Introduction to Nuclear Science

PIXIE-PAN Summer Science Program

University of Notre Dame

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J I N A

The Joint Institute for Nuclear Astrophysics
www.JINAweb.org

Topics we will discuss…

Ground-state properties of the nucleus

size, shape, stability, binding energies, angular momenta

Radioactivity

alpha, beta, and gamma decay

The nuclear force

Nuclear reactions

the compound nucleus, Q values, excited states

Decay modes of an excited nucleus

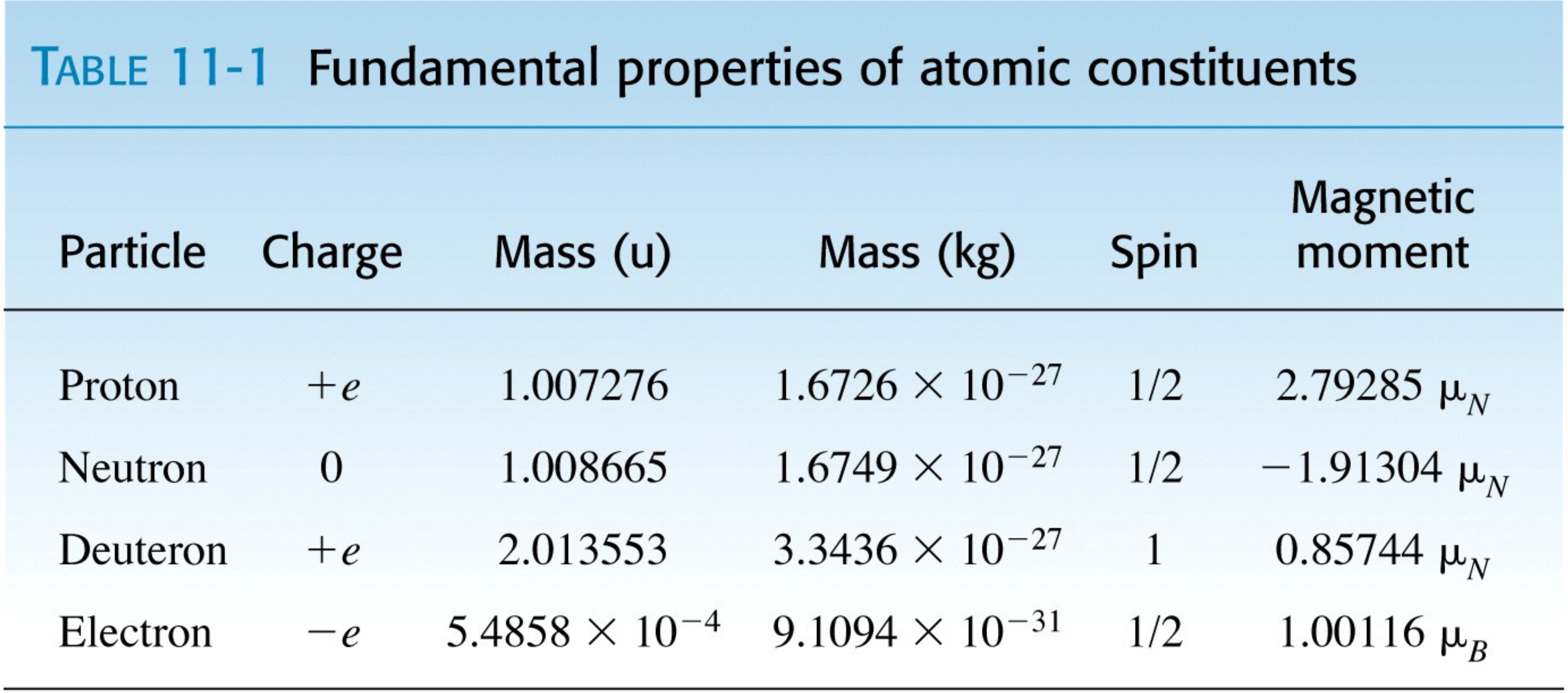
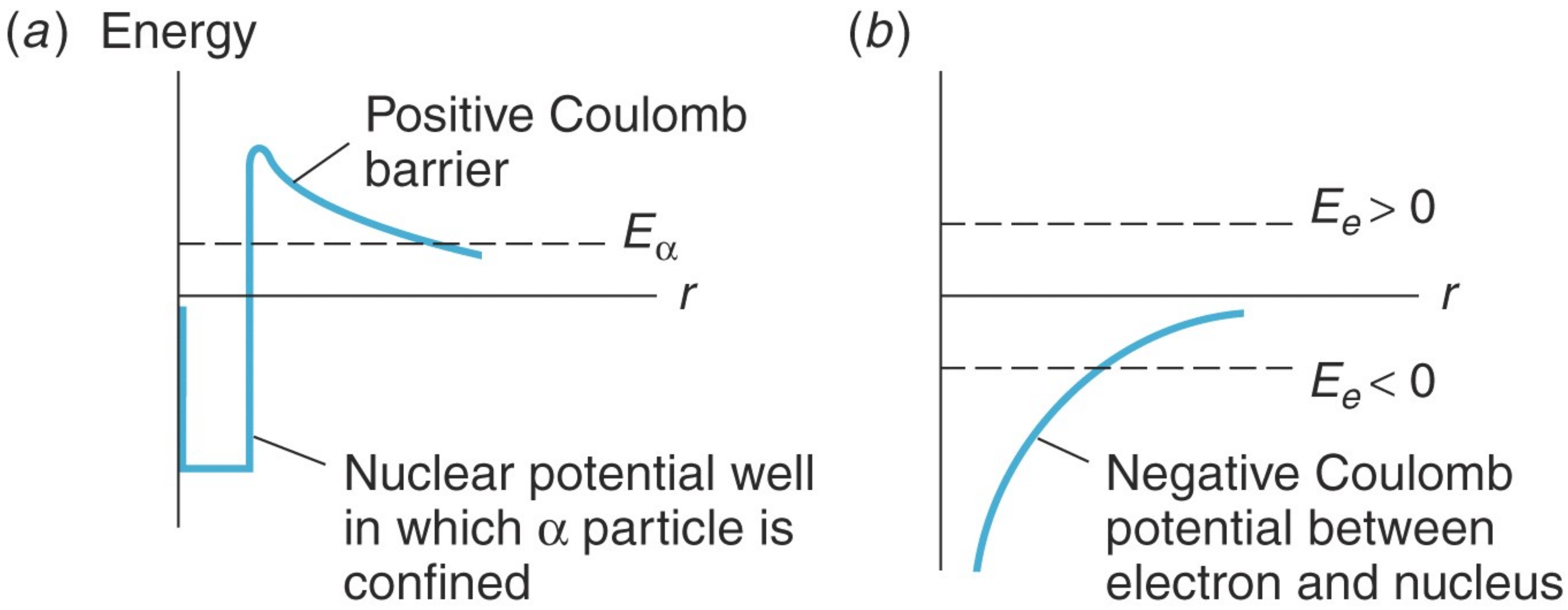
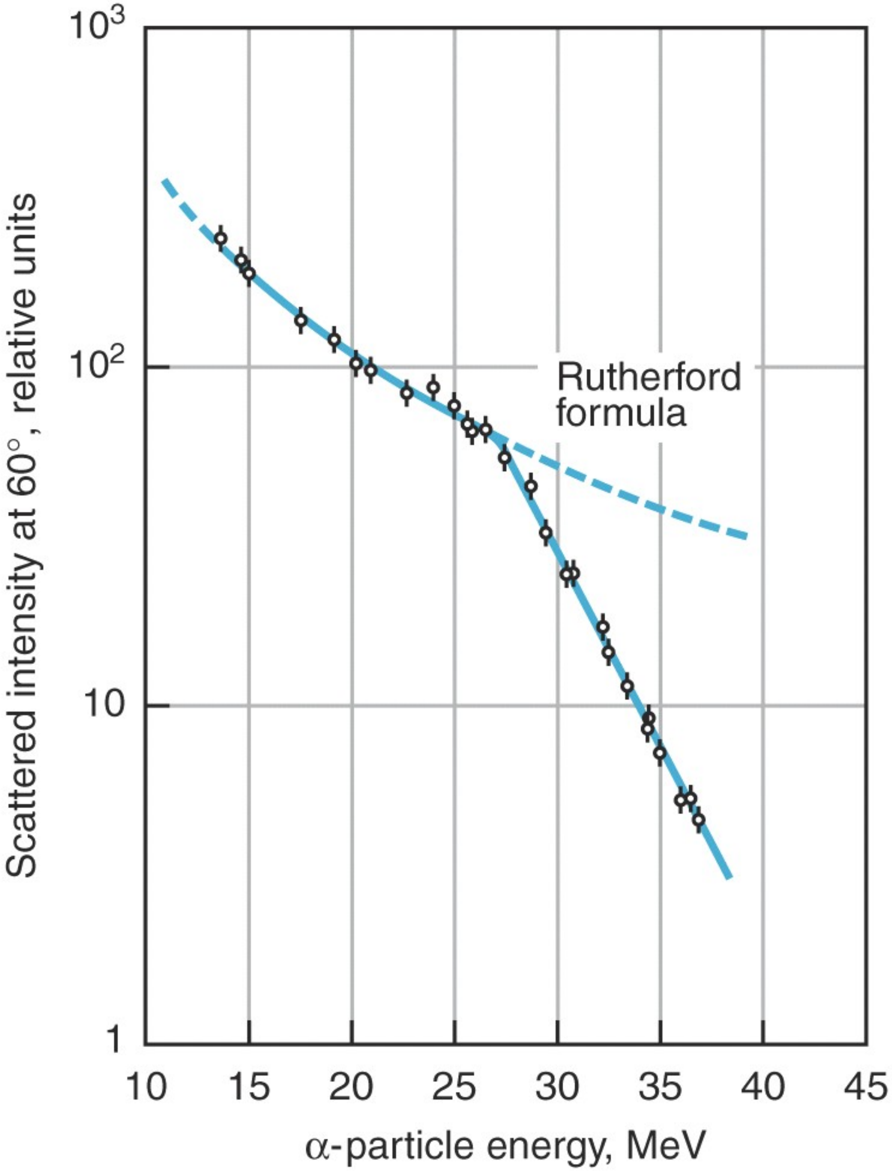


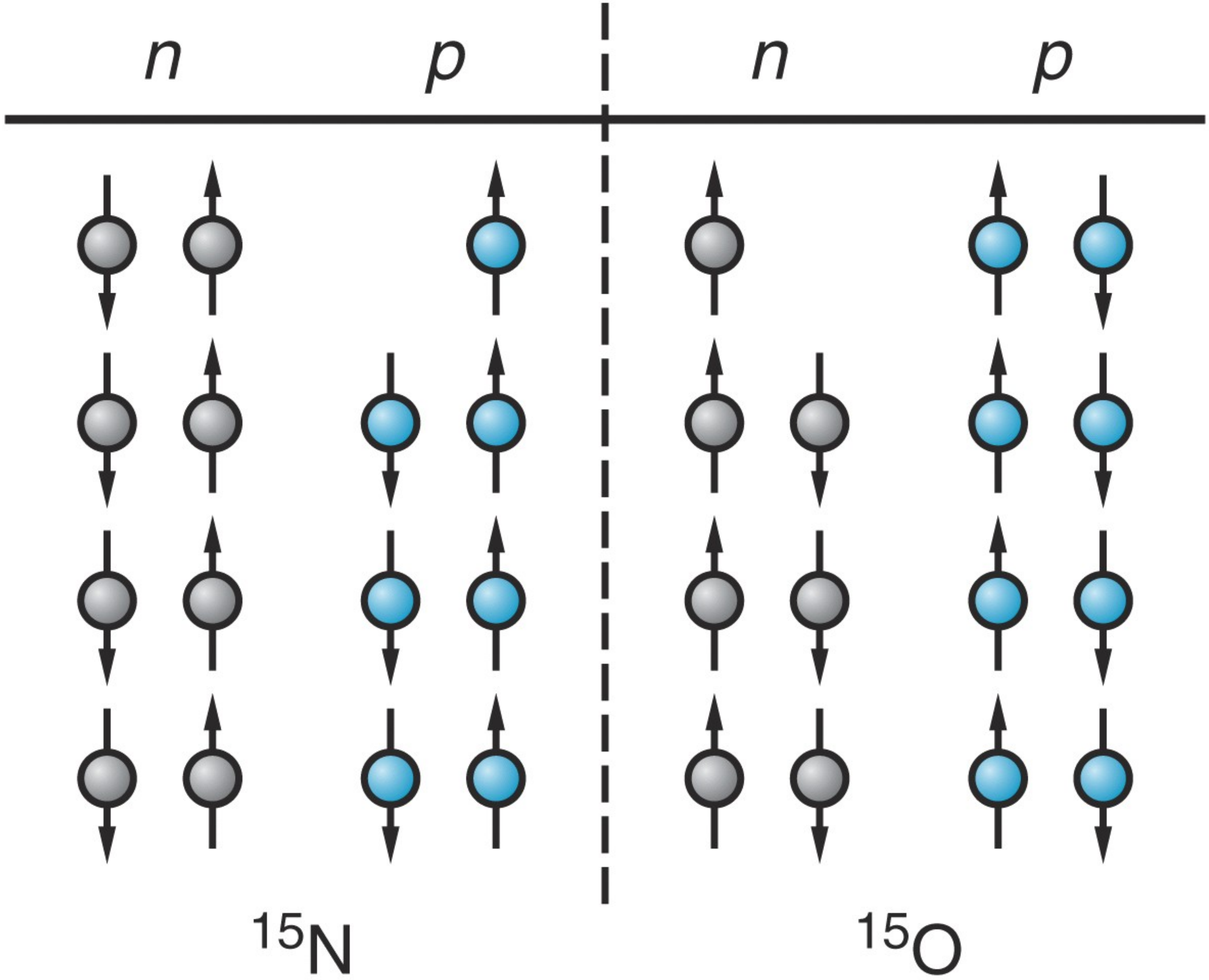
TABLE 11-1 Fundamental properties of atomic constituents

