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Ph 203 L5

Effective Field Theory (Weinberg)

→ For context note:

- Fermi theory of β-decay is also an EFT, since Fermi didn't know about $W^{\pm}$, Z^{0}

→ For NN int. based on QCD EFT start with:

$$\mathcal{L}_{QCD} = \sum_{f=u,d,\dots} \bar{q}_f (i \not{D} - m_f) q_f - \frac{1}{4} G_{\mu\nu,a} G_a^{\mu\nu}$$

$\mu\nu = 0-3$ space time

$a = 1-8 \Rightarrow$ color charge

this is gluon self-interaction

w $\not{D} = \partial_\mu - i g \sum_a \frac{\lambda_a}{2} A_{\mu,a}$

coupling

$A_{\mu,a}$ ↳ QCD vector potential c.f. QED

λ_a: generators of $SU(3)$

↳ Gell-Mann matrices for color triplet r, b, g

3×3 e.g. $\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \dots$

&

$$G_{\mu\nu,a} = \partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} + g f_{abc} A_{\mu,b} A_{\nu,c}$$

f_{abc}: like ϵ_{ijk}, $SU(3)$ structure constants

For N-N force generally only need $q_f = u, d$

w $m_u \simeq 2.5$ MeV

$m_d \simeq 4.9$ MeV

$$\left[\begin{array}{l} m_s \simeq 100\text{ MeV} \\ m_c \simeq 1.2\text{ GeV} \\ m_b \simeq 4.2\text{ GeV} \\ m_t \simeq 173\text{ GeV} \end{array}\right]$$

called "current" quark masses undressed

focussing first on u, d quarks,
@ $E >> GeV$ $m_u \simeq m_d \simeq 0$ gives

$$\mathcal{L}_{QCD} \simeq \sum_f \bar{q}_f i \not{D} q_f - \frac{1}{4} G_{\mu\nu,a} G_a^{\mu\nu}$$

& in this limit helicity $(\vec{\sigma} \cdot \vec{p})$ is conserved
↳ right-handed $\vec{\sigma} \cdot \vec{p} > 0$
left-handed $\vec{\sigma} \cdot \vec{p} < 0$

& get an SU(2) symmetry ⇒ chiral sym.

&

$$\mathcal{L}_{QCD} = \sum_f (\bar{q}_{R,f}\, i \not{D}\, q_{R,f} + \bar{q}_{L,f}\, i \not{D}\, q_{L,f}) - \frac{1}{4} GG$$

note: for massless particles (m or $<< E$) helicity = chirality
but chirality is actually a unique SU(2) sym.
$\binom{u}{d}$ = isospin , $\binom{u_L}{u_R}$ = chirality
w projection operator $= \frac{1}{2}(1 \pm \gamma_5)$

<u>Note:</u>

① Together isospin & chiral symmetry yield <u>2</u> <u>strong</u> conserved currents (for $E \gg m_{u,d}$)

$$V_i^\mu = R_i^\mu + L_i^\mu = \bar{q}\, \gamma^\mu \frac{\tau_i}{2} q \quad \Rightarrow \text{isospin}$$

$$A_i^\mu = R_i^\mu - L_i^\mu = \bar{q}\, \gamma^\mu \gamma_5 \frac{\hat{\tau}_i}{2} q \Rightarrow \text{chiral}$$

② If $E \simeq m_{u,d}$ both isospin & chirality are broken
→ "small" violation of isospin
since $m_d - m_u << m_{p,n}$

→ but large "spontaneous" breakdown of chiral symmetry

→ chiral sym. requires existence of degenerate states ($m_1 = m_2$) with opposite intrinsic parity

but $m_p\,(I=\frac{1}{2}, J^\pi = \frac{1}{2}^+) = 938$ MeV

$m_{N^*}\,(I=\frac{1}{2}, J^\pi = \frac{1}{2}^-) = 1535$ MeV

also $m_\rho\,(1, 1^-) = 770$ MeV

$m_a\,(1\ 1^+) = 1260$ MeV

→ Such spont. broken symmetries lead to appearance of a massive "Goldstone" boson

↳ pion!

$m_\pi \neq 0$ since $m_u, m_d \neq 0$

↳ leads to Modern EFT:

Chiral Perturbation Theory (χEFT)

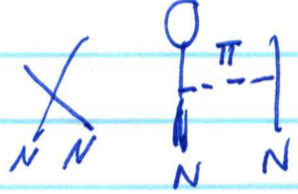
1. Construct general $\mathcal{L}$ using effective d.o.f. π, N w sym + ~~sym~~ of QCD
2. Develop scheme for identifying key Feynman diags using expansion in $\dfrac{Q}{\Lambda_\chi}$ → $Q = p - p'$ mom. xfer, Λ_χ → Cutoff mass

w $\Lambda_\chi > m_\pi$ but $\Lambda_\chi < Q_{\text{perturb. QCD}}$ → $\simeq 2$ GeV

↳ $\Lambda_\chi \simeq 500 - 1000$ MeV

& use "power counting" to identify imp. diags

e.g.

