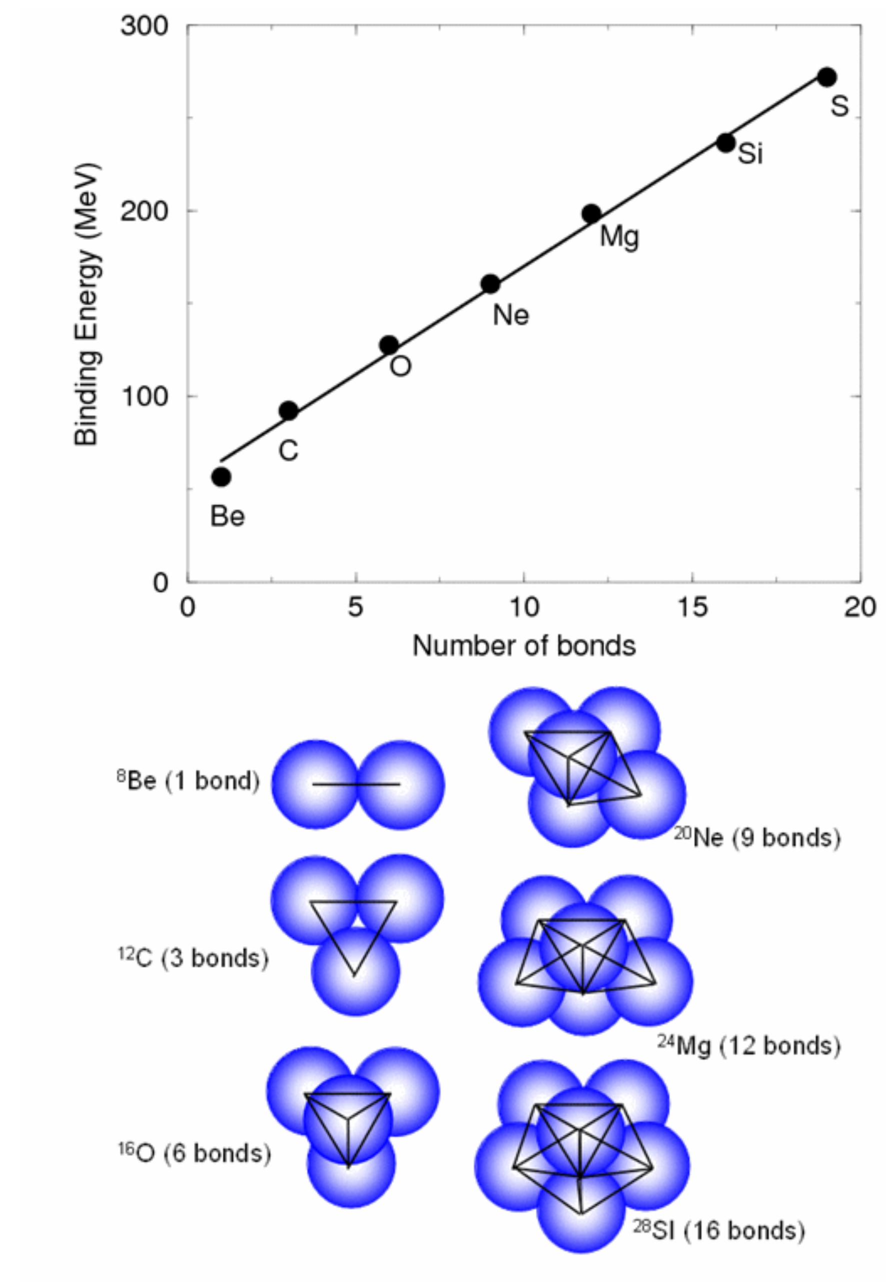
$^{42}_{14}Si_{28}$

$$E(2^+, {}^{34}_{14}Si_{20}) = 3.327 MeV$$

$$E(2^+, {}^{42}_{14}Si_{28}) = 0.742 MeV$$

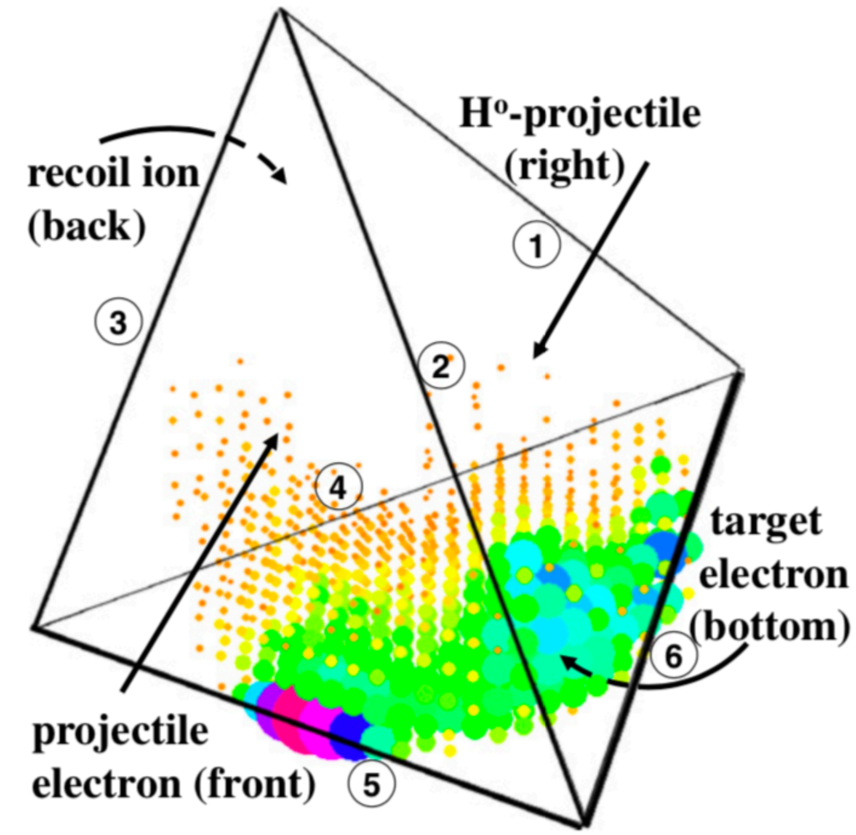
With the α decay of heavy nuclei, came the idea that clusters of α particles ($^4He = 2p + 2n$) might be preformed prior to emission





Martin Freer 2007 *Rep. Prog. Phys.* **70** 2149

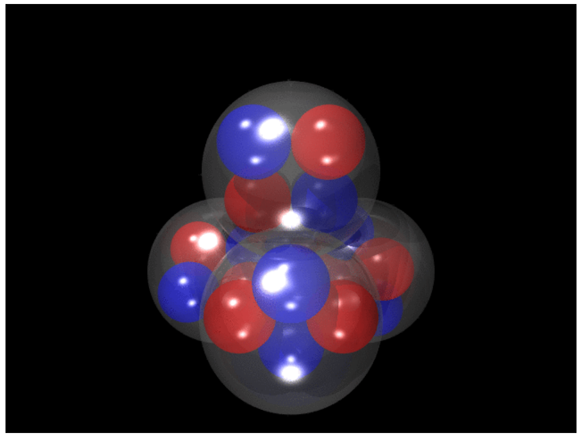
STUDY OF CLUSTERING IN ^{16}O BY FOUR α-DECAY



- ^4He = 2 protons + 2 neutrons, or also called α particle
- 2 α = ^8Be is UNBOUND - doesn't exist
- triple α process in stars instead to produce ^{12}C = 3 α

- Hoyle state in ^{12}C = excited, spinless state that is produced in the triple α process

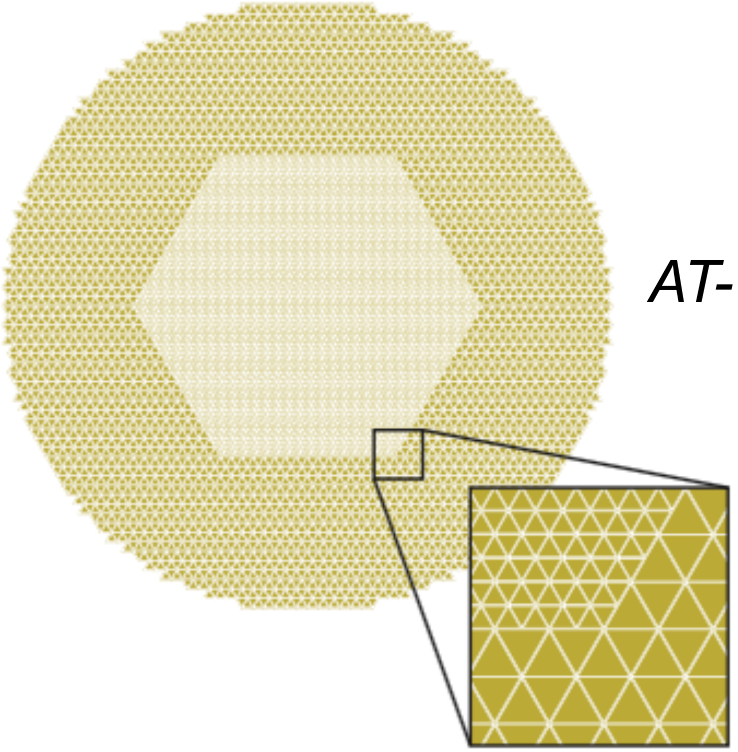
  - ^{12}C Hoyle state confirmed to be a 3α cluster
  - Mostly sequential decay = not linear chain structure
  - Structure as linear chain challenged by some theories and its mostly sequential decay
  - No other heavier nuclei have confirmed α-condensate states, Hoyle-like / linear chain
  - Study of ^{16}O like R. Smith et al., PRL 119, 132502 (2017)



➡Direct measurement of 4 α decay from the $\mathbf{0^+_6}$ Hoyle-like state candidate at 15.097(5) MeV