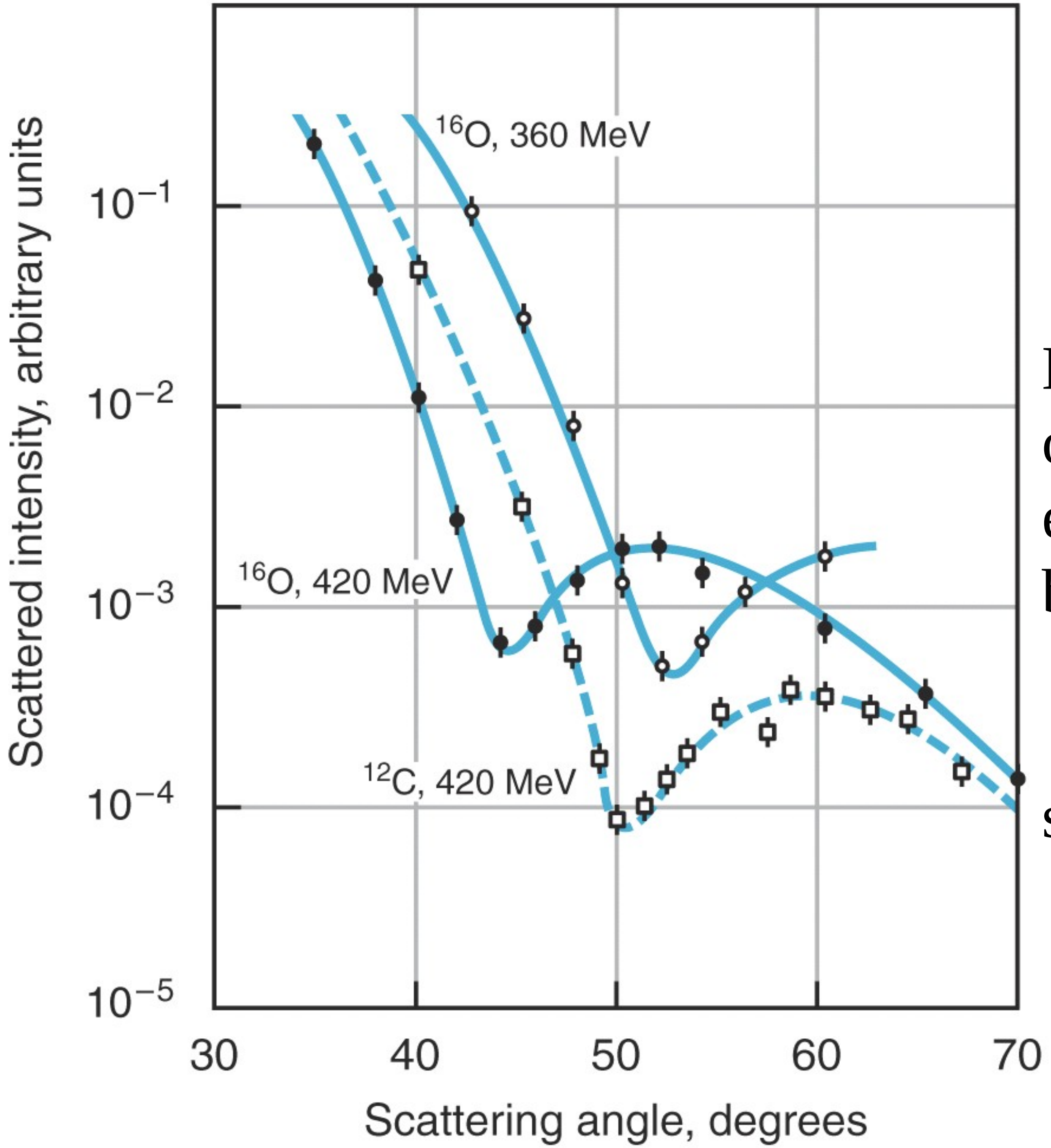
Particle	Charge	Mass (u)	Mass (kg)	Spin	Magnetic moment
Proton	$+e$	1.007276	1.6726×10^{-27}	1/2	$2.79285\ \mu_N$
Neutron	0	1.008665	1.6749×10^{-27}	1/2	$-1.91304\ \mu_N$
Deuteron	$+e$	2.013553	3.3436×10^{-27}	1	$0.85744\ \mu_N$
Electron	$-e$	5.4858×10^{-4}	9.1094×10^{-31}	1/2	$1.00116\ \mu_B$


(a) Energy
Positive Coulomb barrier
E_α
r
Nuclear potential well in which α particle is confined
(b)
$E_e > 0$
r
$E_e < 0$
Negative Coulomb potential between electron and nucleus



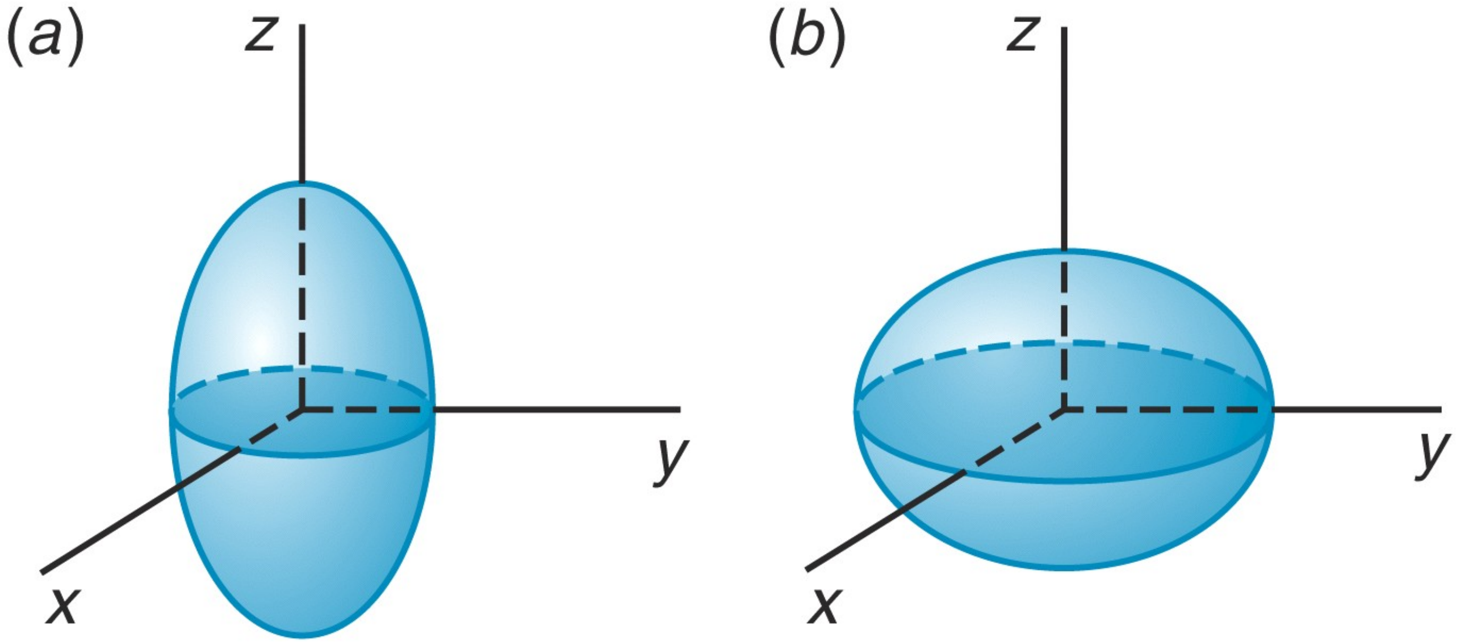
The radius of the nucleus…


n
p
n
p
^{15}N
^{15}O



Diffraction pattern of high-energy electrons scattered by ^{16}O and ^{12}C

$\sin\theta = 0.61\ \lambda/R$

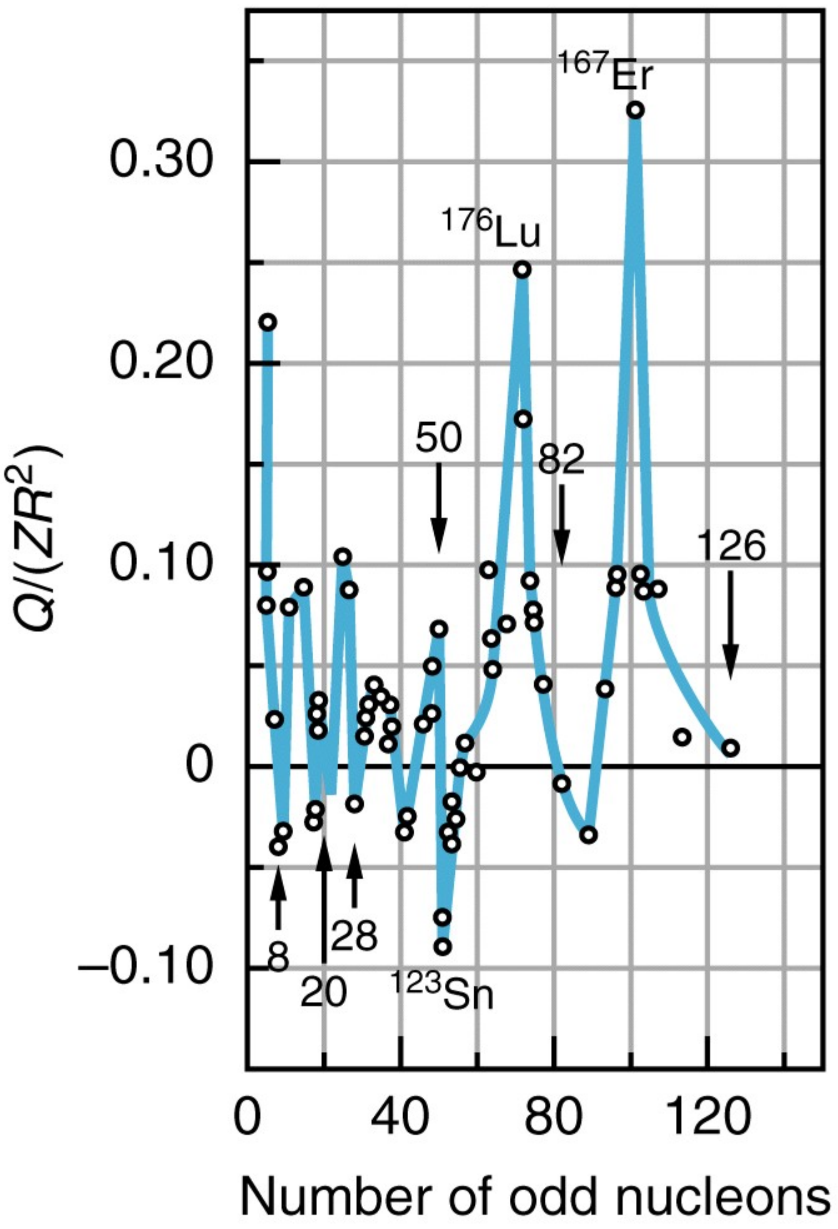


Non-spherical nuclear shapes. The electric quadrupole moment is given by $3z^2 - x^2 - y^2 - z^2$