Leading order 

$\Rightarrow \left(\dfrac{Q}{\Lambda_\chi}\right)^0$ ← power

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then scale diags by power × low energy constant

$\hookrightarrow \left(\frac{Q}{\Lambda_\chi}\right)^n \times \quad C_{n_i}$

fit these to data @ low E

Show Pic of Diags:

Posted on Syllabus

Nucleon-Nucleon Scattering Up to N^5LO in Chiral Effective Field Theory

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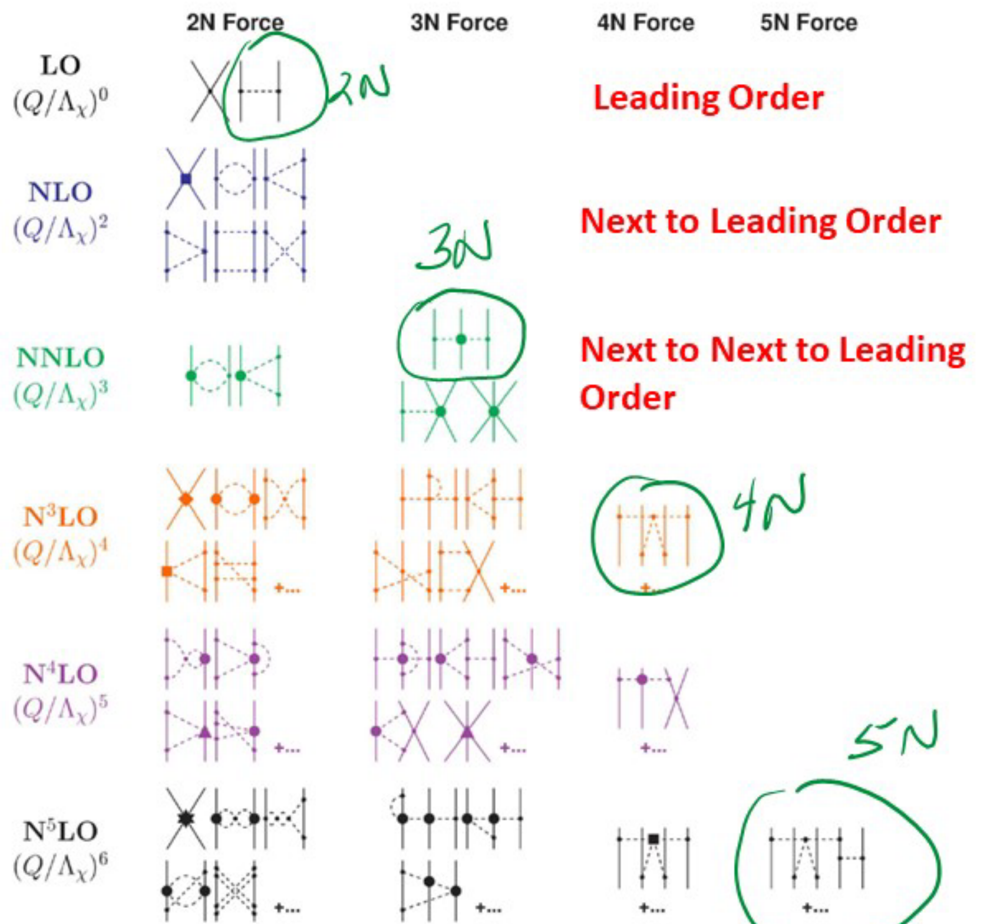

FIGURE 1 | Hierarchy of nuclear forces up to N^5LO or sixth order of the chiral expansion. Only some representative diagrams are included. Small dots, large solid dots, solid squares, triangles, diamonds, and stars denote vertexes of index $\Delta_i = 0, 1, 2, 3, 4$, and 6, respectively. Reprinted figure with permission from Entem et al. [37], copyright (2017) by the American Physical Society.

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Note: ① @ each order several LEC's extracted via fits

② @ higher order can use lower order LEC's (sometimes)

③ If higher order terms are smaller → convergence (Maybe?!)