➡ Analysis of decay with 4-particle Dalitz plot

AT-TPC DETECTOR



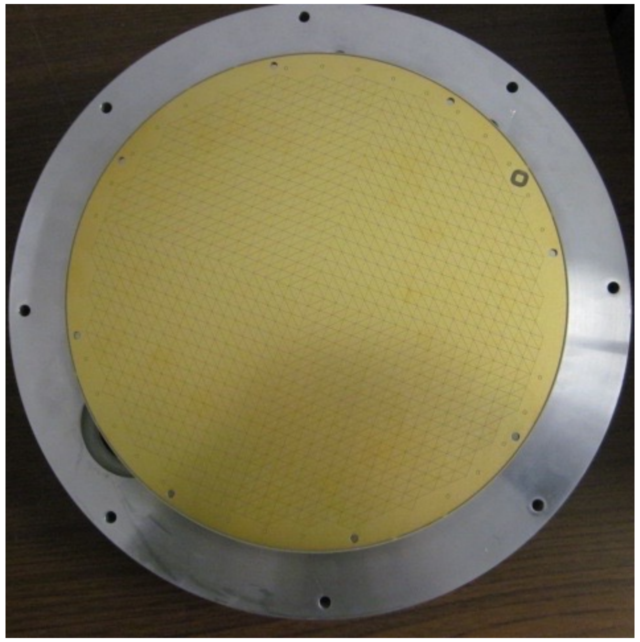
AT-TPC

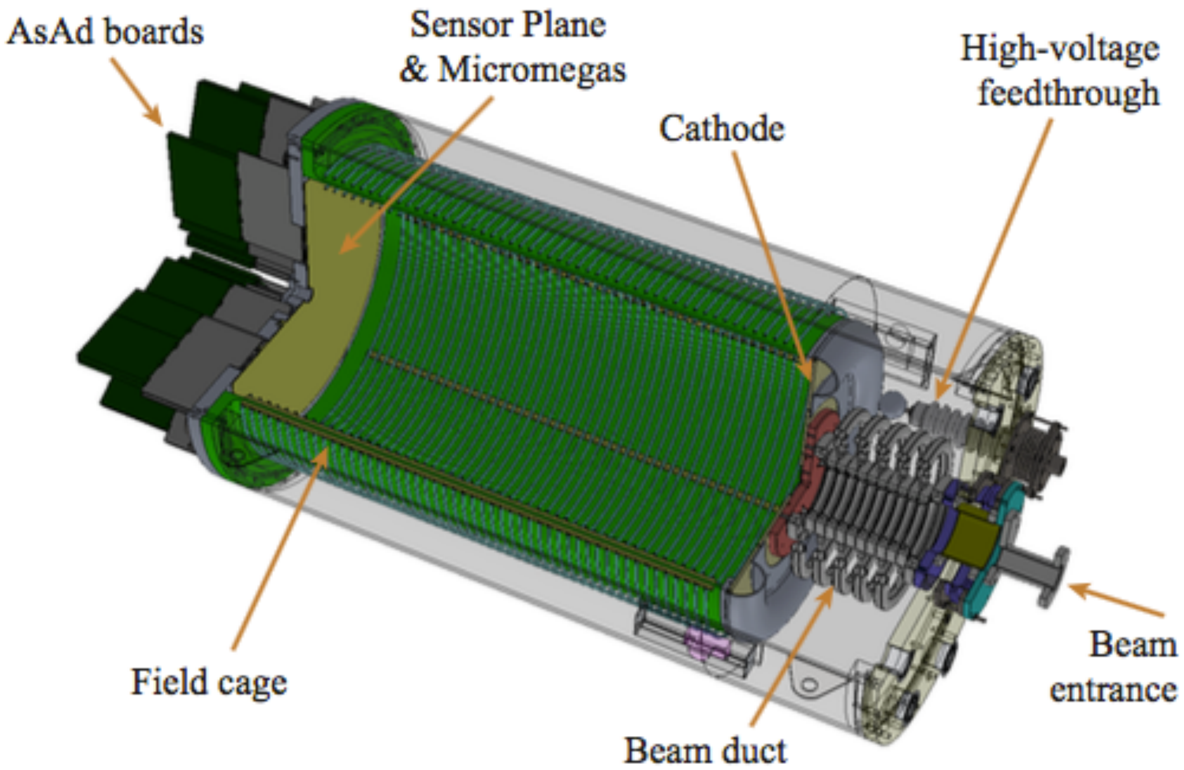
- Active Target of 1 m length, 55 cm diameter

➡ Thick target, good resolution, 4π detection

- MicroMegas detection pad plane
- 10,240 pads, equilateral triangles
- GET electronics for internal trigger
- Coupling with magnetic field
- Prototype (1/2 size) used for travel with ~2000 triangular pads

Prototype



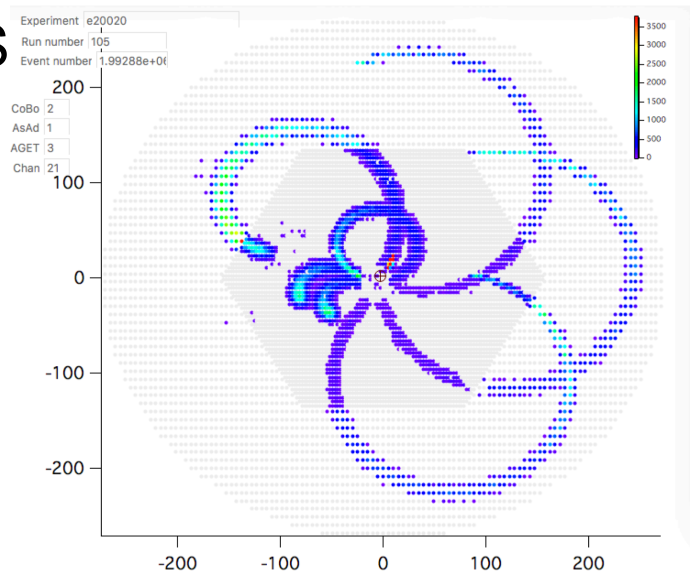


Resolution capabilities

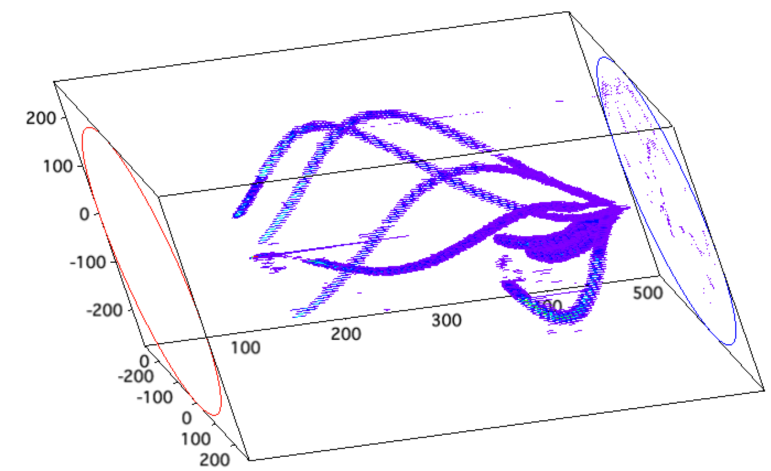
- Scattering angle = 1° for (α, α')
- Energy resolution of 30-40 keV/u in c.m.

^{16}O EXPERIMENT @ REA6 WITH SOLARIS (2021)

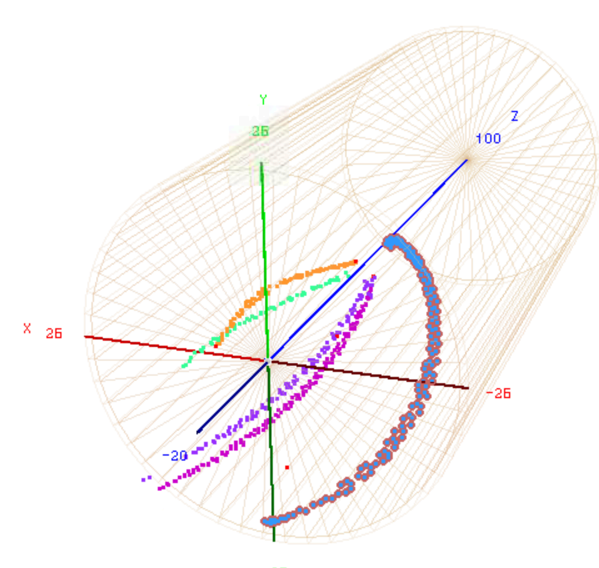
- ReA campaign in 2021 during transition to FRIB
- Stable or long-lived isotopes beams
- Upgrade to ReA6 with beams up to 10 AMeV
- New solenoid SOLARIS (4T) coupled to AT-TPC or HELIOS



	Smith et al.	AT-TPC
Reaction	^{12}C (α, α')	^{16}O (α, α')
Energy (MeV/nucleon)	10	10
Beam Intensity (pps)	1E+10	5E+03
Beam Time (hours)	60h	120h
Target Density (at/cm²)	5E+18	2.5E+21
Detection Efficiency	0.01	0.5
Cross section (mbarn)	0.86	0.17
Counts from N-α decay of Hoyle	93,000	**465**