> 0 for a football on end

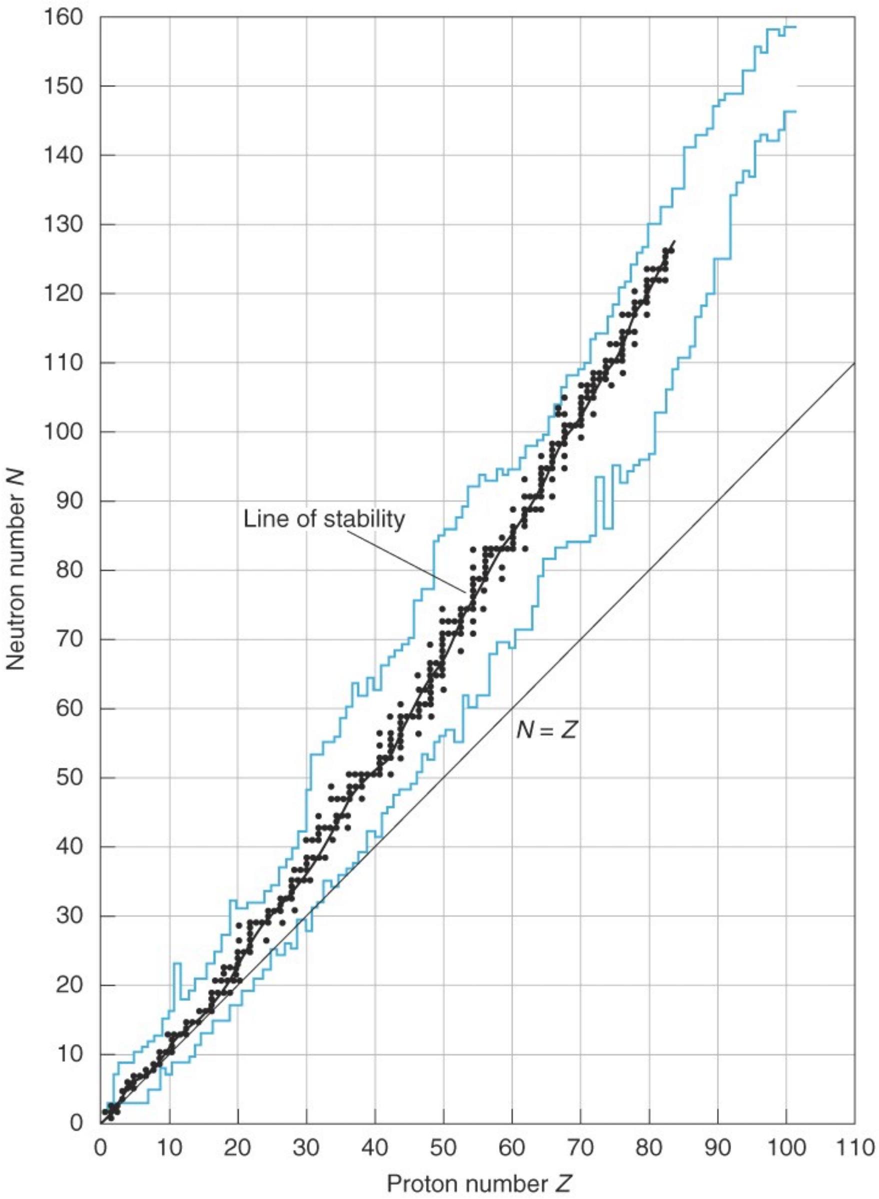
$= 0$ for a sphere

< 0 for an egg on the table

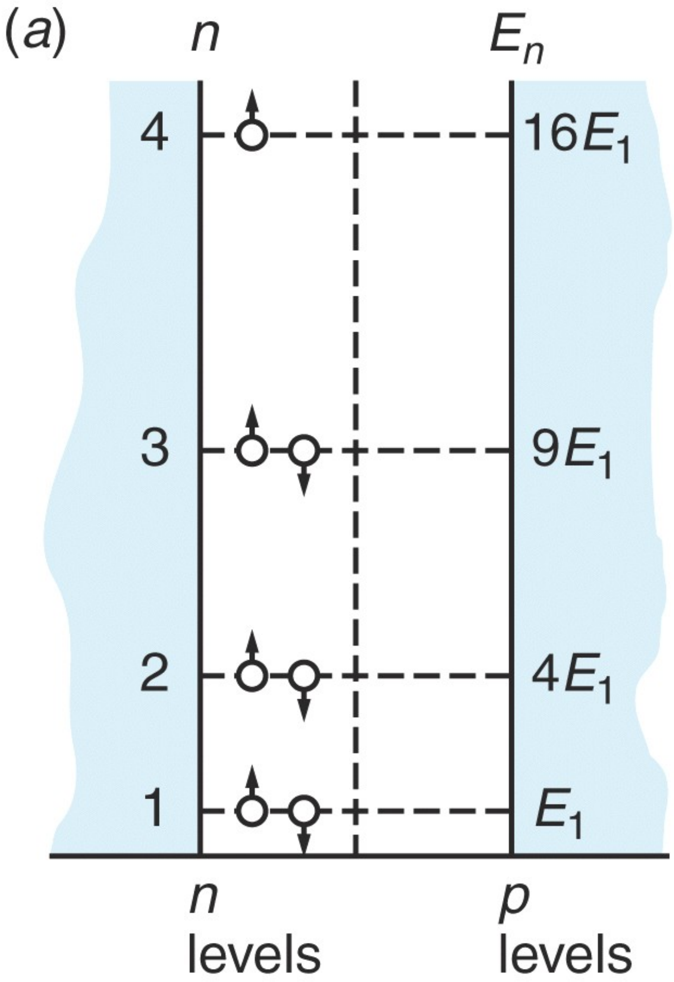


Quadrupole moments of a number of odd-A nuclei. The arrows point to spherical nuclei.

The numbers are the shell-model 'magic numbers' about which we will talk later.



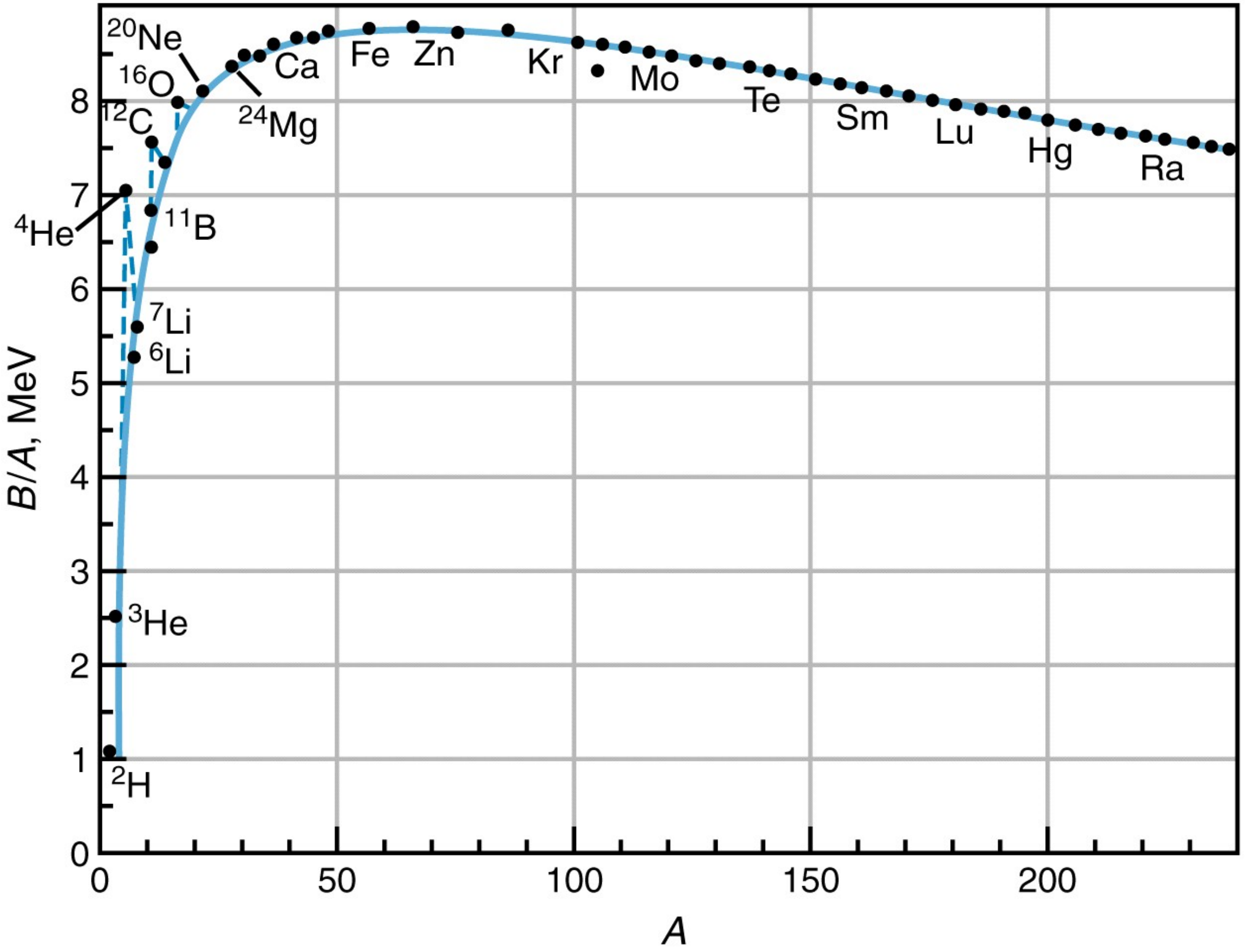
Of the 3000 or so known nuclides, there are only 266 whose ground states are stable. The rest are radioactive



Any idea what this is about?

TABLE 11-2 *N* versus *Z* for stable isotopes

	Z	
N	**Even**	**Odd**
Even	159	50
Odd	53	4



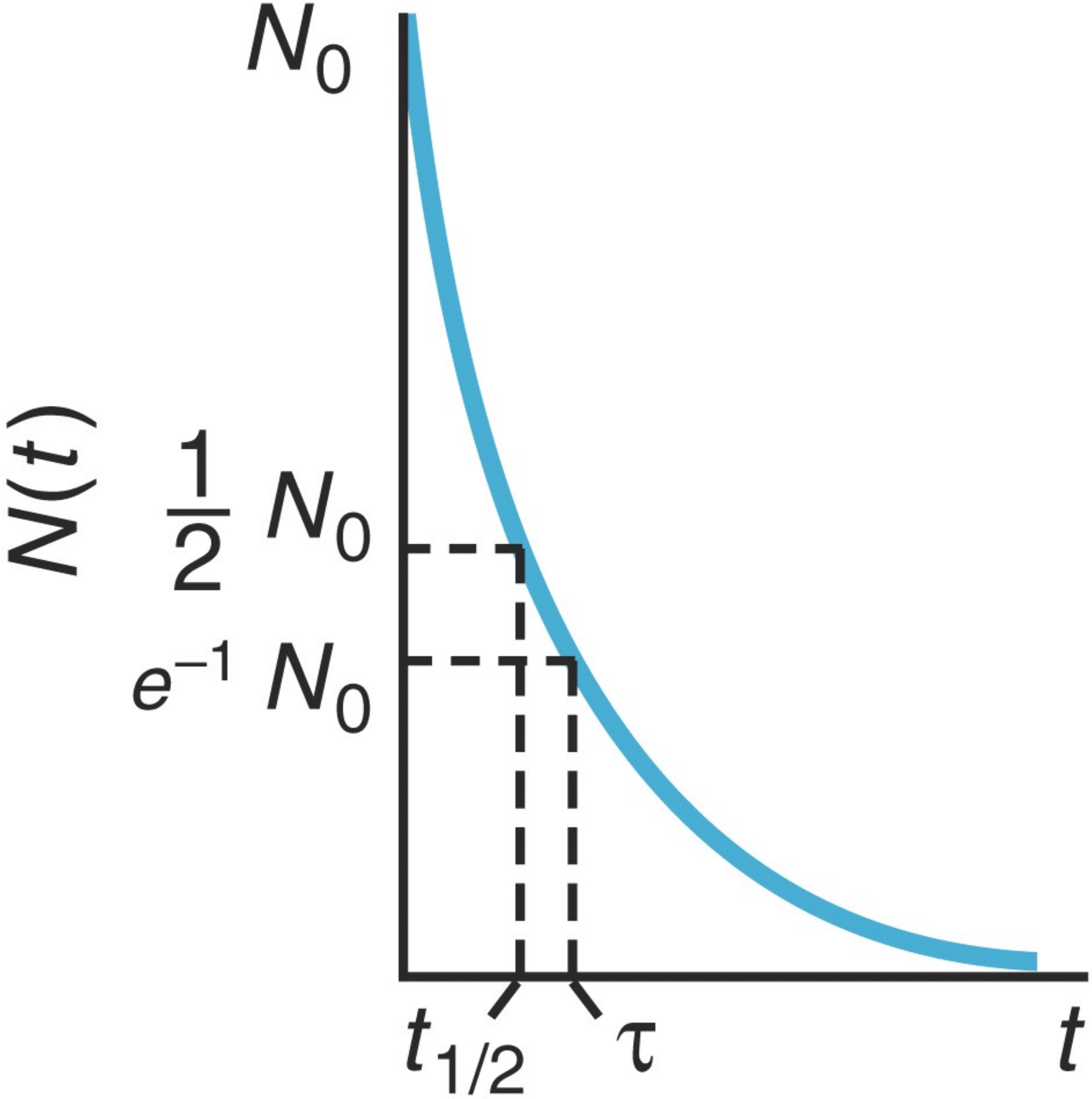
The curve of binding energy: binding energy per nucleon. Note that above mass 40 or so, it is constant