Results for N-N Phase Shifts:

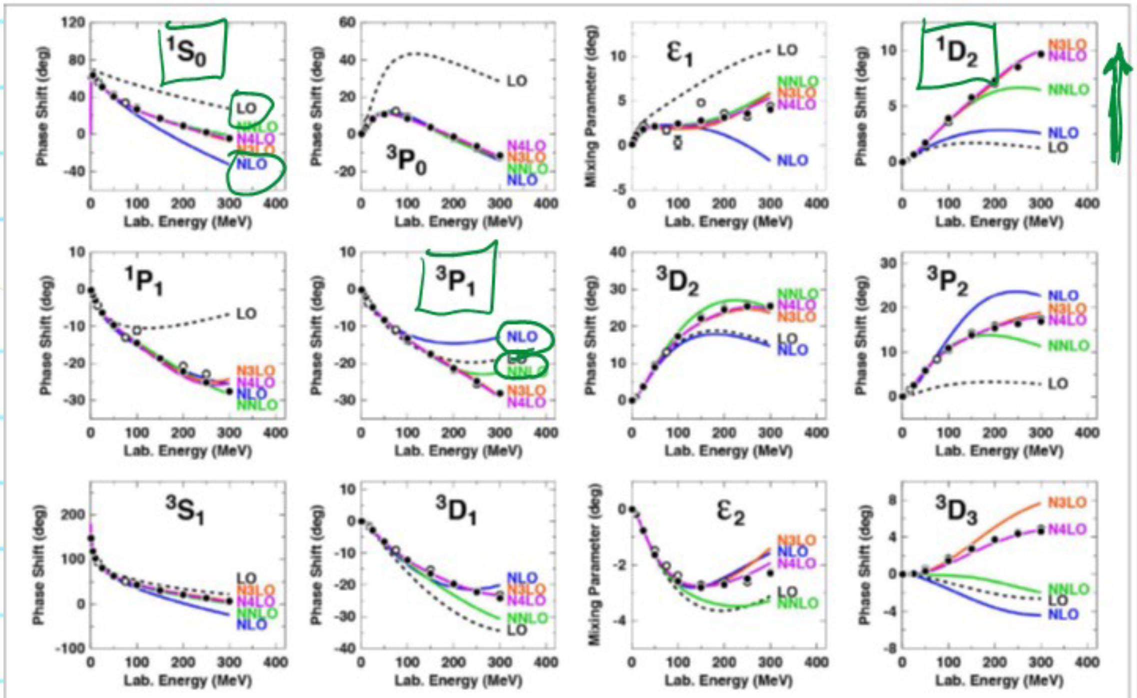

FIGURE 15 | Chiral expansion of neutron-proton scattering as represented by the phase shifts in S, P, and D waves and mixing parameters ϵ_1 and ϵ_2. Five orders ranging from LO to N^{4}LO are shown as denoted. A cutoff $\Lambda = 500$ MeV is applied in all cases. The filled and open circles represent the results from the Nijmegen multi-energy np phase-shift analysis [93] and the GWU single-energy np analysis SP07 [95], respectively. Reprinted figure with permission from Entem et al. [37], copyright (2017) by the American Physical Society.

TABLE 4 | χ^2/datum for the fit of the 2016 NN data base by NN potentials at various orders of chiral EFT ($\Lambda = 500$ MeV in all cases).

T_{lab} bin (MeV)	No. of data	LO	NLO	NNLO	N^{3}LO	N^{4}LO
			Proton-proton			
0–100	795	520	18.9	2.28	1.18	1.09
0–190	1206	430	43.6	4.64	1.69	1.12
0–290	2132	360	70.8	7.60	2.09	1.21
			Neutron-proton			
0–100	1180	114	7.2	1.38	0.93	0.94
0–190	1697	96	23.1	2.29	1.10	1.06
0–290	2721	94	36.7	5.28	1.27	1.10
			pp plus np			
0–100	1975	283	11.9	1.74	1.03	1.00
0–190	2903	235	31.6	3.27	1.35	1.08
0–290	4853	206	51.5	6.30	1.63	1.15

From Entem et al. [37]

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Is χEFT better than Phenom. NN or OBEP?
Theorists say Yes!!
1. Allows estimate of uncertainty @ each order
2. Automatically includes 3NF, 4NF, ...
3. Fewer Params:
AV18 + 3NF needs 50 parms
N^3LO needs 24 parms

PIC of ^2H & ^3H Results

TABLE 5 | Two- and three-nucleon bound-state properties as predicted by *NN* potentials at various orders of chiral EFT (Λ = 500 MeV in all cases).