* DWUCK calculations
Direct Decay Limit (^{12}C) < 0.04%



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TYPES OF RADIATION

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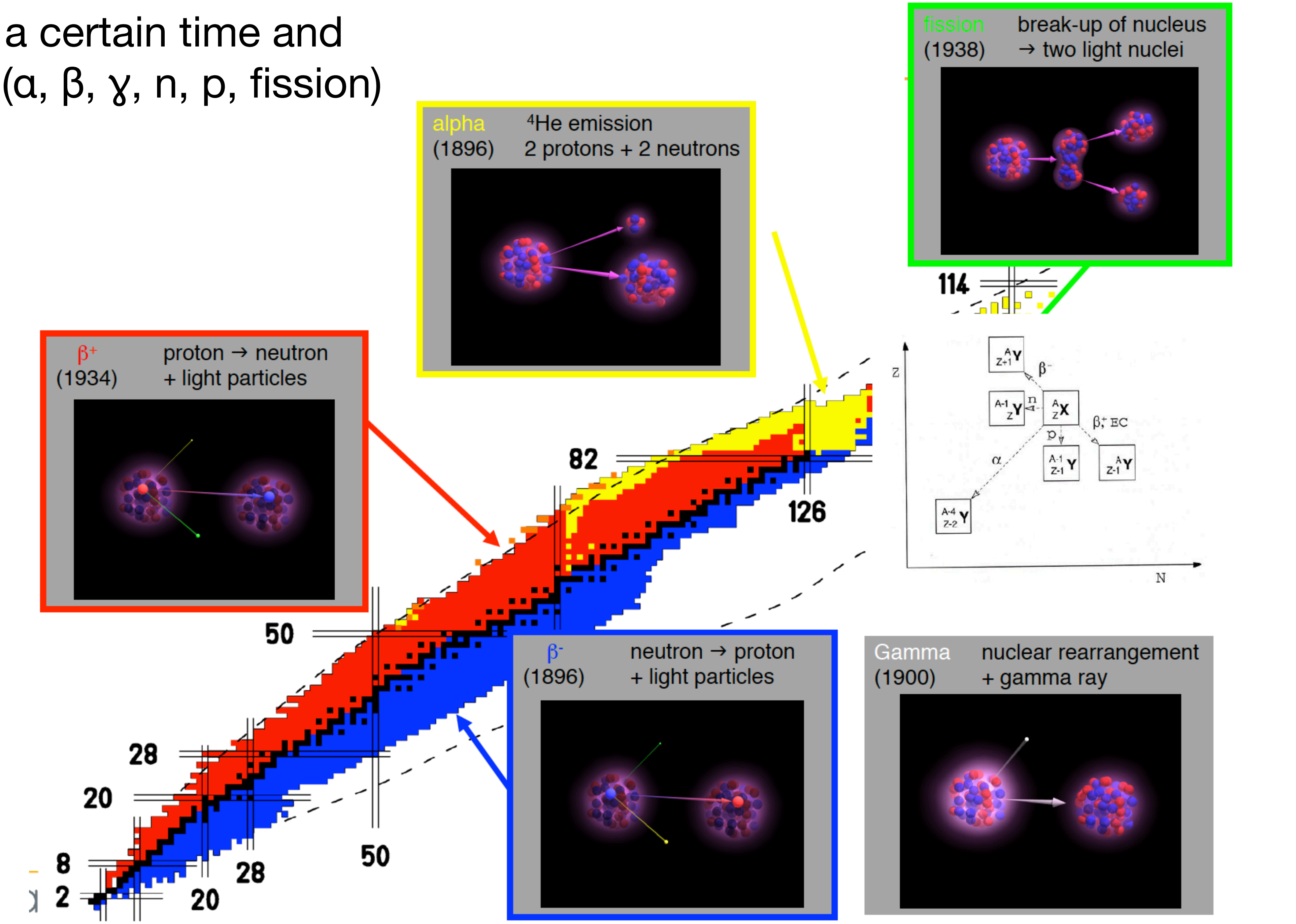
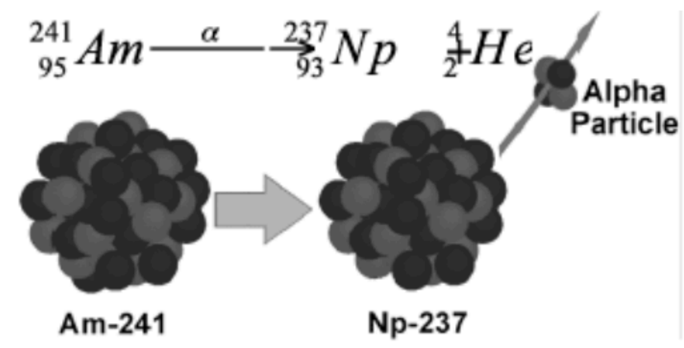
- All other colors show radioactive nuclei
- They will decay within a certain time and with a certain method (α, β, ɣ, n, p, fission)

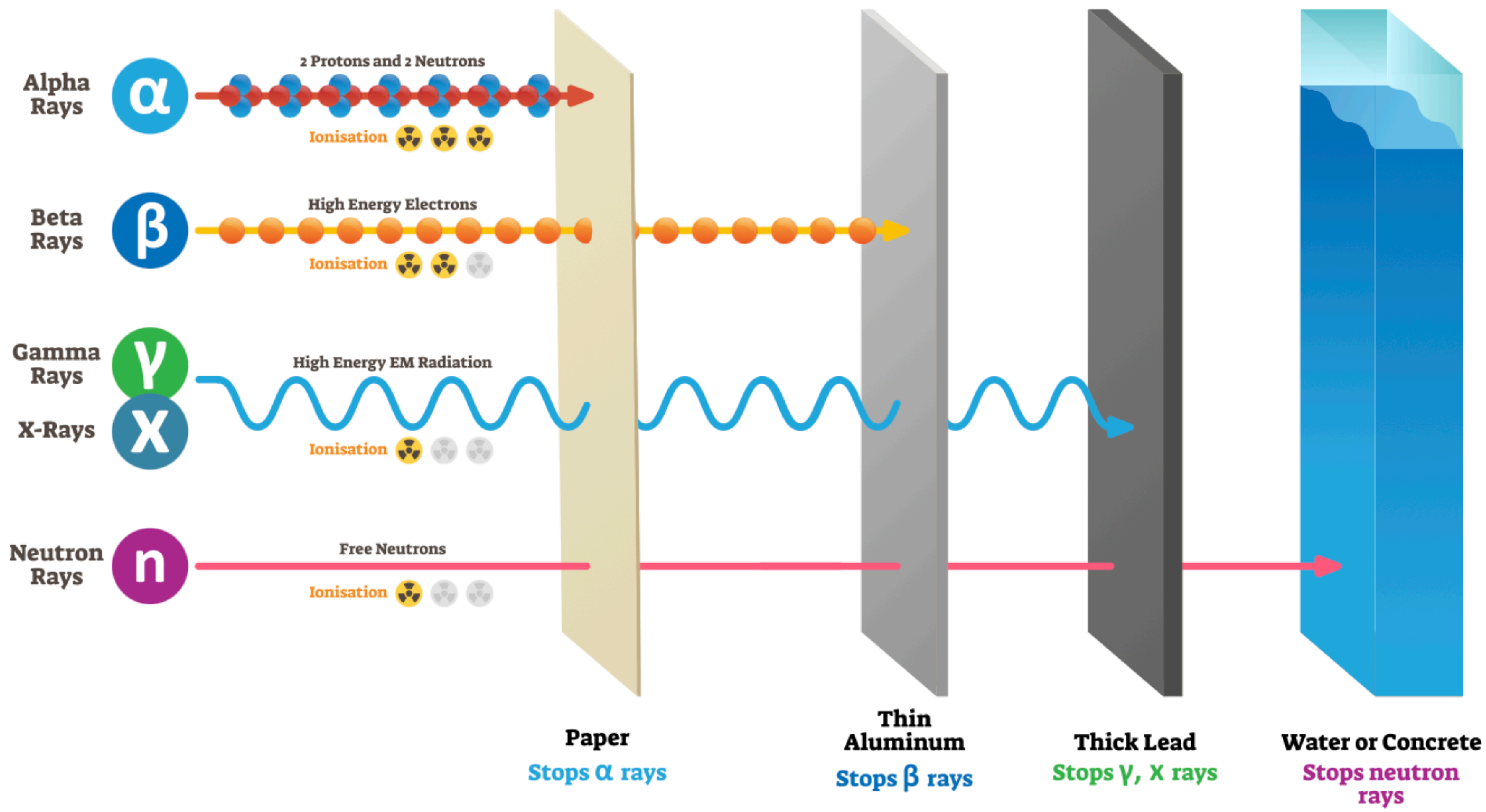


ALPHA DECAY

$$^{A}_{Z}X_{N} \rightarrow ^{A-4}_{Z-2}X_{N-2} + \alpha$$



- Particle α = nucleus $^{4}_{2}He$
- Possible from Z>50 and N<N$_{stable}$
- Dominant for Z>82



Stopped by paper and dead layer of skin

BETA DECAY

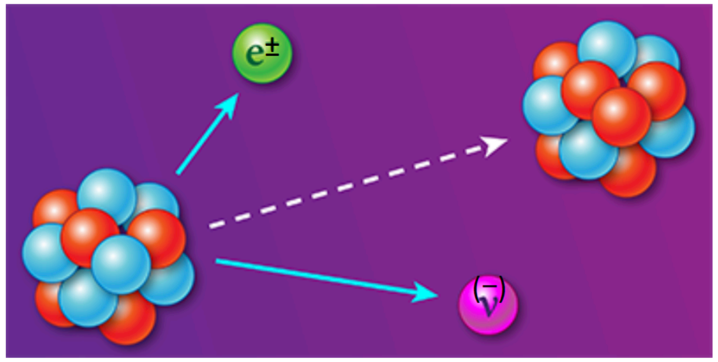
Neutron decay: $n \rightarrow p + e^- + \nu_e$