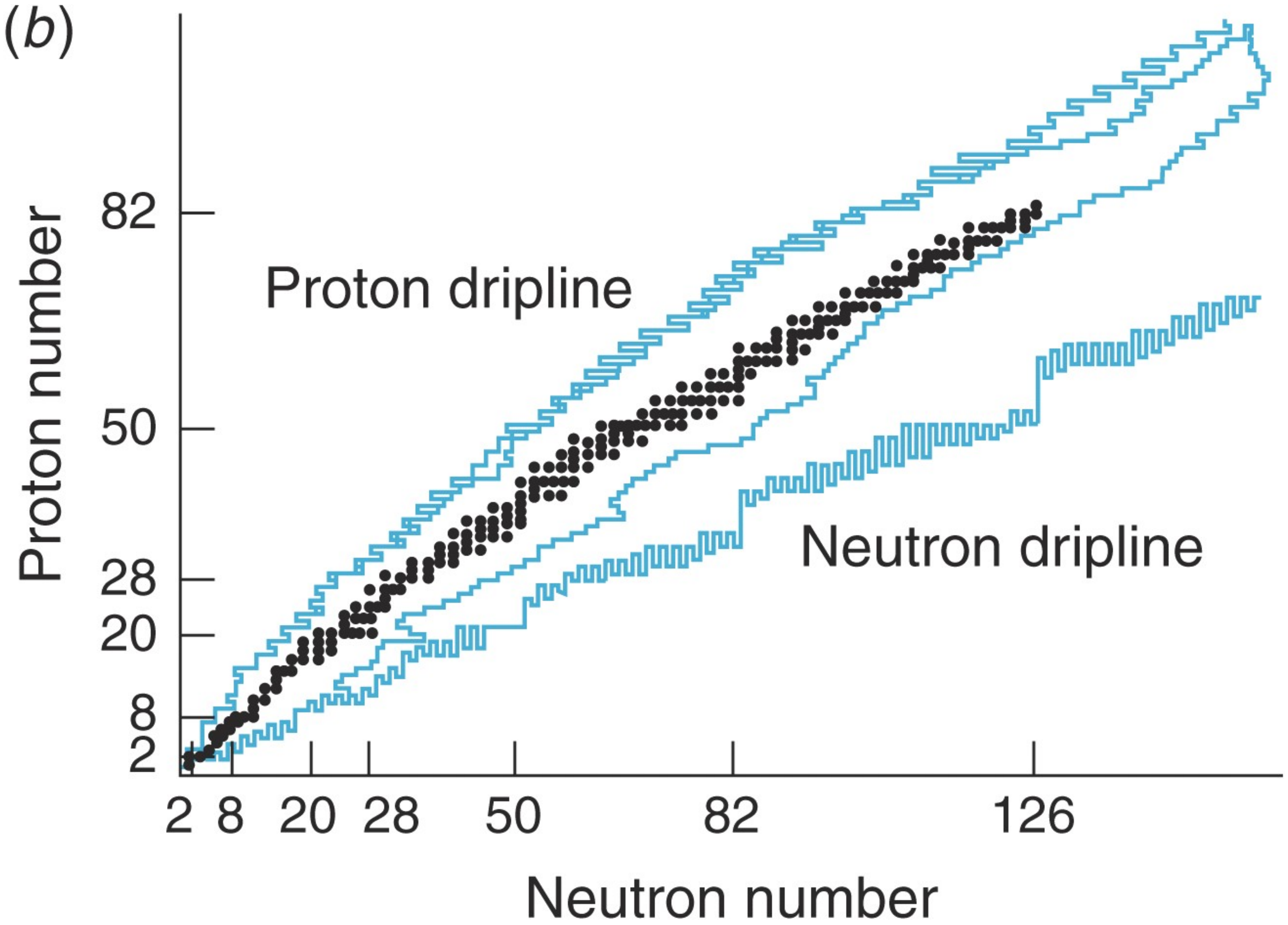
Radioactivity

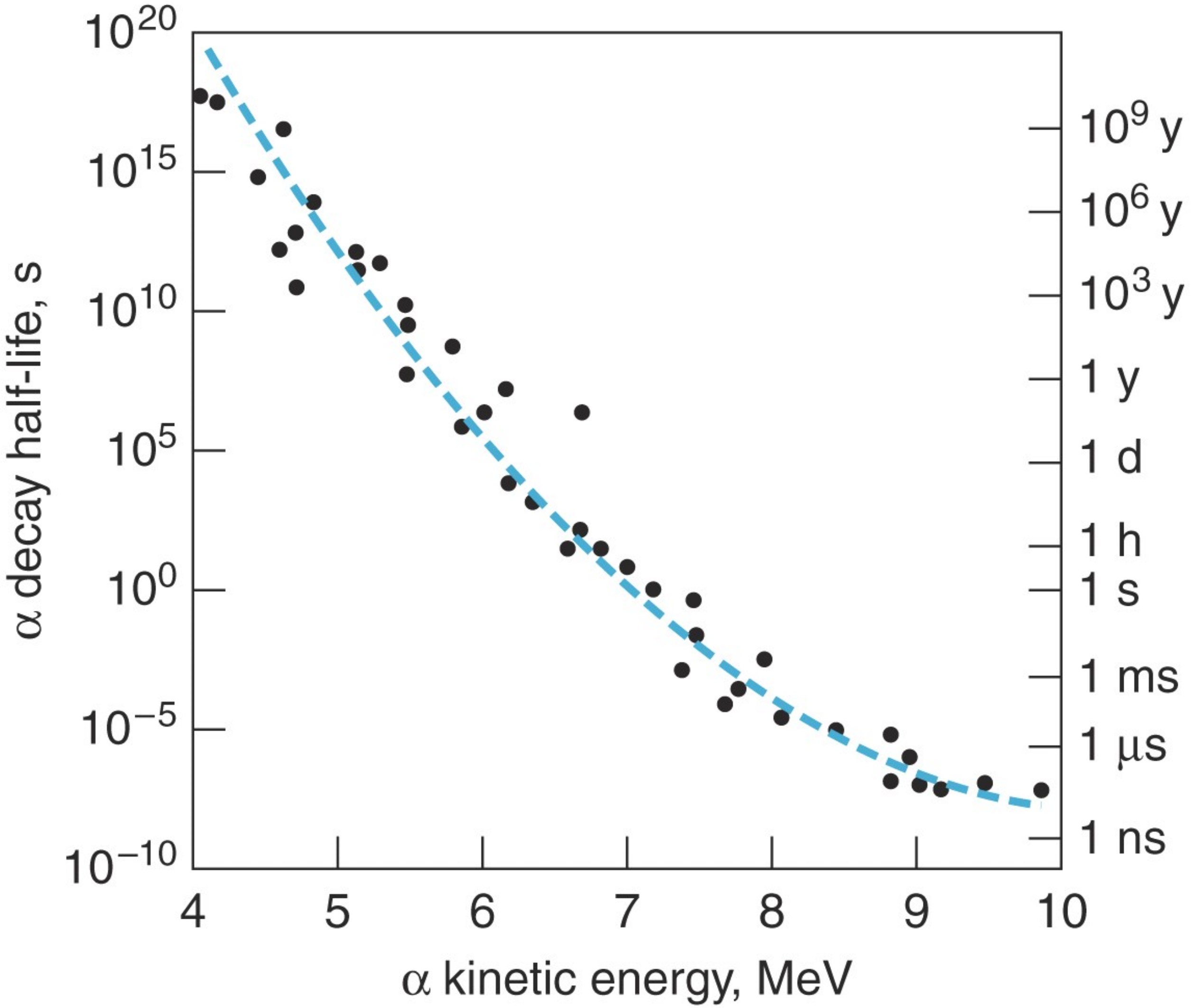
For a nucleus to be radioactive at all, its mass must be greater than the sum of the masses of the decay products.

We will look briefly at three types of decay: alpha, beta, and gamma

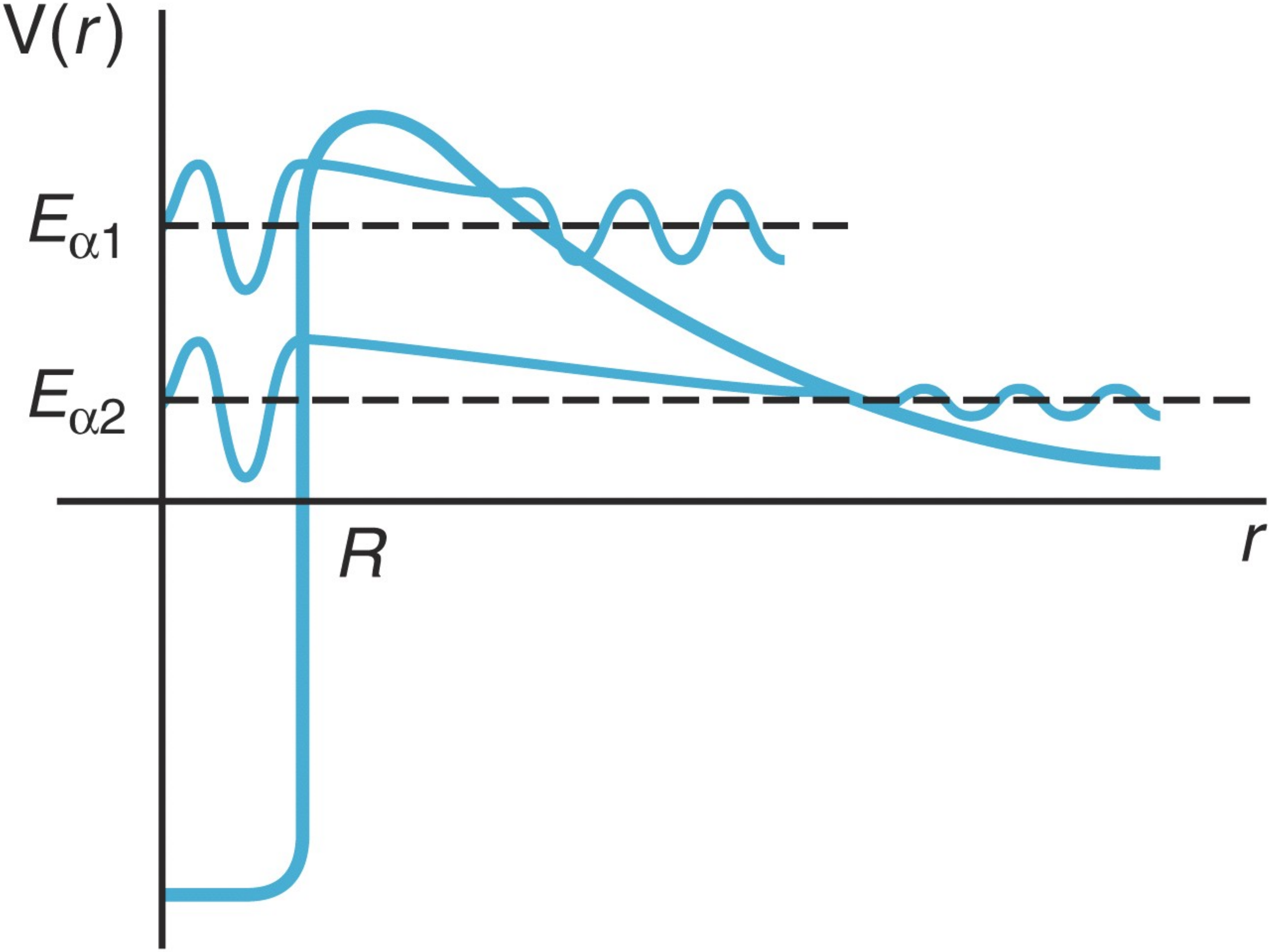
Many of the heavy nuclei are unstable to alpha decay, and because the Coulomb barrier inhibits the decay process, the half life for alpha decay can be very long if the decay energy is small. All very heavy nuclei (Z>83) are theoretically unstable to α decay since the mass of the parent is greater than the sum of the masses of the decay products


N_0
$N(t)$
$\frac{1}{2} N_0$
$e^{-1} N_0$
$t_{1/2}$
τ
t


(b)
Proton number
82
50
28
20
8
2
Proton dripline
Neutron dripline
2
8
20
28
50
82
126
Neutron number