	LO	NLO	NNLO	N^3LO	N^4LO	Empirical[a]
Deuteron						
B_d (MeV)	2.224575	2.224575	2.224575	2.224575	2.224575	2.224575(9)
A_S (fm$^{-1/2}$)	0.8526	0.8828	0.8844	0.8853	0.8852	0.8846(9)
η	0.0302	0.0262	0.0257	0.0257	0.0258	0.0256(4)
r_{str} (fm)	1.911	1.971	1.968	1.970	1.973	1.97507(78)
Q (fm^2)	0.310	0.273	0.273	0.271	0.273	0.2859(3)
P_D (%)	7.29	3.40	4.49	4.15	4.10	–
Triton						
B_t (MeV)	$\boxed{11.09}$	8.31	8.21	8.09	8.08	$\boxed{8.48}$

(Deuteron: Binding energy B_d, asymptotic S state A_S, asymptotic D/S state η, structure radius r_{str}, quadrupole moment Q, D-state probability P_D; the predicted r_{str} and Q are without meson-exchange current contributions and relativistic corrections. Triton: Binding energy B_t.) B_d is fitted, all other quantities are predictions.
[a]See Table XVIII of Machleidt [18] for references; the empirical value for r_{str} is from Jentschura et al. [92].

TABLE 6 | χ^2/datum for the fit of the *pp* plus *np* data up to 190 MeV and two- and three-nucleon bound-state properties as produced by *NN* potentials at NNLO and N^4LO applying different values for the cutoff parameter Λ.

	NNLO			N^4LO		
Λ(MeV)	450	500	550	450	500	550
χ^2/datum pp & np						
0–190 MeV (2903 data)	4.12	3.27	3.32	1.17	1.08	1.25
Deuteron						
B_d (MeV)	2.224575	2.224575	2.224575	2.224575	2.224575	2.224575
A_S (fm$^{-1/2}$)	0.8847	0.8844	0.8843	0.8852	0.8852	0.8851
η	0.0255	0.0257	0.0258	0.0254	0.0258	0.0257
r_{str} (fm)	1.967	1.968	1.968	1.966	1.973	1.971
Q (fm^2)	0.269	0.273	0.275	0.269	0.273	0.271
P_D (%)	3.95	4.49	4.87	4.38	4.10	4.13
Triton						
B_t (MeV)	8.35	8.21	8.10	8.04	8.08	8.12

For some of the notation, see **Table 5**, where also empirical information on the deuteron and triton can be found.

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Low E - Hi E connection:

Recall: g coupling in $\mathcal{L}_{QCD}$

$\alpha_s \propto g^2$

← strong interaction coupling constant

Asymptotic Freedom (- sign) causes

$\alpha_s \downarrow$ as $E \uparrow$ opposite of QED α_{EM}

Pic of α_s vs Q

for $\alpha_s \lesssim 0.3$ QCD is perturbative

but for $E < M_\pi$, $\alpha_s > 1$!

Non-Perturbative

Strong coupling constant: $\alpha_s(Q)$

$$r_{probe} \sim \lambda \sim \frac{1.2\ \mathrm{fm}}{Q(\mathrm{GeV})} < r_{NN}$$

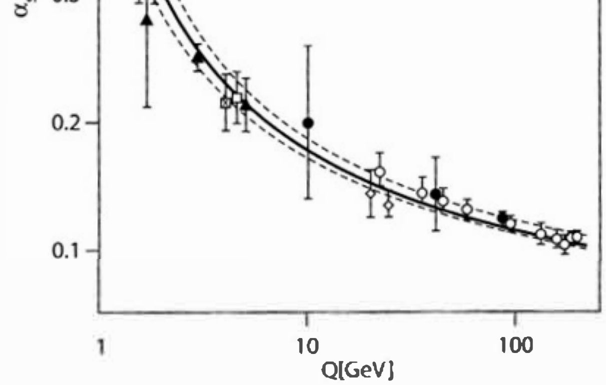

Figure 1.6 The running coupling constant $\alpha_s(Q^2)$ as a function of momentum transfer Q^2 determined from a variety of processes. The figure is from [Bet00].

Strong coupling constant: $\alpha_s(Q)$

https://www.scientificamerican.com/article/physicists-finally-know-how-the-strong-force-gets-its-strength/

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Physicists Finally Know How the Strong Force Gets Its Strength

New discoveries demystify the bizarre force that binds atomic nuclei together

Experimental determination of the QCD effective charge $\alpha_{g_1}(Q)$

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Abstract

The QCD effective charge $\alpha_{g_1}(Q)$ is an observable that characterizes the magnitude of the strong interaction. At high momentum Q, it coincides with the QCD running coupling $\alpha_s(Q)$. At low Q, it offers a nonperturbative definition of the running coupling. We have extracted $\alpha_{g_1}(Q)$ from measurements carried out at Jefferson Lab that span the very low to moderately high Q domain, $0.14 \le Q \le 2.18$ GeV. The precision of the new results is much improved over the previous extractions and the reach in Q at the lower end is significantly expanded. The data show that $\alpha_{g_1}(Q)$ becomes Q-independent at very low Q. They compare well with two recent predictions of the QCD effective charge based on Dyson-Schwinger equations and on the AdS/CFT duality.