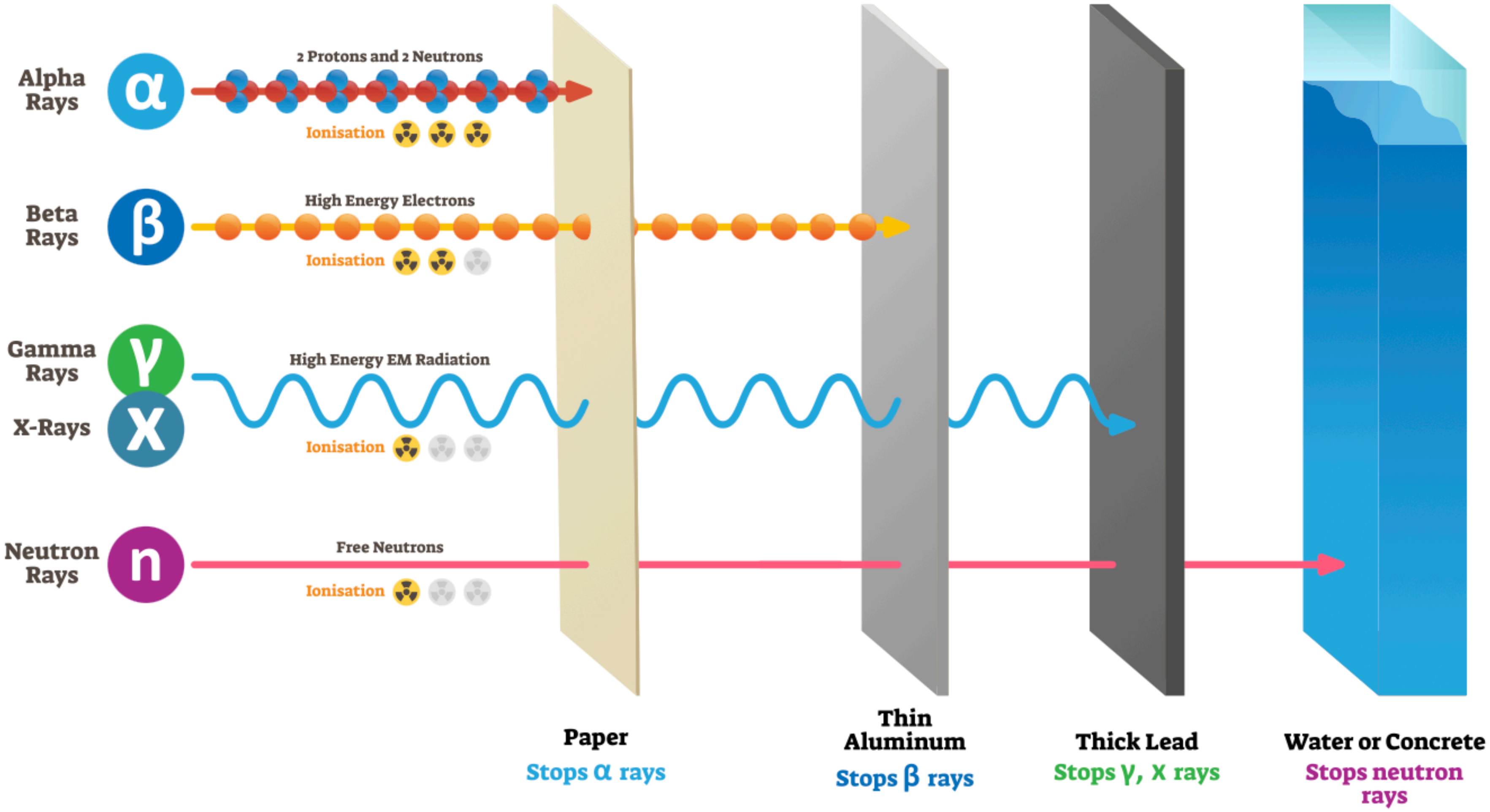
β^- decay: ${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \bar{\nu}_e$ **Neutron-rich side**

β^+ decay: ${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z-1}Y_{N+1} + e^+ + \nu_e$

EC decay: ${}^{A}_{Z}X_N + e^- \rightarrow {}^{A}_{Z-1}Y_{N+1} + \nu_e$

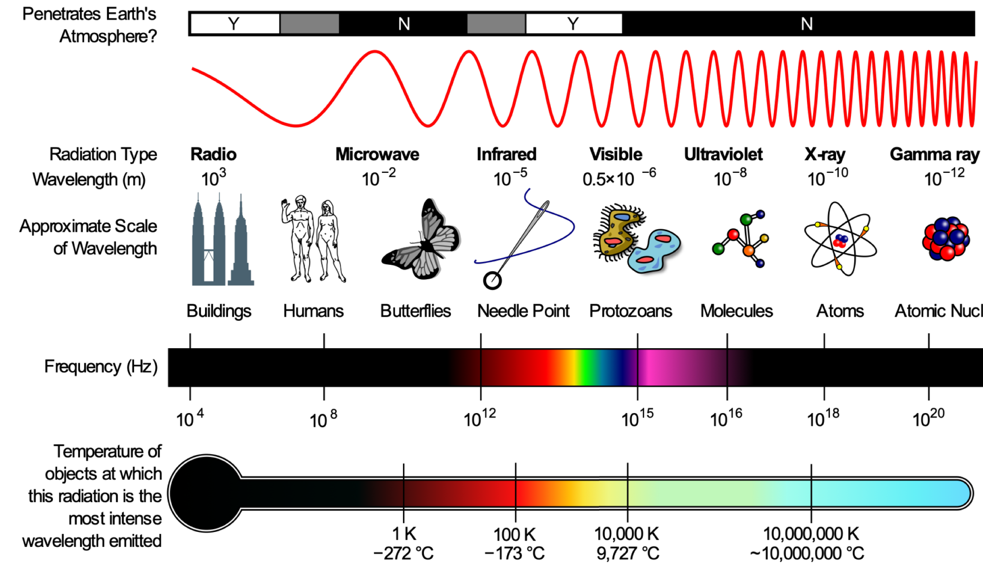
} **Proton-rich side**



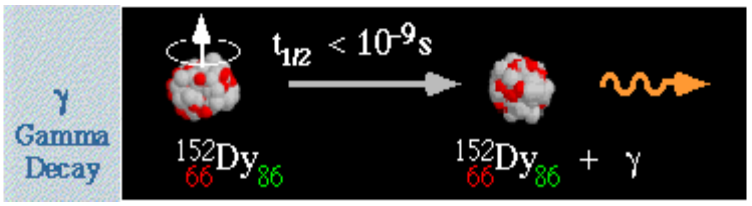


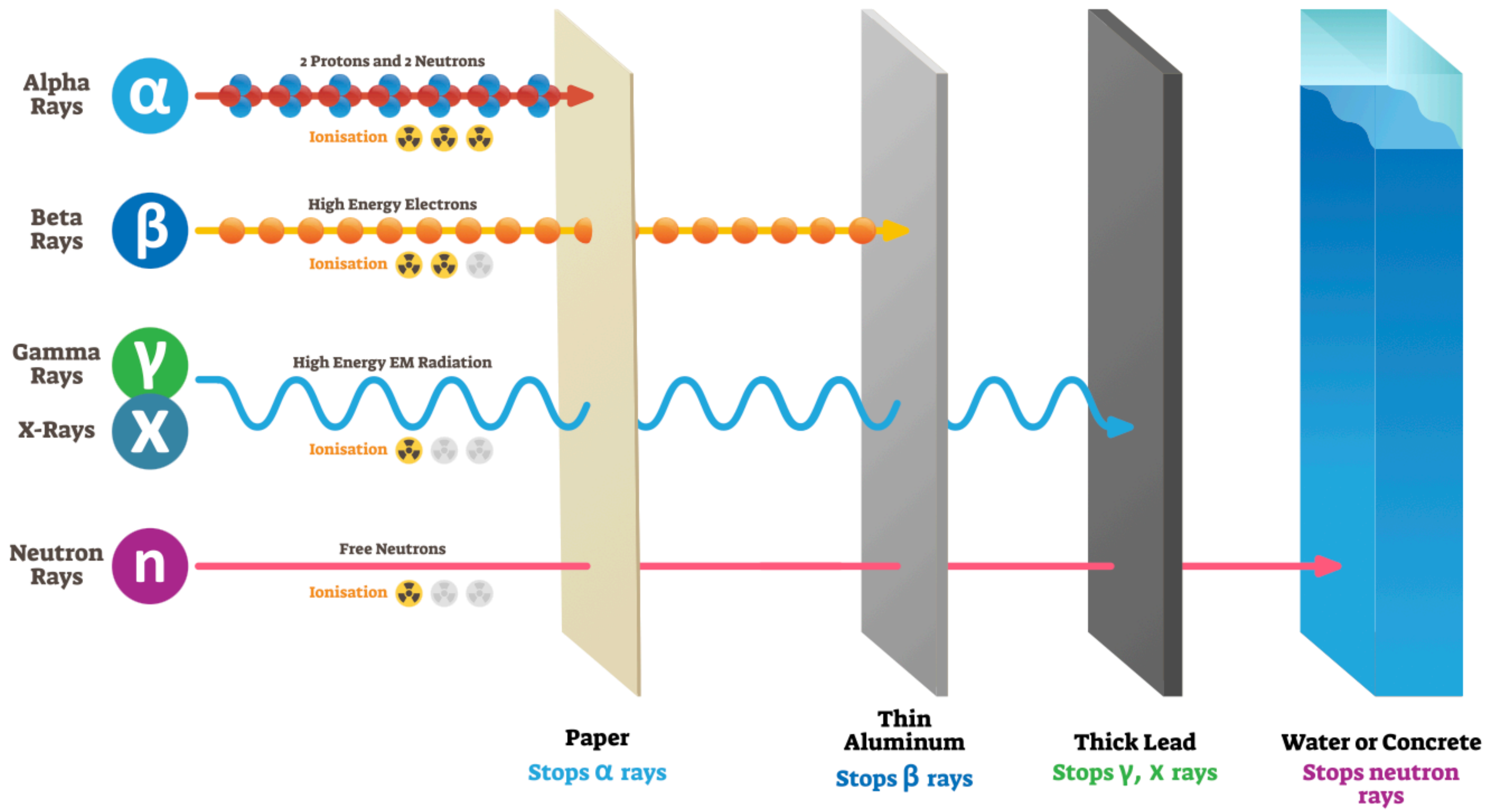
A 1 MeV beta can travel up to 4 m in air and 1 cm in plastic

GAMMA DECAY



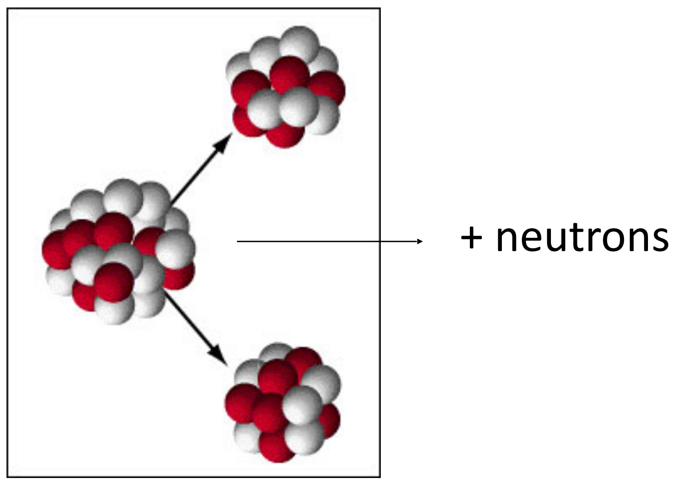
- X-rays and gamma (ɣ) rays are photons – no charge
- A nucleus in an excited state (one nucleon in a higher shell) will want to deexcite and produce ɣ rays