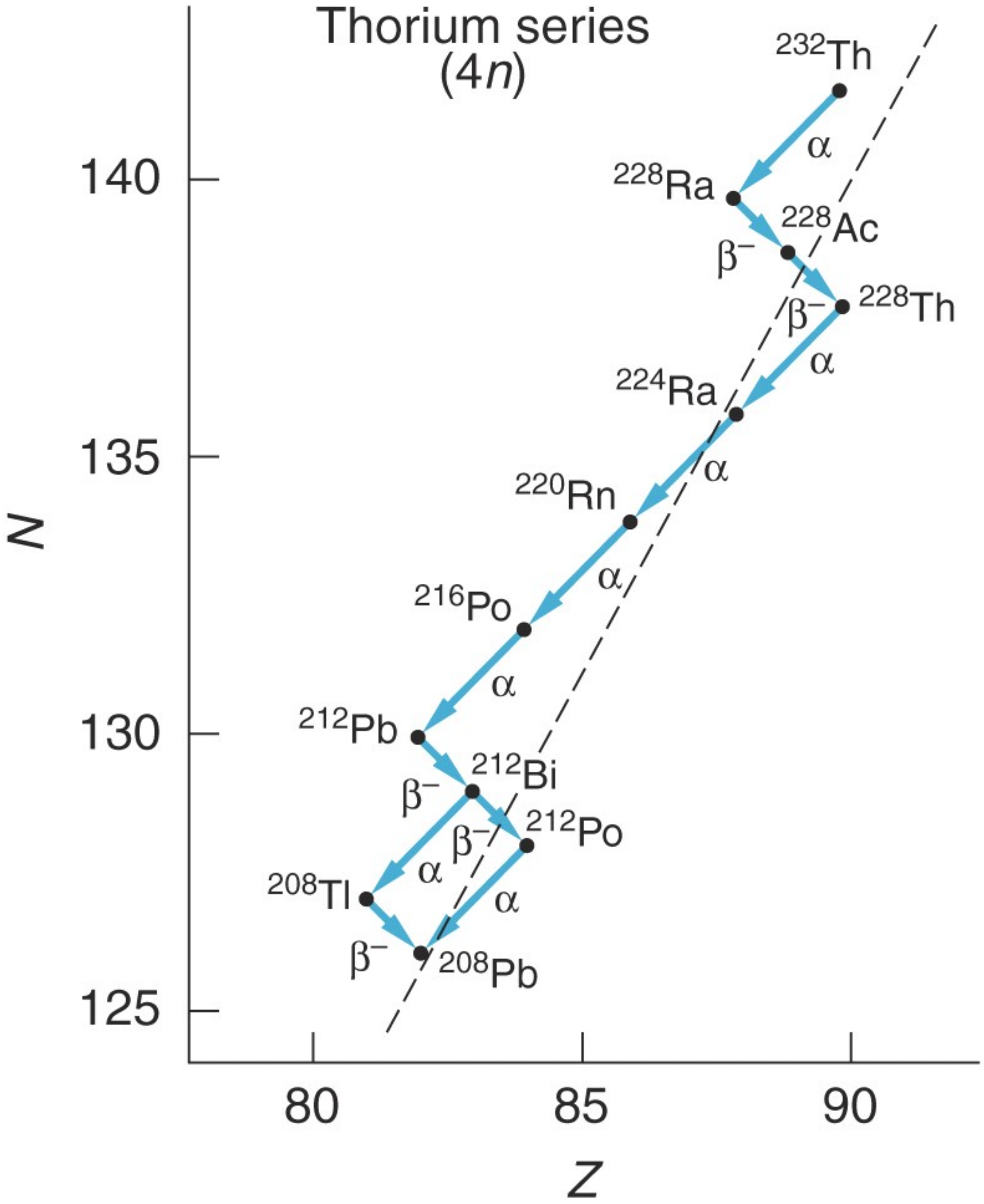


The Geiger-Nuttall relation

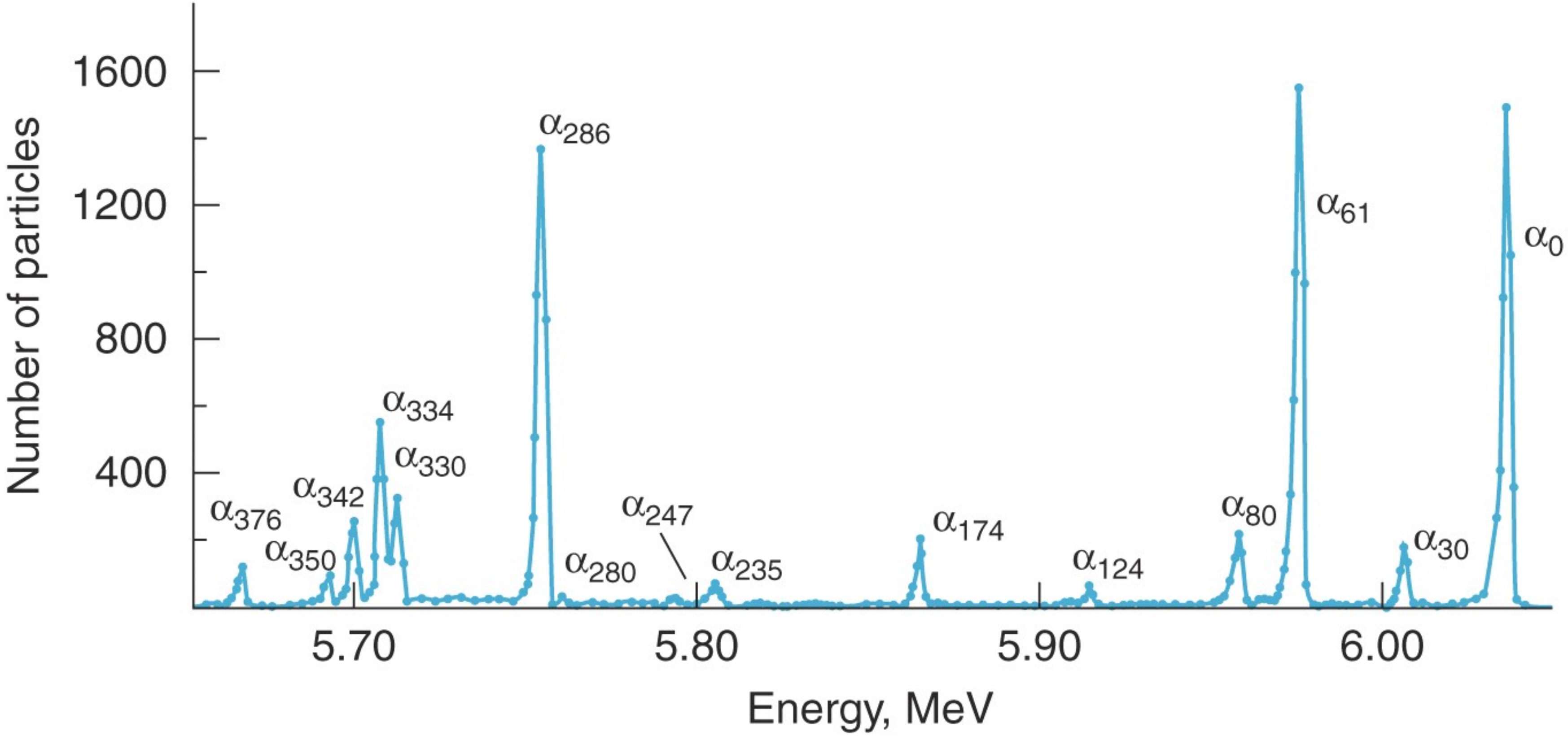

V(r)
$E_{\alpha 1}$
$E_{\alpha 2}$
R
r

Alpha decay

The broken line is the line of stability, i.e., the floor of the energy valley we saw earlier

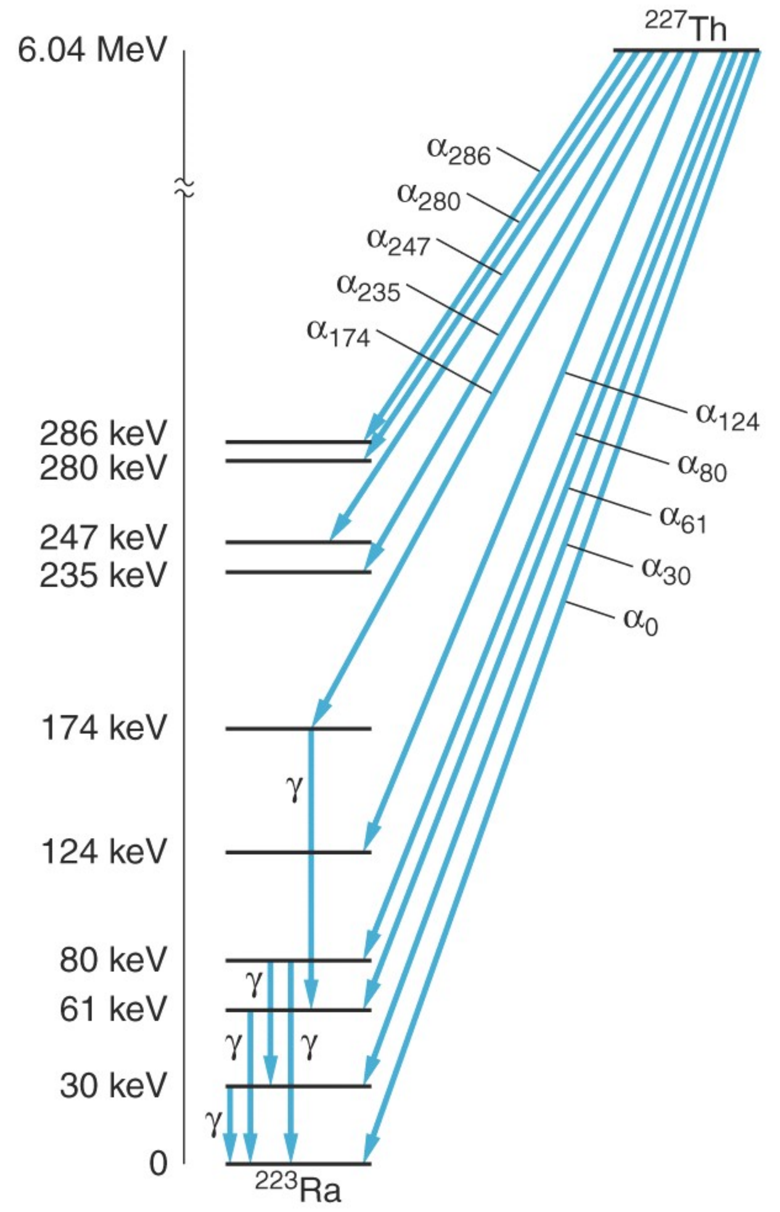


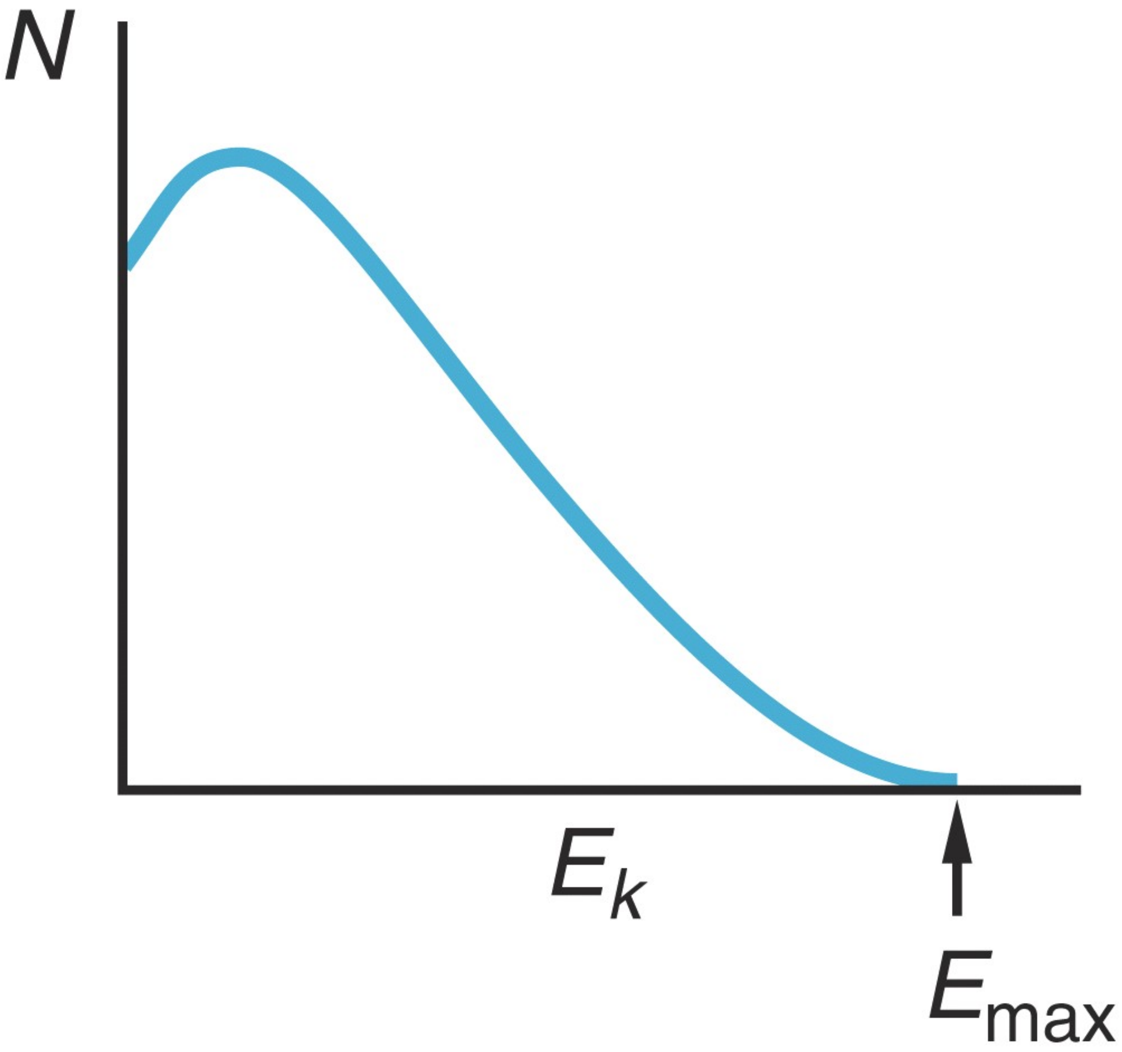
The alpha-particle spectrum from ^{227}Th… the highest energy alpha particles corresponds to decay to the ground state of ^{223}Ra



The energy levels of ^{223}Ra can be determined from the measurement of the alpha-particle energies we saw in the pervious slide.