$\alpha_s \to \pi$

consistent w AdS/CFT

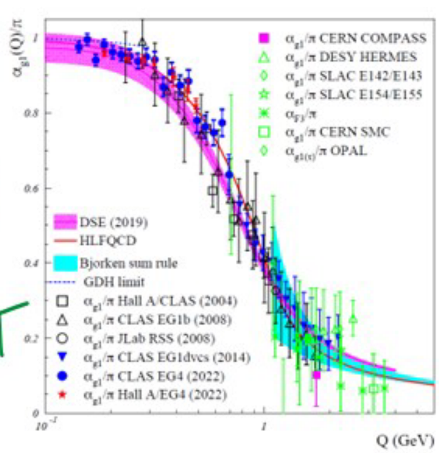

FIG. 1: Effective charge $\alpha_{g_1}(Q)/\pi$ obtained from JLab experiments E03006/E97110 [33] (solid stars), E03006/E05111 [33] (solid circles) and EG1dvcs [32] (solid triangles) and from COMPASS [31] (solid square). Inner error bars represent the statistical uncertainties and outer ones the systematic and statistical uncertainties added quadratically. The open symbols show the older world data [27–30] with the error bars the quadratic sum of the systematic and statistical uncertainties. Also shown are the HLFQCD [24] (red line,

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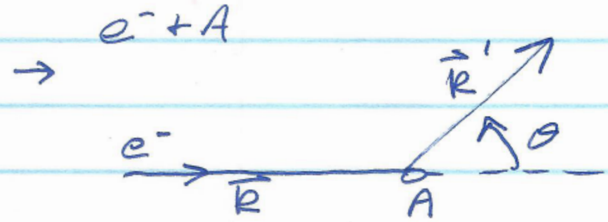
Physical properties of Nuclei:

1. Nuclear Size via charge radius
2. " Binding Energy
3. " Stability
4. " Excited states, decays, reactions, ... nucl. data

I Nuclear Size

Assuming $\rho_p \simeq \rho_n$, charge radius (R_{ch}) $\simeq$ matter radius (R_m)

→ For precise R_{ch} can use $e^- + A$ scattering
(also $\mu^- A$ atoms spectroscopy) more later
& $n + A$ scattering



in Born Approx (Non. Relativ. for now)

$$f(\theta) = \frac{-m_e}{2\pi\hbar^2} \int e^{\vec{q}\cdot\vec{r}'} V(r')\, d^3r'$$

$$\vec{q} = \vec{k} - \vec{k}'$$

for point-like target $[V(r) \propto \delta(r)]$

$k = \frac{1}{4\pi\epsilon_0}$

$$\frac{d\sigma}{d\Omega} = \frac{d\Omega}{d\Omega_{Ruth}} = |f(\theta)|^2 = \left[k \frac{Ze^2}{2T_{cm} \sin^2(\theta_{cm}/2)} \right]^2$$

T_{cm} ← c.m. Kin. Energy

for Nucleus with charge distrib.

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$$V(\vec{r}) = \int \rho(\vec{R})\, V_{point}(\vec{r}-\vec{R})\, d^3R \qquad V_{point} = \frac{Ze^2}{4\pi\epsilon_0 r}$$

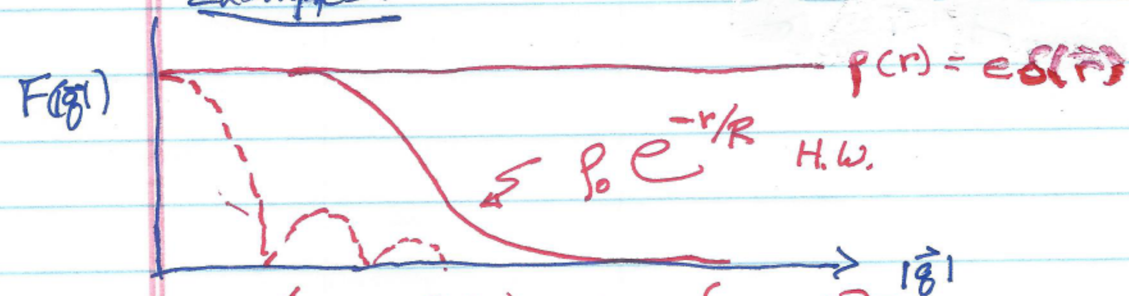
then

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth} \times |F(|\vec{q}|)|^2$$

$$\hookrightarrow F(|\vec{q}|) = \int \rho(\vec{R})\, e^{i\vec{q}\cdot\vec{R}}\, d^3R \quad \text{w } \int \rho(\vec{R})\, d^3R = 1$$