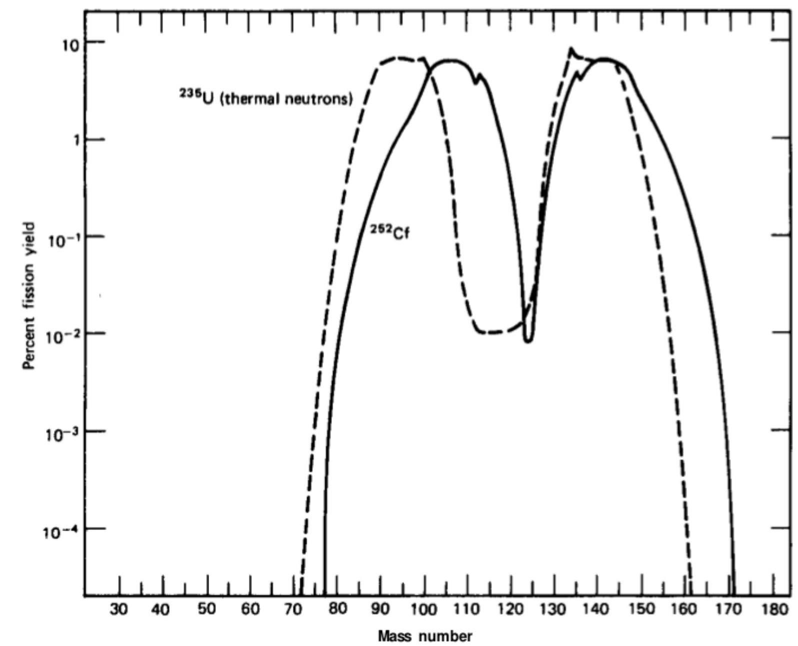




Lead is good for shielding x-rays and ɣ rays

SPONTANEOUS FISSION



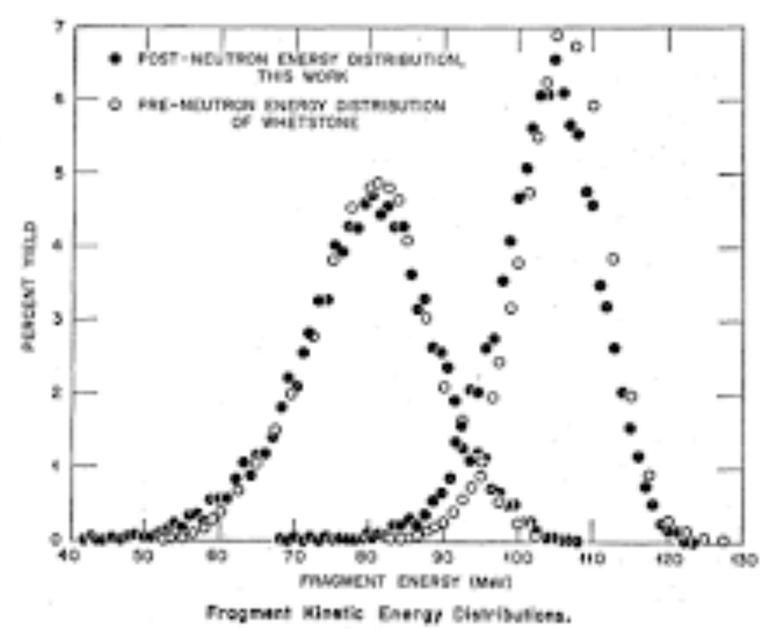


Symmetric fission

Nuclei that can spontaneously decay into two lighter fragments
Example: ^{252}Cf (half-life = 85 y if only via fission)

Possible when the nucleus gets big (Z>100)

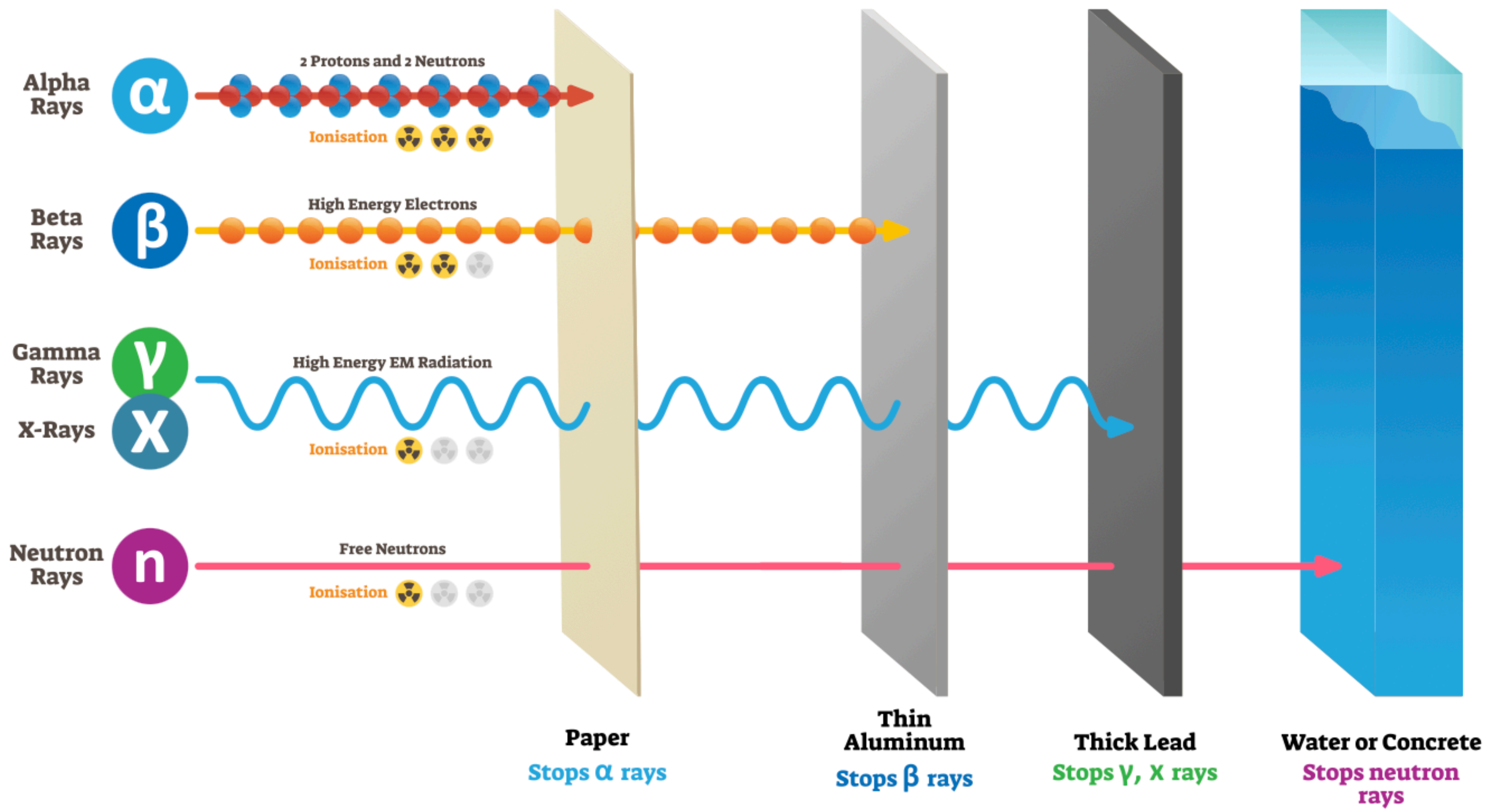
However, we usually have other decay processes that will compete with fission, such as alpha decay
Half-life of ^{252}Cf = 2.65y



Asymmetric fission

OTHER DECAYS & RADIATION

- Proton decay = for very proton-rich nuclei, that have so many protons that it is not stable anymore and just rejects it
- Neutron decay = same on the neutron-rich side



Neutron shielding thickness depends on the energy of the neutron

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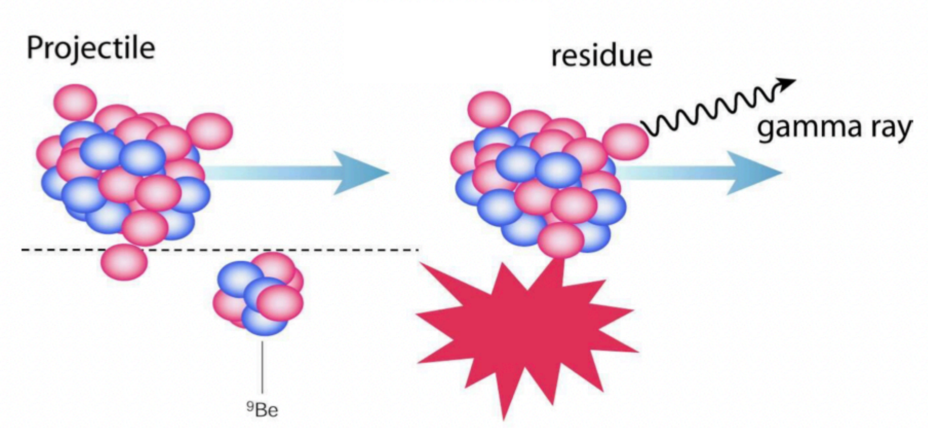
NUCLEAR REACTIONS

- Most nuclei are unstable, and decay within a certain time, or half-life
- For nuclei farther away from the stable ones, their half-life gets shorter

How to study nuclei that live for less than a second?
We can use the normal decay of an isotope, but then we have no control on when it happens

➡ Create the nucleus of interest via an induced reaction
➡ Use collisions and study the reaction fragments with detectors



NUCLEAR REACTIONS

- Elastic or Inelastic collision: SAME nuclei incoming as outgoing, change in trajectory of the particle, transfer of energy (only for inelastic) and heavier nucleus at excited state

$$ {}^{A}_{Z}X_N + A \rightarrow {}^{A}_{Z}X_N + A $$

- Transfer (low energy <50 MeV/u) or knockout reactions (higher energy): remove or add one or two nucleons to a nucleus