Not all of the gamma-ray transitions are shown





The energy spectrum of electrons emitted in beta decay

Beta decay

β^- decay: $${}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+1}X_{N-1} + \beta^- + \overline{\nu}_e$$

A neutron changes into a proton and emits an electron

$$Q = (M_P - M_D)c^2$$

β^+ decay: $${}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z-1}X_{N+1} + \beta^+ + \nu_e$$

A proton changes into a neutron and emits a positron

$$Q = (M_P - M_D + 2m_e)c^2$$

Electron capture: a process that competes with β^+ decay in which a proton in the nucleus captures an atomic electron and changes into a neutron with the emission of a neutrino

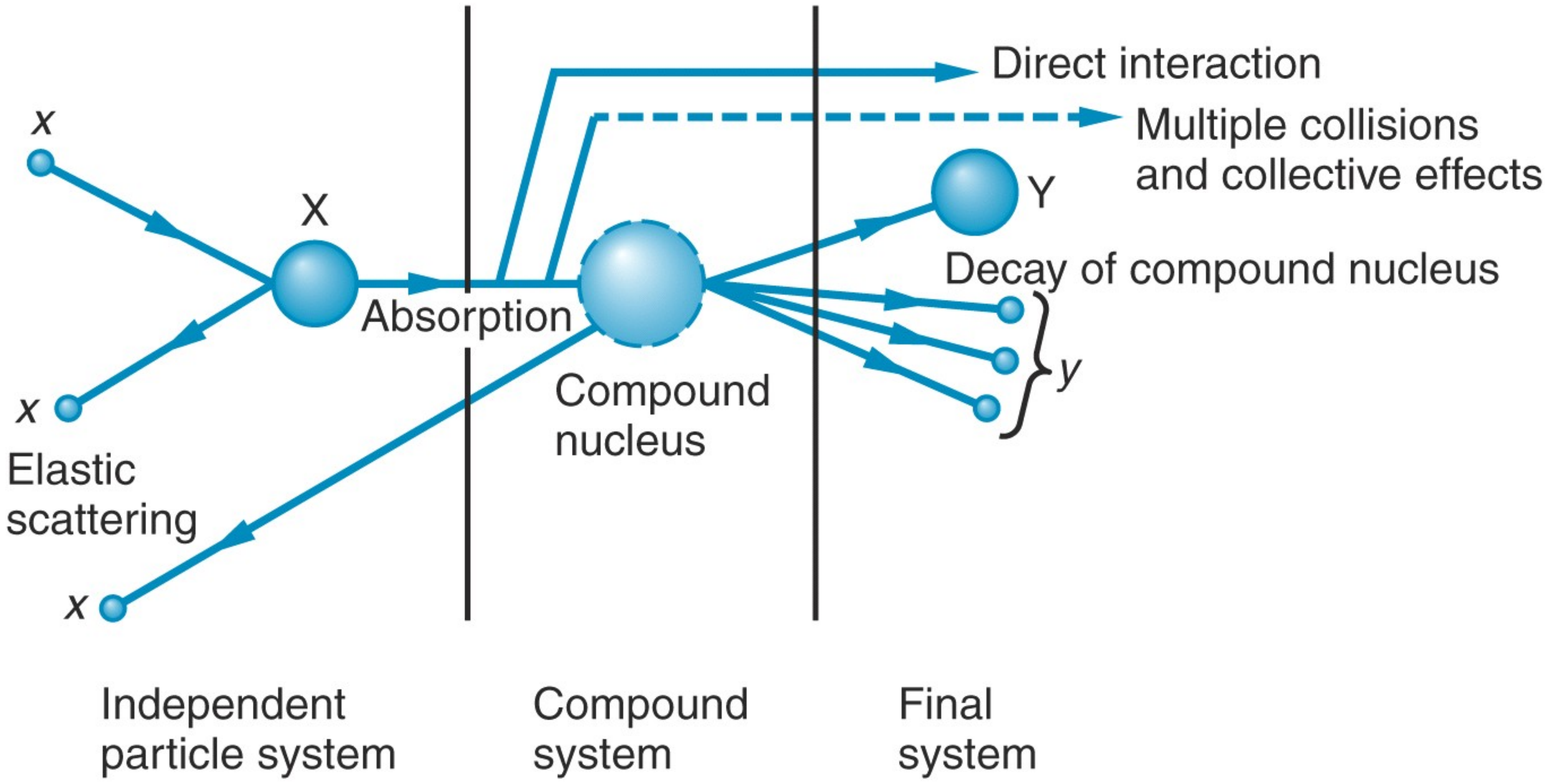
Gamma decay

A process in which a nucleus in an excited state decays to a lower energy state of the same isotope by the emission of a photon. We saw an example of this earlier in the decay of ^{223}Ra

Internal conversion is a competing process especially for lower-lying energy states, in which the excitation energy of the state is transferred to an orbital electron which is ejected from the atom. The ejected electron is observed to have a kinetic energy equal to the nuclear transition energy minus the electron's atomic binding energy

The compound nucleus–the key to understanding nuclear reactions

$X(x,y)Y$



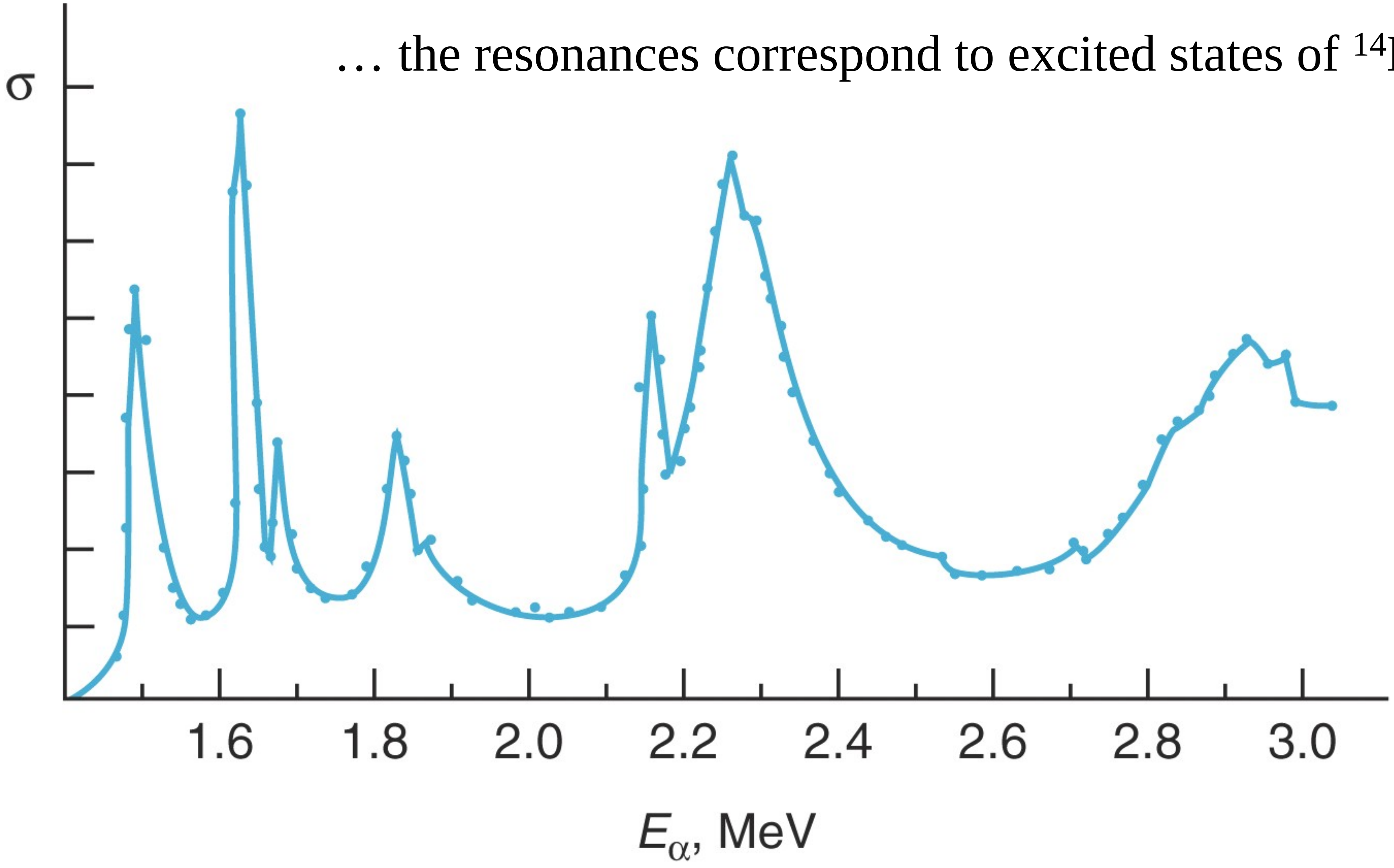
$$Q = (m_x + m_X - m_y - m_Y)\, c^2$$

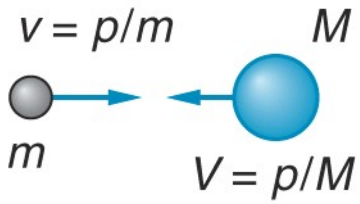
Some examples

$$^{10}\mathrm{B} + \alpha \longrightarrow {}^{14}\mathrm{N}^* \longrightarrow \begin{array}[t]{l} {}^{12}\mathrm{C} + d \\ {}^{10}\mathrm{B} + \alpha \\ {}^{14}\mathrm{N} + \gamma \\ {}^{13}\mathrm{N} + n \end{array}$$

Cross section for the ^{10}Be + α reaction

… the resonances correspond to excited states of ^{14}N

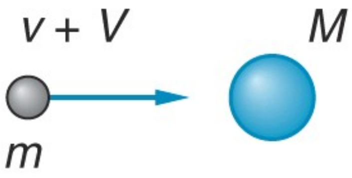




CM system

$$p = mv = MV$$

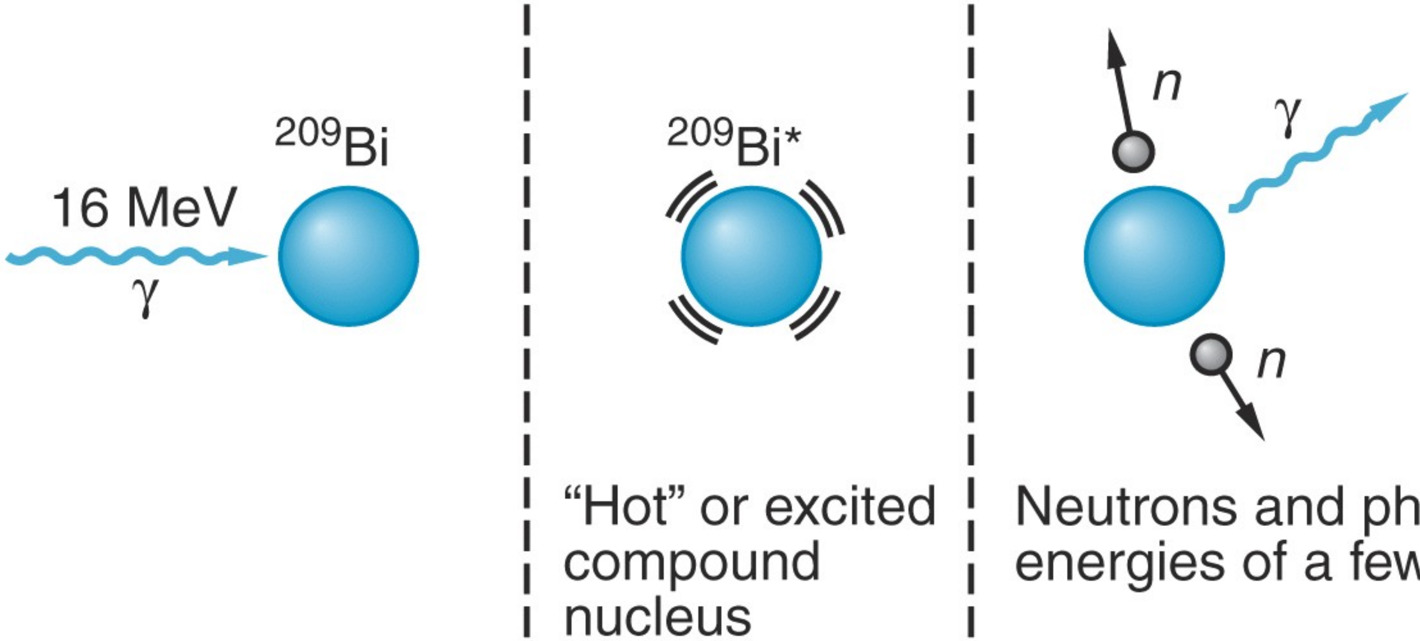
$$E_{CM} = p^2/2m + p^2/2M = (m + M)p^2/2mM$$