& $\rho(\vec{r})$ is FT of $F(|\vec{q}|)$

Examples:



$$\hookrightarrow \left.\begin{aligned} \rho(r) &= \rho_0 \text{ for } r \le R \\ &= 0 \text{ f } r > R \end{aligned}\right\} \text{“Square Well”}$$

$\Rightarrow$

Can measure charge radius for nuclei via low $|\vec{q}|$ measurements of $F(|\vec{q}|) \Rightarrow$ e.g. $|\vec{q}| \ll \frac{1}{R_{ch}}$ using

$$\left(R_{ch}^{rms}\right)^2 = \lim_{q\to 0}\left[6 \times \left|\frac{dF(|\vec{q}|)}{d|\vec{q}|^2}\right|\right] \Rightarrow \text{see H.W.}$$

R. Hofstadter '61 Nobel:

$$\underline{R_A = 1.2\text{ fm} \times A^{1/3}}, \quad A = N + Z$$

$\hookrightarrow$ for $A > 12$

Note: $A^{1/3}$ implies "close-packing"

$\Leftrightarrow \dfrac{\#\text{ nucleons}}{\text{Volume}} = \text{const.} \equiv \rho_N$ nuclear density same for all nuclei

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this suggests "saturation" of Nucl. Force (due to repulsive core)

↳ $\rho_N^{central}$ does not increase w/ mass

↳ different from gravity

II) Nuclear Binding Energy

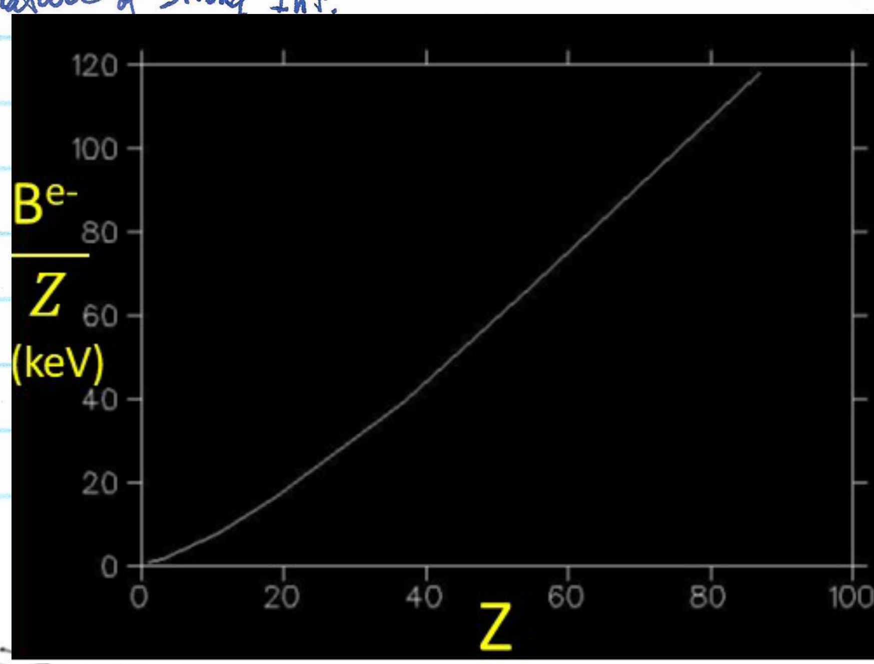
Defined via $B(N, Z) = Zm_p + Nm_n - M(N, Z)$

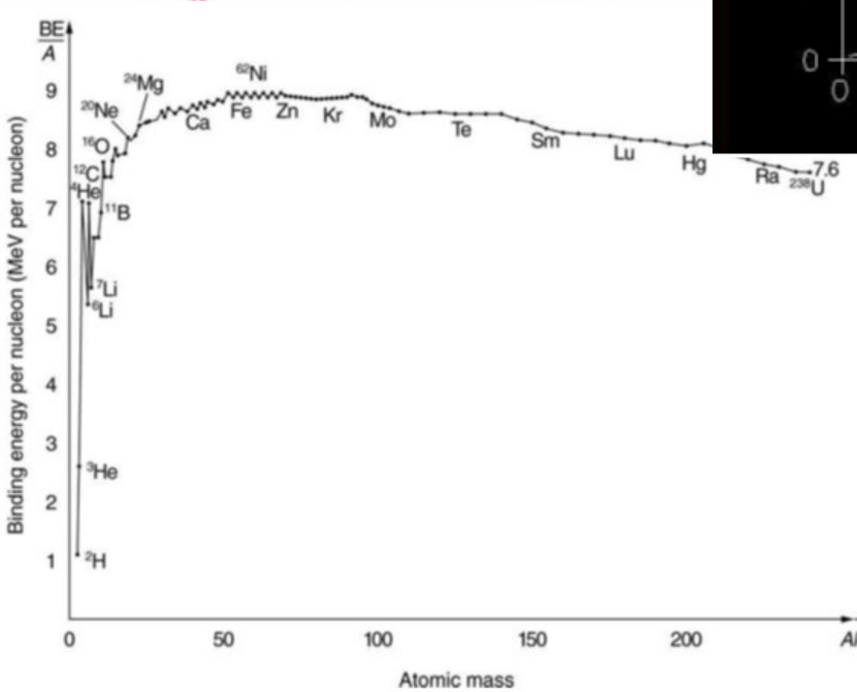
e^- binding removed

$B > 0$

Pics of $\frac{B^{e^-}}{Z}$ for e^- binding (for comparison)