One proton removal reactions:

$$ {}^{A}_{Z}X_N + p \rightarrow {}^{A-1}_{Z-1}X_N + 2p $$

$$ {}^{A}_{Z}X_N + d \rightarrow {}^{A-1}_{Z-1}X_N + {}^{3}He $$

One neutron removal

$$ {}^{A}_{Z}X_N + p \rightarrow {}^{A-1}_{Z}X_{N-1} + d $$

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- Fragmentation: removal of a larger number of nucleons
- Fission: breakup of a heavy nucleus into two smaller fragments
- Fusion: fusion of two nuclei into heavier one

CONSERVATION PRINCIPLES

In nuclear reactions, a few principles are ALWAYS observed:

- Conservation of energy in the system = total energy in the initial system is the same in the final system
- Conservation of proton, neutron, mass number = valid for all nuclear reactions EXCEPT β decay (weak interaction)

Example: a (d, p) reaction

$$^{16}_{6}C_{10} + d \rightarrow ^{A}_{Z}X_{N} + p$$

(1) How many protons /neutrons are transferred? $d \rightarrow p$ so one neutron is picked up by a nucleus

(2) What is the outgoing nucleus $^{A}_{Z}X_{N}$? Write up the conservation of proton and neutron numbers:

$$^{16}_{6}C_{10} + d \rightarrow ^{A}_{Z}X_{N} + p$$
$$^{16}_{6}C_{10} + ^{2}_{1}H_{1} \rightarrow ^{A}_{Z}X_{N} + ^{1}_{1}p_{0}$$

Initial	Final
$Z_{initial} = 6 + 1 = 7 = Z_{tot}$	$Z_{tot} = Z_{final} = 7 = Z + 1$
$N_{initial} = 10 + 1 = 11 = N_{tot}$	$N_{tot} = N_{final} = 11 = N + 0$

$^{A}_{Z}X_{N}$

$Z = 6$

$N = 11$

COLLABORATIONS

AT-TPC COLLABORATION

FRIB / Michigan State University
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RCNP & Osaka University
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J. Lou* (Peking University)
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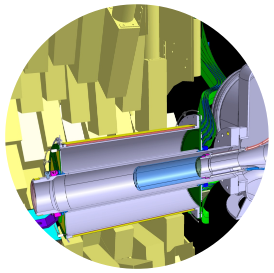
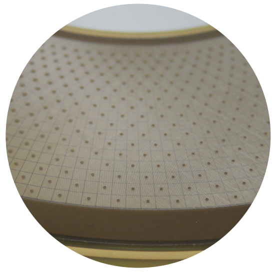
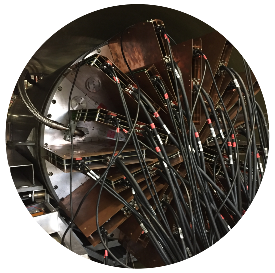
Hooi Jin Ong* (Institute of Modern Physics)
C. Santamaria (MSU[2])
D. Suzuki* (RIKEN Nishina Center)

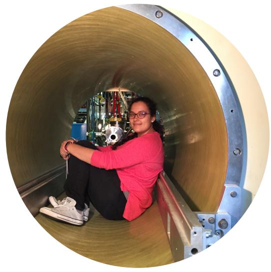
And the rest of the AT-TPC collaboration





THANK YOU FOR YOUR ATTENTION !

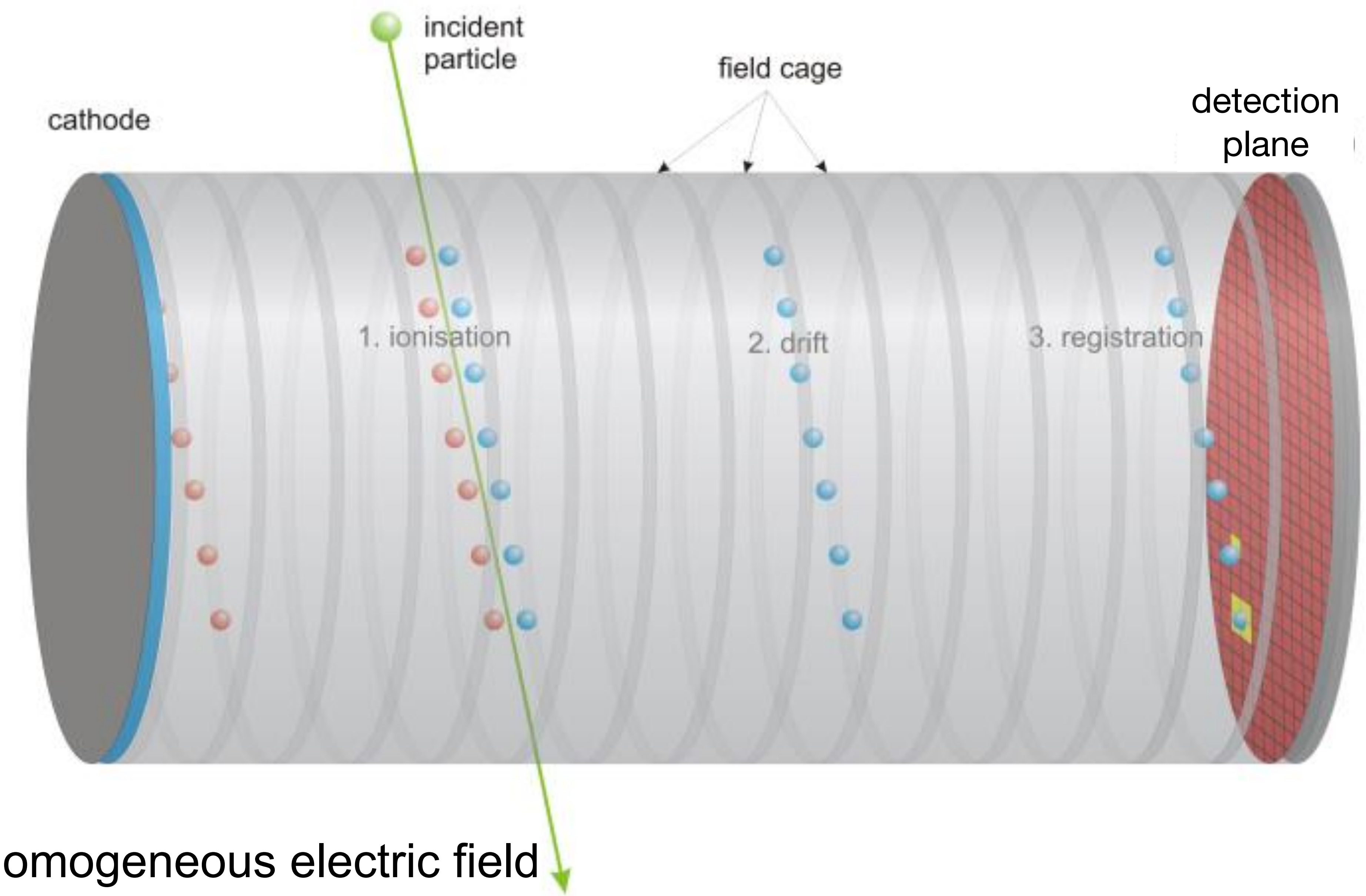




EXTRAS

ACTIVE TARGET

- Active Target = our target material is ALSO our detector
- Mostly gaseous or liquid detectors
- Example: Time Projection Chamber (TPC) for charged particles

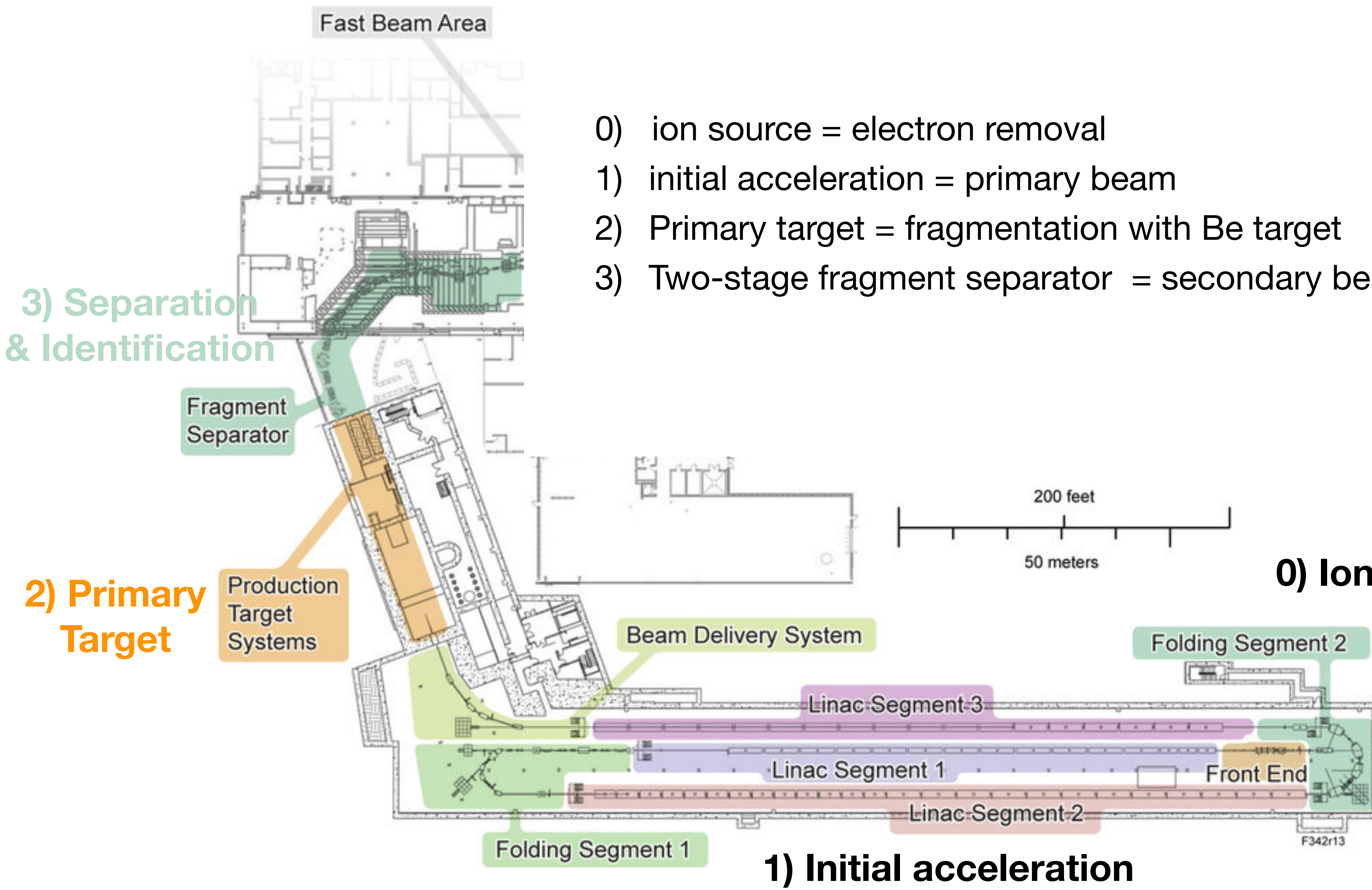


- Homogeneous electric field
- Ionization and drift of electrons towards the pads, or detection plane
- 2D picture of all charged particles in the volume from the pads + third dimension from the time of arrival