Lab system

$$p_{lab} = m(v + V) = mv(1 + m/M) = \frac{M + m}{M} p$$

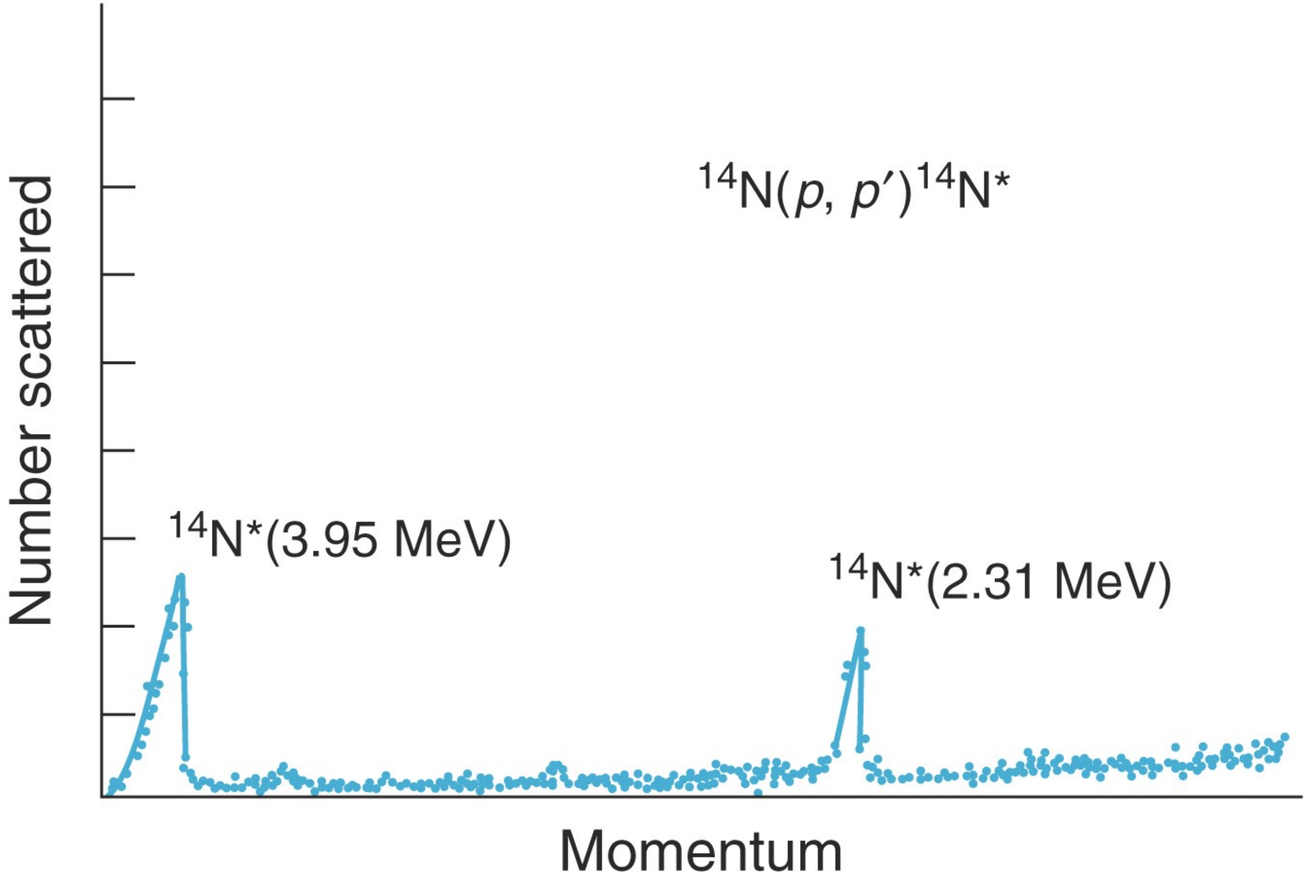
$$E_{lab} = \frac{p_L{}^2}{2m} = \left(\frac{p^2}{2m}\right)\left(\frac{M + m}{M}\right)^2 = \frac{M + m}{M} E_{CM}$$

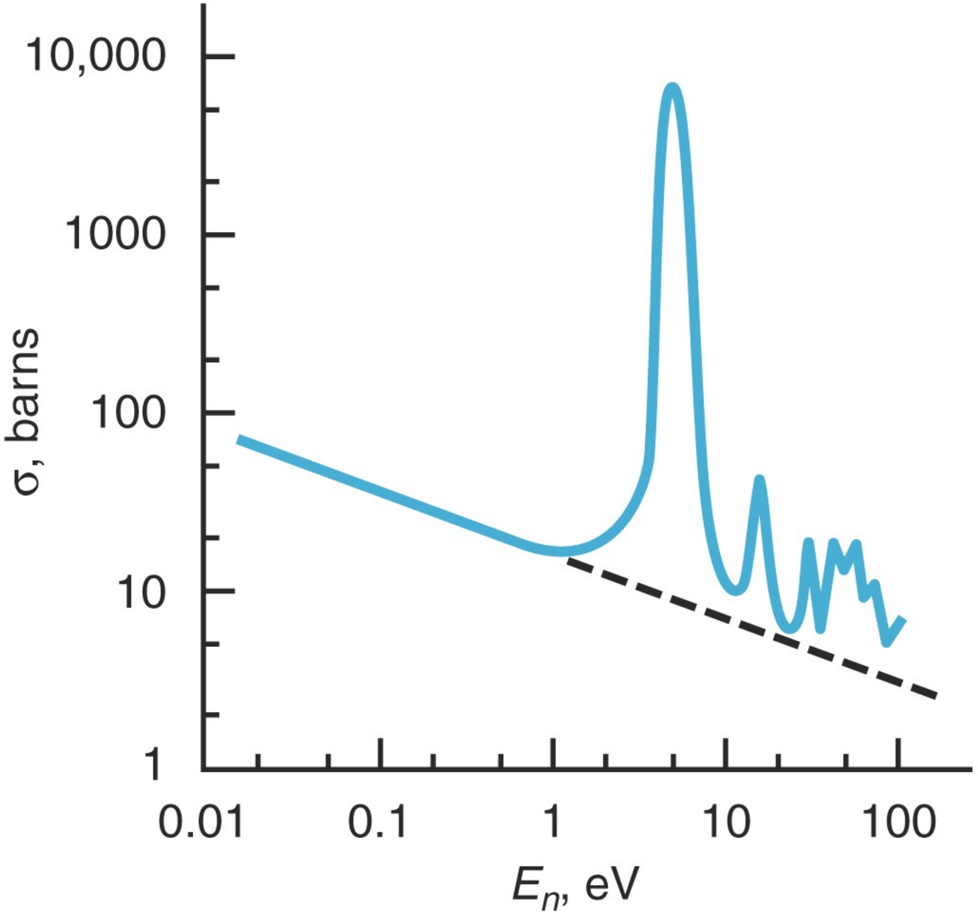


“Hot” or excited compound nucleus

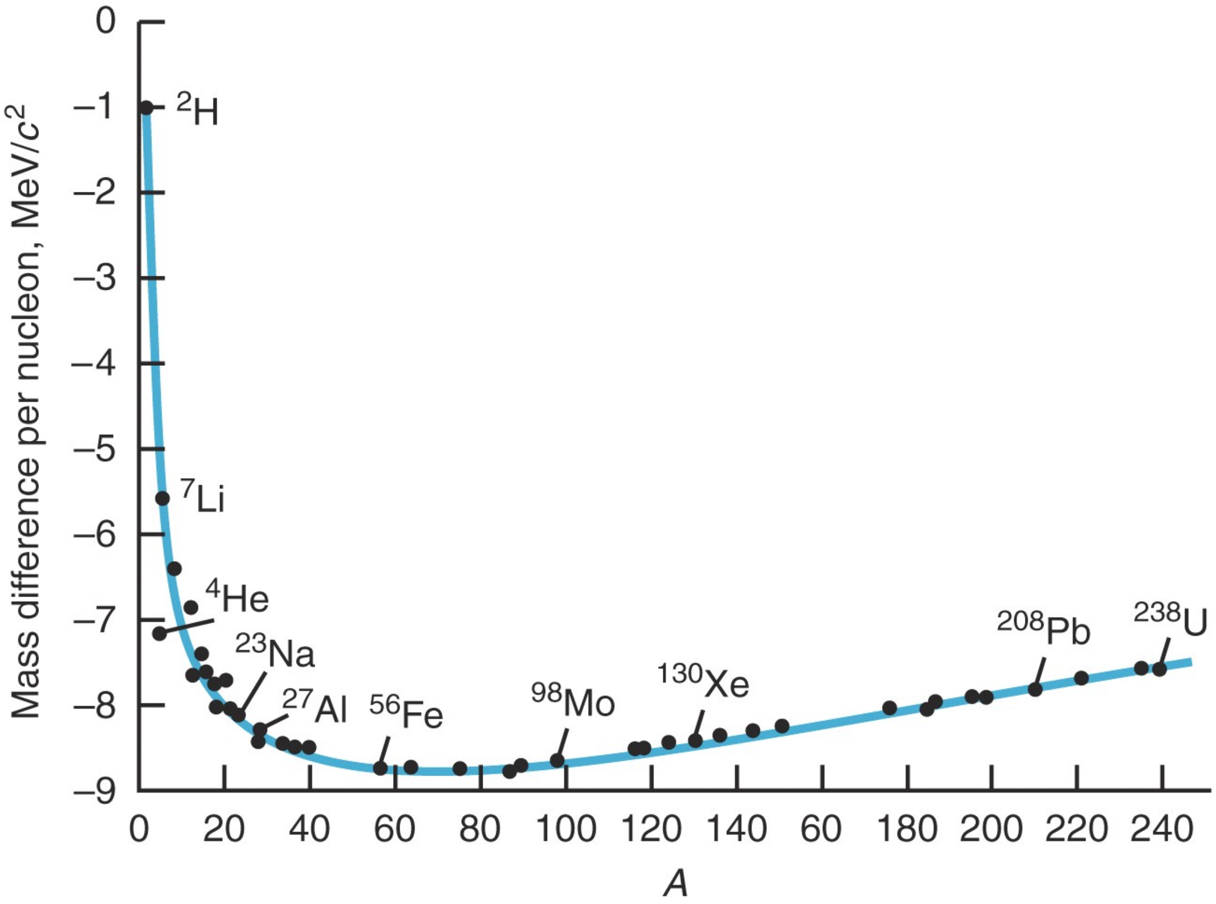
Neutrons and photons with energies of a few MeV boil off

The same kind of information about excited states of ^{14}N can be obtained by inelastic proton scattering





The effect of resonances on the cross section (here the neutron-capture on silver) can be quite dramatic. The dashed line is an extension of the 1/*v* behavior expected in the absence of resonances



Before we leave this, look at the flipped version of the plot of B/A *vs* A that we saw earlier. Note that the rest energy per nucleon is less for intermediate mass nuclei than for very heavy or light ones….the key to fission

The Nuclear Force

About a hundred times stronger than the Coulomb force

Very short range–goes to zero beyond about 3 fm

Charge independent–does not matter if the particles are protons or neutrons

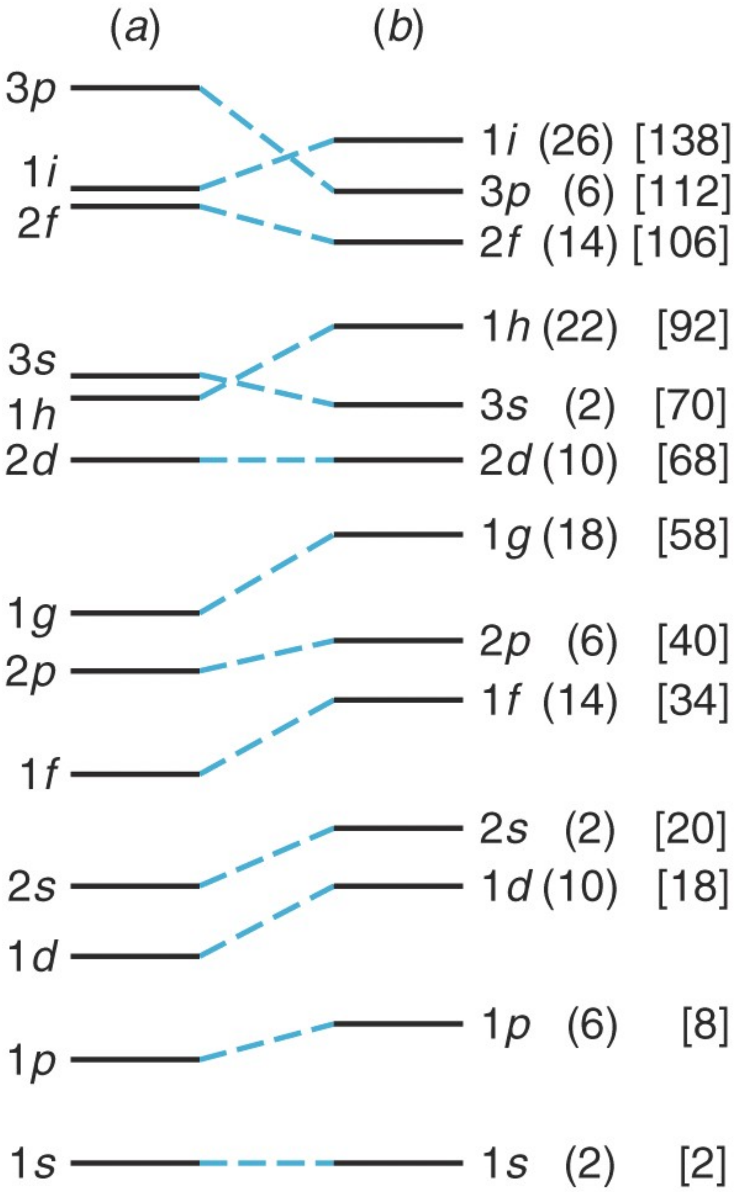
Saturated–is constant at about 8 MeV/nucleon above A=20 or so