& $\frac{B^{nuc}}{A}$ vs A ⇒ signature of strong Int.





BE shape allows energy "production" via

1. Fusion for $A < 50$
   e.g. $^3He + {}^3He \rightarrow {}^4He + 2p + 12.9\,MeV$

2. Fission for $A > 50$
   e.g. $^{238}U \rightarrow {}^{95}Sr + {}^{140}Xe + 3n + 171\,MeV$

III Nuclear Stability

251 Nuclides (fixed Z, N) are stable
(or have $\tau \gtrsim 10^{20}$ yrs $\Rightarrow \tau_{univ.} \simeq 1.4 \cdot 10^{10}$ yrs

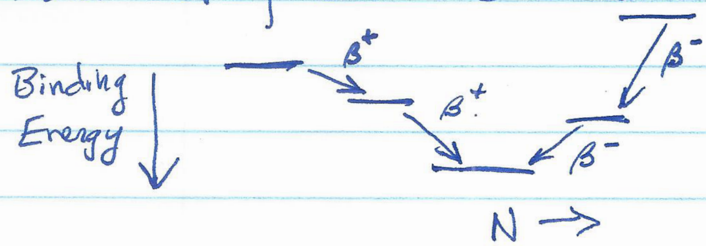
~3000 Nuclides have $\tau < 10^{20}$ yrs observed

~7000 total Nuclides predicted to exist

What are Decay Processes?

A. Weak decays

Consider set of Isobars $\equiv$ same A, but diff. N, Z

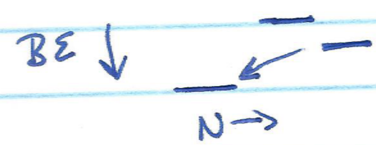


- β^- decay: $A(N,Z) \rightarrow A(N-1, Z+1) + e^- + \bar{\nu}_e$
  $(n \rightarrow p)$
- β^+ decay: $A(N,Z) \rightarrow A(N+1, Z-1) + e^+ + \nu_e$
  $(p \rightarrow n)$

- e^--capture: $A(N, Z) + e^- \to A(N+1, Z-1) + \nu_e$
  $(p \to n)$

Above account for $> 90\%$ of known unstable nuclei
but also:

- Double β^--decay possible



$$A(N, Z) \to A(N-2, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$\tau > 10^{18} \text{ yrs}$$

0ν DBD violates Lepton # conservation

↳ $A(N, Z) \to A(N-2, Z+2) + 2e^-$

↳ Beyond Standard Model

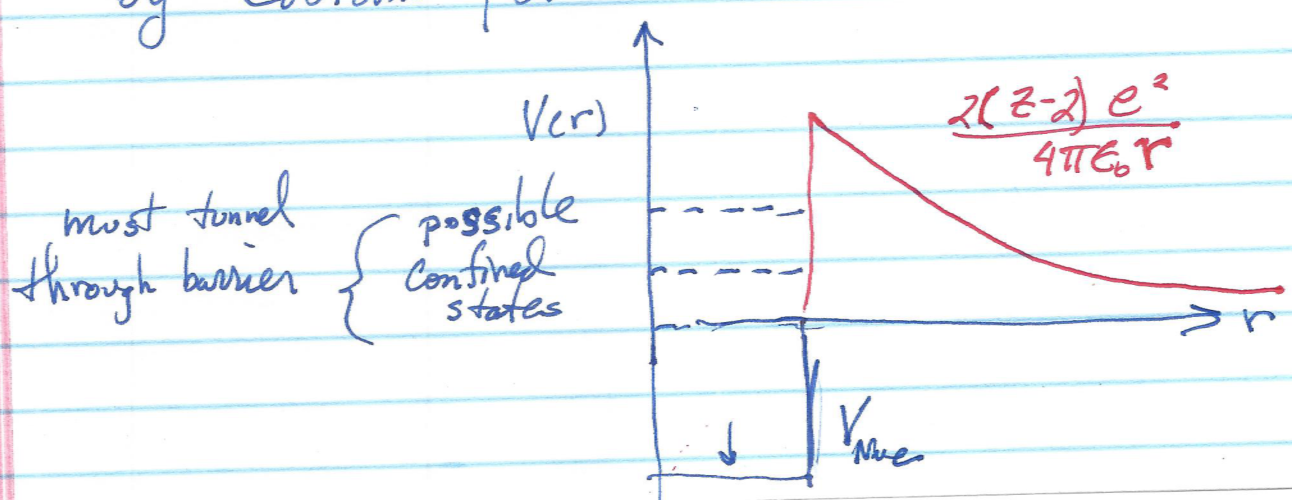
$\nu_e = \bar{\nu}_e \Rightarrow$ Majorana vs