NUCLEAR PHYSICS ACCELERATOR

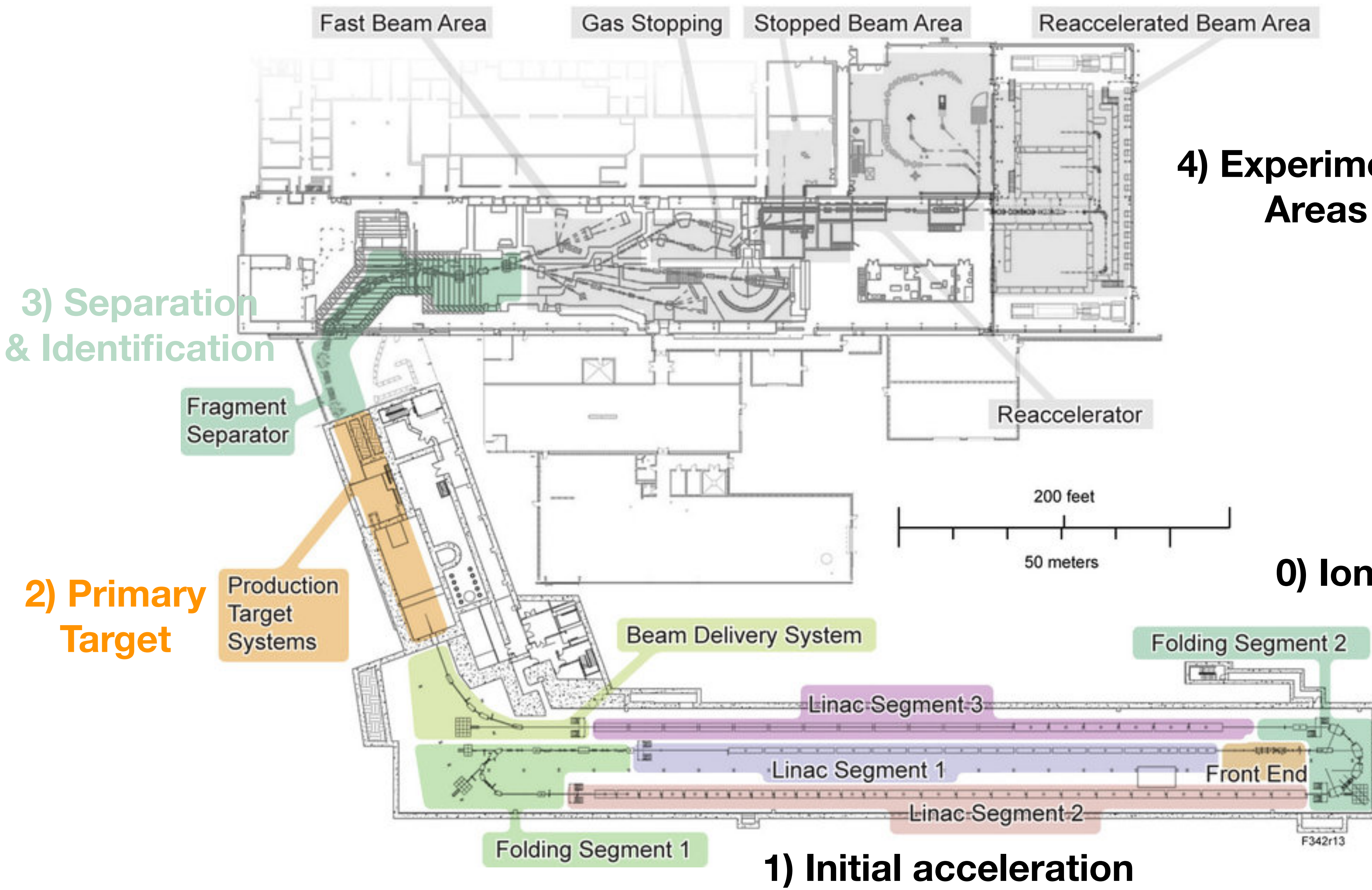
- Most nuclei we produce do NOT exist in nature
- Need an accelerator!

0) ion source = electron removal
1) initial acceleration = primary beam
2) Primary target = fragmentation with Be target
3) Two-stage fragment separator = secondary beam



FRIB @ MICHIGAN STATE UNIVERSITY

- FRIB = Facility for Rare Isotope Beams (started in June 2022)
- Primary beams from ^{16}O to ^{238}U from 150 MeV/u to 290 MeV/u (β= 0.5-0.6)