Depends on the spin orientation of the nucleons

Suspected to be an exchange force in which the attraction is due to an exchange of pions

These are the energy levels for a single particle in an infinite square well (a) and in a finite square well with rounded rather than sharp corners (b)

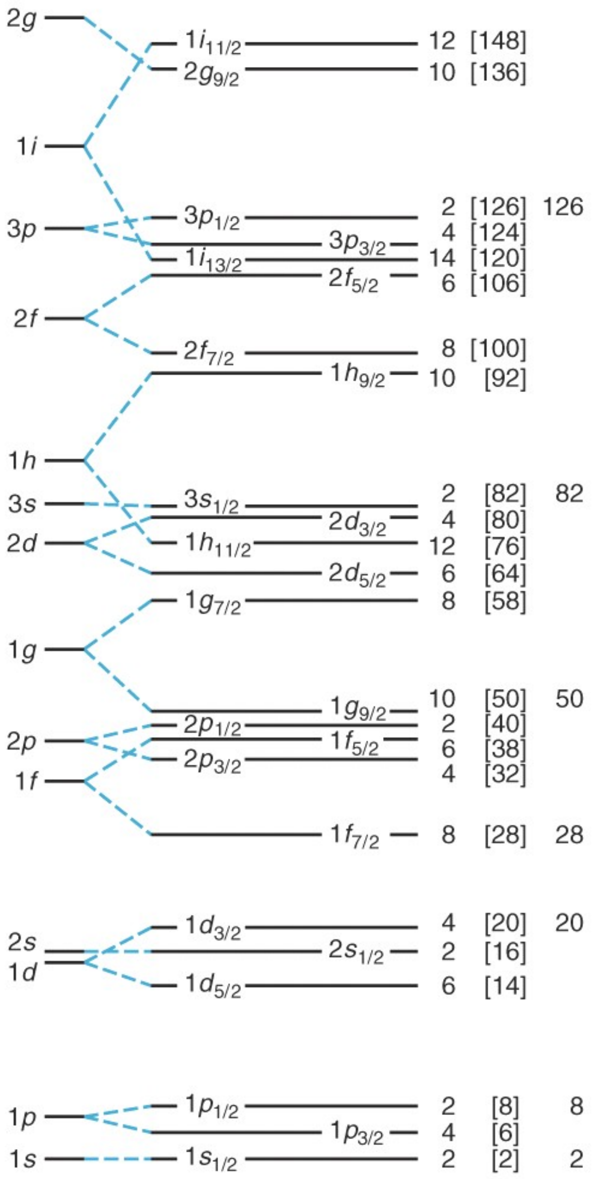
The maximum number of particles in each level is given in parentheses, followed by the total number of particles through that level



The nuclear shell model

It is an independent-particle model, similar to that used for assigning energy states to atomic electrons, but one that makes use of a strong spin-orbit coupling for each nucleon.

The model accounts for the shell-like structure of protons and neutrons and explains the ‘magic numbers’



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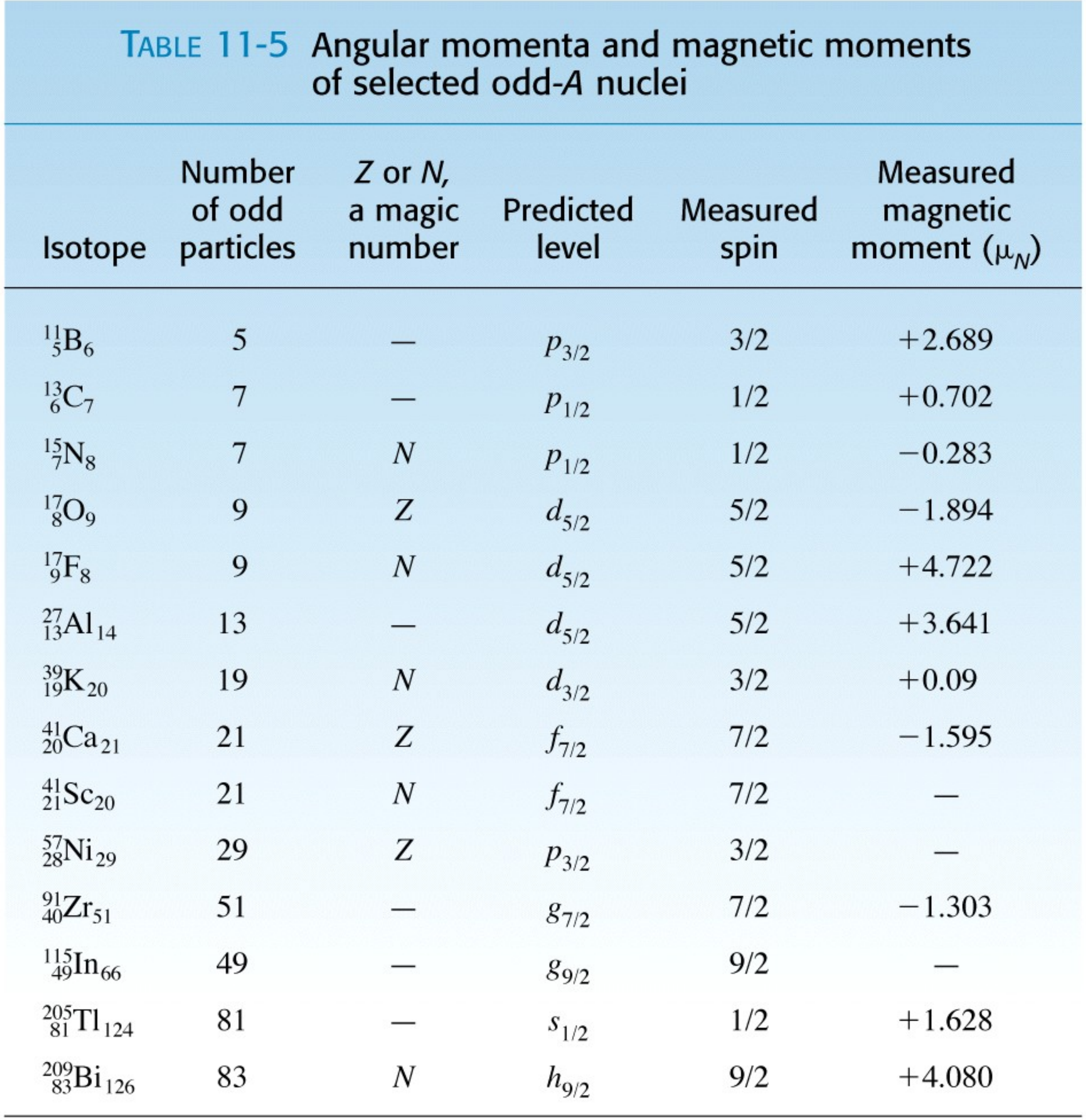

TABLE 11-5 Angular momenta and magnetic moments of selected odd-*A* nuclei

Isotope	Number of odd particles	*Z* or *N*, a magic number	Predicted level	Measured spin	Measured magnetic moment (μ_N)
$^{11}_{5}\mathrm{B}_{6}$	5	—	$p_{3/2}$	3/2	+2.689
$^{13}_{6}\mathrm{C}_{7}$	7	—	$p_{1/2}$	1/2	+0.702
$^{15}_{7}\mathrm{N}_{8}$	7	*N*	$p_{1/2}$	1/2	−0.283
$^{17}_{8}\mathrm{O}_{9}$	9	*Z*	$d_{5/2}$	5/2	−1.894
$^{17}_{9}\mathrm{F}_{8}$	9	*N*	$d_{5/2}$	5/2	+4.722
$^{27}_{13}\mathrm{Al}_{14}$	13	—	$d_{5/2}$	5/2	+3.641
$^{39}_{19}\mathrm{K}_{20}$	19	*N*	$d_{3/2}$	3/2	+0.09
$^{41}_{20}\mathrm{Ca}_{21}$	21	*Z*	$f_{7/2}$	7/2	−1.595
$^{41}_{21}\mathrm{Sc}_{20}$	21	*N*	$f_{7/2}$	7/2	—
$^{57}_{28}\mathrm{Ni}_{29}$	29	*Z*	$p_{3/2}$	3/2	—
$^{91}_{40}\mathrm{Zr}_{51}$	51	—	$g_{7/2}$	7/2	−1.303
$^{115}_{49}\mathrm{In}_{66}$	49	—	$g_{9/2}$	9/2	—
$^{205}_{81}\mathrm{Tl}_{124}$	81	—	$s_{1/2}$	1/2	+1.628
$^{209}_{83}\mathrm{Bi}_{126}$	83	*N*	$h_{9/2}$	9/2	+4.080

Summary

It's been a quick trip, and I hope a not-too-boring one. We touched on a number of topics:

Ground-state properties of the nucleus

Radioactivity

Nuclear reactions and the compound nucleus

Decay modes of an excited nucleus

The nuclear force and the shell model

I hope that there was something in there that you found interesting.

If questions arise during the school year, please call (574.631.8591) or drop me a note at ahyder@nd.edu

Tony Hyder

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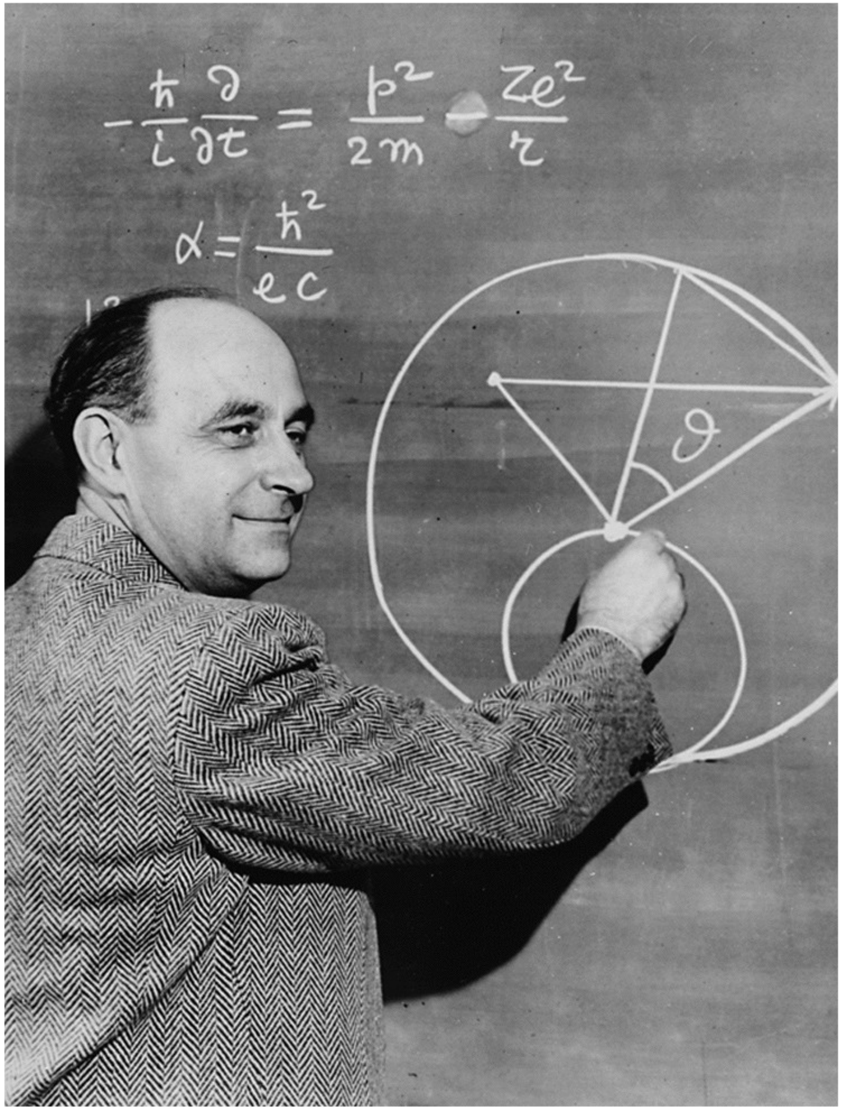

Bonus:

a. Who is this?

b. What’s wrong with this picture?