$\nu_e \neq \bar{\nu}_e \Rightarrow$ Dirac ν

B. Strong Decays

- α-decay $\nearrow {}^4He$

↳ often viewed as pre-existing α particle confined by Coulomb Potential



tunnelling prob. can be very small:

$\tau_{^{238}U \to ^{234}Th + \alpha} = 4.5 \cdot 10^{9}$ yrs

Note:

1. α-decay primarily occurs for nuclei w $A > 56$
2. Source of 99% of terrestrial ^4He

- Spontaneous Fission

e.g. $^{252}_{98}Cf \to ^{97}_{36}Kr + ^{151}_{62}Sm + 4n$

$Z \nearrow$ other options possible

$\langle N_n \rangle = 3.7$

- Cluster decays: ^{12}C, ^{14}C, ^{24}Si observed

- 2 proton decay
  ↳ correlated pair of protons emitted

- n & p "dripping" n/p drip line...
  ↳ not considered decay since it occurs "instantly" e.g. time to cross nucleus $\sim 10^{-21}$ sec

  non-Poissonian process

Look @ Chart of Nuclei

Google: NNDC, IAEA

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IV Nuclear Excited States

Nuclei often possess many energy levels that are β-stable & particle-stable (α, n, p, ...) but not ~~γ~~ EM-stable, i.e. many bound states compared to deuteron

→ Often need 4-10 MeV excitation before p or n are unbound (aka "drip off")

→ These states can decay to gnd. state via EM transitions
- ↳ photon/γ-ray emission
- ↳ internal conversion (virtual γ kicks out inner shell e^-)
- ↳ e^+e^- decay

γ-decay Selection Rules

Multipolarity: $|J_f - J_i| \le \lambda \le J_f + J_i$

Parity Change: $\pi_i \pi_f = (-1)^\lambda \; E\lambda$

$\pi_i \pi_f = (-1)^{\lambda+1} \; M\lambda$

∴ e.g. $2^+ \to 0^+$ is E2

$1^- \to 0^+$ is M1

$0^+ \to 0^+$ is impossible ($J_\gamma = 1$) but e^+e^- is OK

$2^+ \to 1^+$ is either M1 or E2

γ-decay Rate

$\Gamma \propto E_\gamma^{2\lambda+1}$; e.g. $\dfrac{\Gamma_{E3}(E_\gamma)}{\Gamma_{E1}(E_\gamma)} \simeq 4 \cdot 10^{-11} \dfrac{E_\gamma^7}{E_\gamma^3}$

E_γ in MeV

Big Suppress. if $E_\gamma <$ MeV → Int. Conv.

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Weird States
Long-lived Isomers (Metastable)
^{180m}Ta $\tau > 10^{17}$ yrs

Constraints on the Decay of ^{180m}Ta

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(Majorana Collaboration)

(Received 2 June 2023; revised 15 August 2023; accepted 12 September 2023; published 11 October 2023)

^{180m}Ta is a rare nuclear isomer whose decay has never been observed. Its remarkably long lifetime surpasses the half-lives of all other known β and electron capture decays due to the large K-spin differences and small energy differences between the isomeric and lower-energy states. Detecting its decay presents a significant experimental challenge but could shed light on neutrino-induced nucleosynthesis mechanisms, the nature of dark matter, and K-spin violation. For this study, we repurposed the Majorana Demonstrator, an experimental search for the neutrinoless double-beta decay of ^{76}Ge using an array of high-purity germanium detectors, to search for the decay of ^{180m}Ta. More than 17 kg, the largest amount of tantalum metal ever used for such a search, was installed within the ultralow-background detector array. In this Letter, we present results from the first year of Ta data taking and provide an updated limit for the ^{180m}Ta half-life on the different decay channels. With new limits up to 1.5×10^{19} yr, we improved existing limits by 1–2 orders of magnitude which are the most sensitive searches for a single β and electron capture decay ever achieved. Over all channels, the decay can be excluded for $T_{1/2} < 0.29 \times 10^{18}$ yr.

DOI: 10.1103/PhysRevLett.131.152501