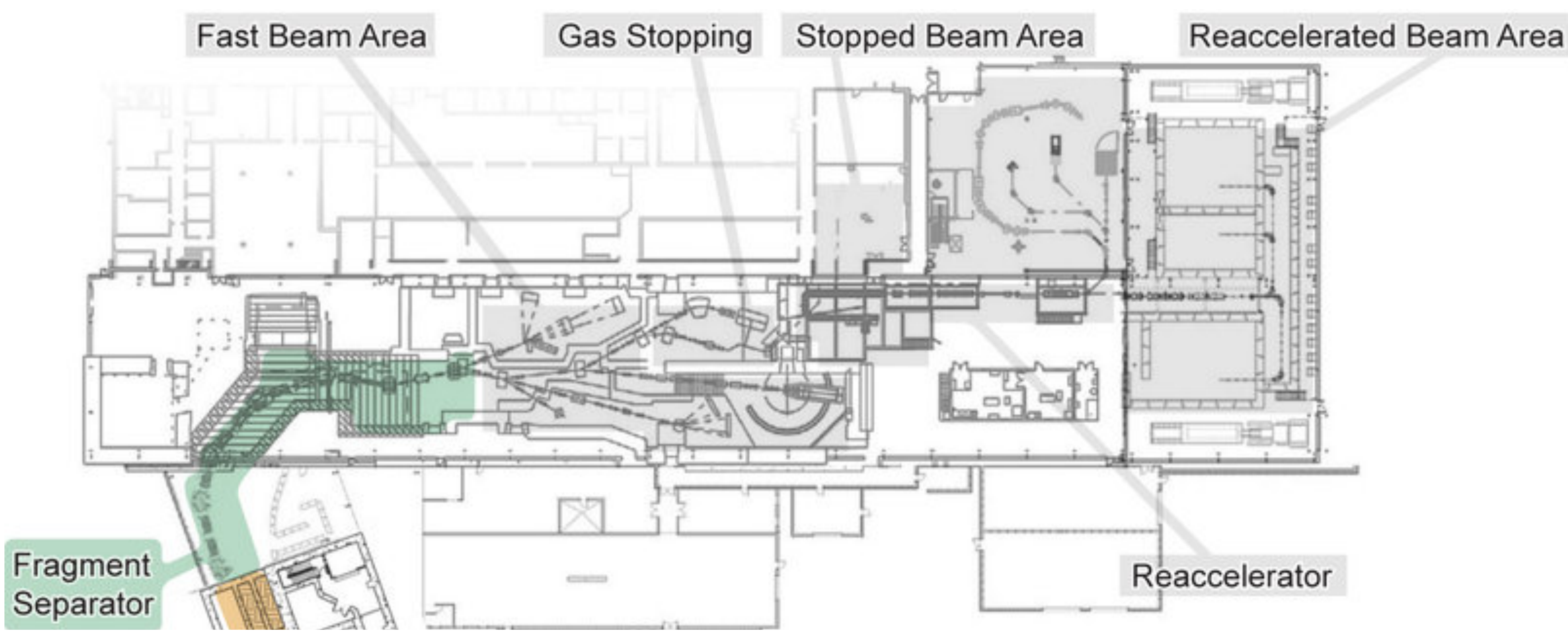
FRIB

FRIB VIDEO

https://www.youtube.com/watch?v=P4rG-5y9ums

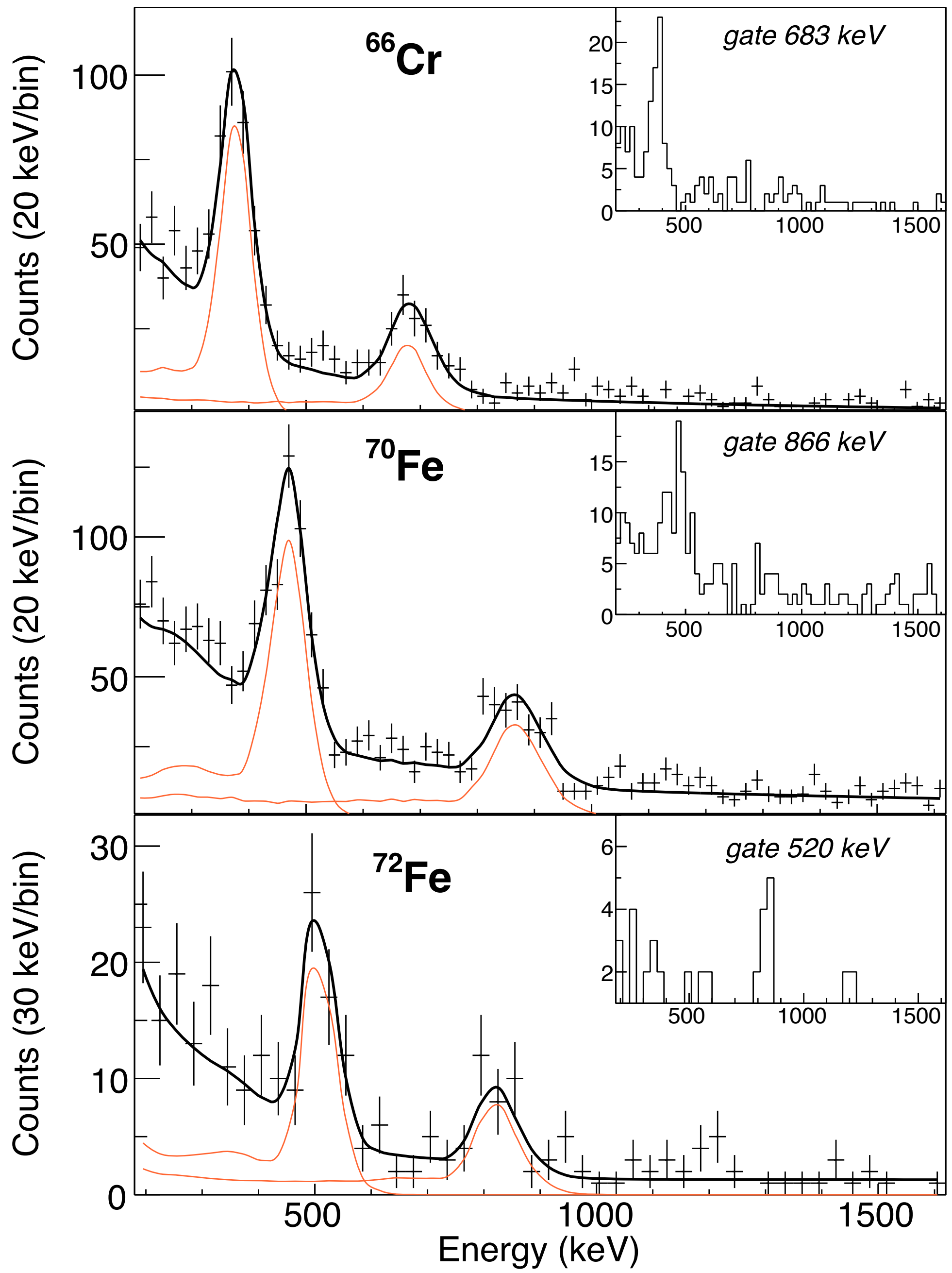
4) EXPERIMENTAL AREAS

- Use the secondary beam we created & separated before
- Collision with a secondary target
- Need to detect the products of those reactions: protons, neutrons, electrons, ɣ rays (photons), heavier particles…
- For every experiment, we will need to choose the detection system that fits BEST
- We don't have a system that can do everything…

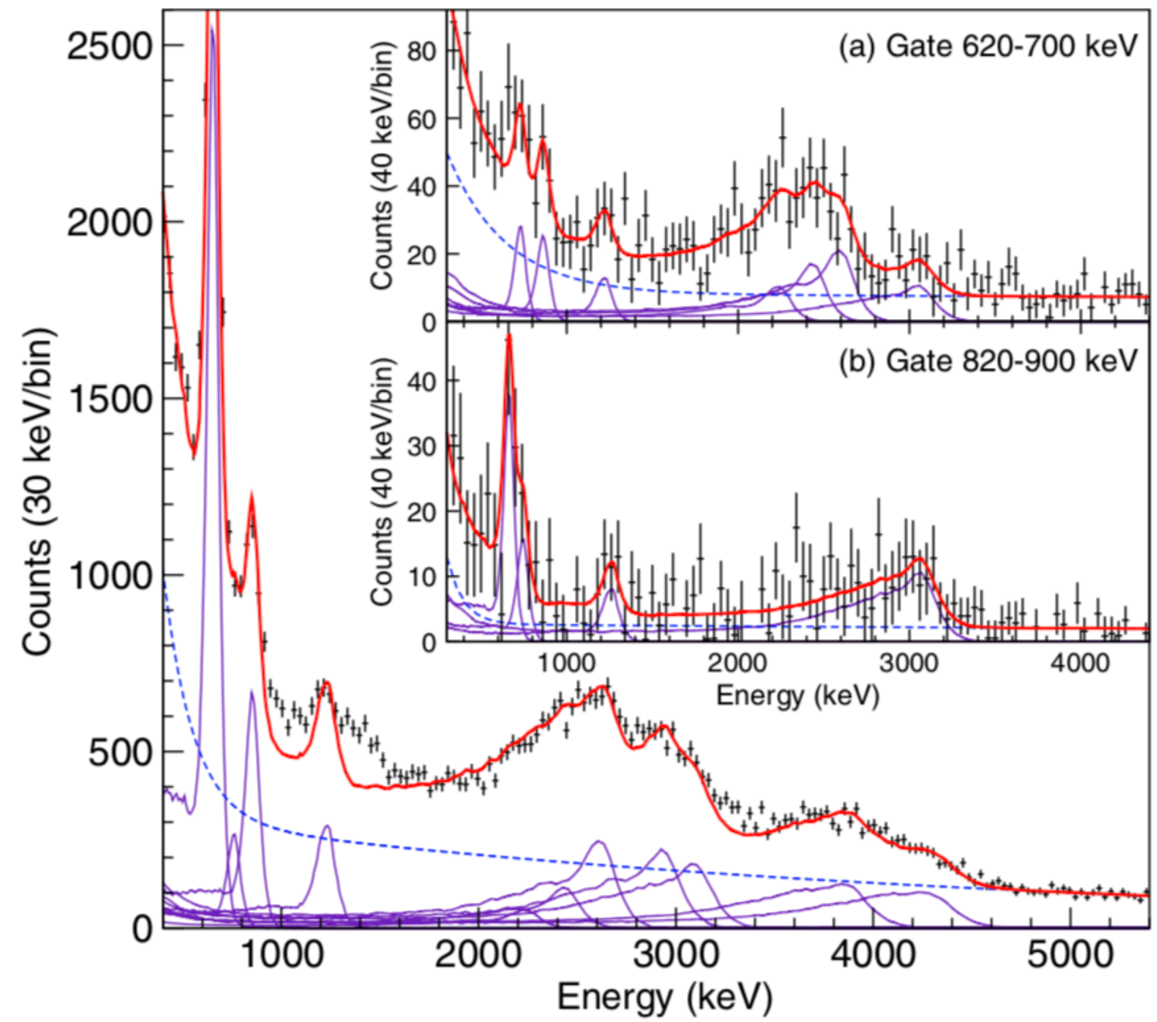


1ST SEASTAR CAMPAIGN RESULTS

C.S. *et al.*, PRL **115**, 192501 (2015)



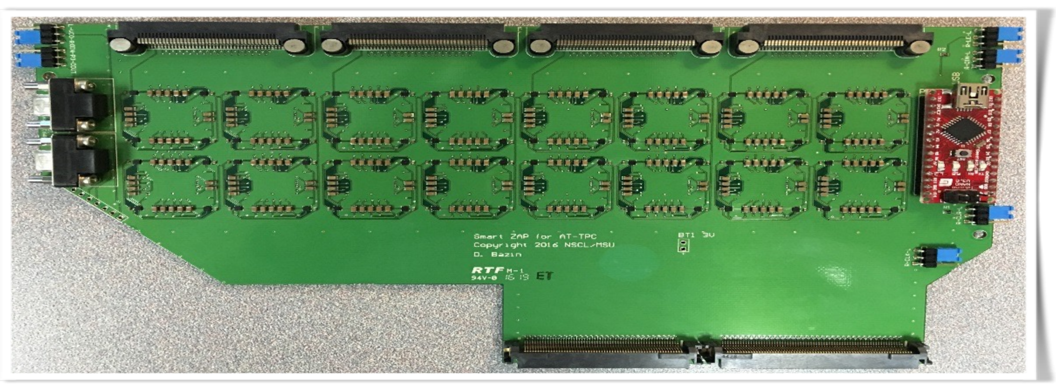
L. Olivier *et al.*, PRL **119**, 192501 (2017)

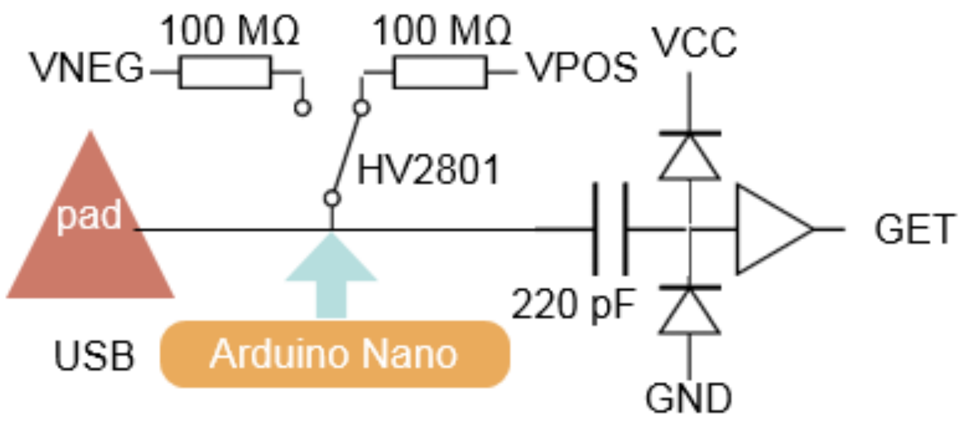


X.Y. Liu *et al.*, “Spectroscopy of $^{65,67}{}_{27}$Mn: Strong coupling in the N = 40 “island of inversion” ”, Phys. Let. B **784**, 392–396 (2018).
M.L. Cortés *et al.*, “Inelastic scattering of neutron-rich Ni and Zn isotopes off a proton target”, Phys. Rev. C **97**, 044315 (2018).

Smart ZAP board

D. Bazin @ NSCL





AT-TPC filled with 200 Torr of He (90%) + CO_2 (10%)