Intro to Nuclear Physics

but really ...

Tidbits on nuclear/particle physics
gathered from electron scattering
Human hair diameter $\sim 0.1 \text{ millimeters (mm, } 10^{-4}, \sim 0.5 \times \text{JLab beam diameter)}$

Atom diameter $\sim 0.3 \text{ nanometers (nm, } 10^{-9} \text{ m)}$ - changes across periodic table, bond type, net charge ($\pm \text{ ion})$... [2018.0]

Nucleus diameter $\sim 1.8 \text{ (H) - 12 (U) femtometers (fm, } 10^{-15} \text{ m, also called a } \text{fermi})$

$\Rightarrow \text{ Atom } \div \text{ Nucleus } \sim 50000$ for a 6 fm nucleus

$\sim \text{ football field length (360')} \div \text{ thickness of nickel coin (0.077'')}$

How do we “see” the nucleus arrangement ..? 

- Smash two of them together and see what comes out ..!? - yes, but it is like determining the original shapes of two glasses out of the fragments.

- Can we do some sort of “precision surgery”? - yes, use electrons to measure the charge and current distributions of a nucleus [1948.0]. $e^-$ interact electromagnetically only and show no structure so far.
Becquerel [2018.2] had shown that the fast particles of $\beta$ decay were the electrons of Thompson [2018.1].

Einstein had introduced his special theory of relativity [2018.3] to describe object motion when $v \rightarrow c$

Stern-Gerlach had shown that the orbital angular momentum of atomic electrons (Silver atoms) was quantized as expected from the “old” quantum theory of Bohr. ([2009.0], Chapter 6)

Uhlenbeck and Goudsmit came to the $1/2$ electron spin by analyzing the hydrogen atomic spectra [1971.0]

The calculated (Schrodinger eq.) and measured ([1927.0]) magnetic moment of hydrogen in the ground state did not match. Pauli fixed the problem “by hand” (the 3 Pauli matrices). Dirac introduced the relativistic wave equation for spin $1/2$ massive particles like the electron [2018.4]
Mott calculated the differential cross section (an area) per unit of solid angle (steradian, [2018.5]) for elastic scattering of relativistic electrons, polarized (bunch of $e^-$ with their spin axes parallel) and unpolarized, off point atomic nuclei ([1929.0]). For unpolarized, in the lab frame:

$$\frac{d\sigma}{d\Omega} = \frac{(Z\alpha)^2 E' \cos^2(\theta/2)}{4 E^3 \sin^4(\theta/2)}$$

Energy, momentum conservation:

$$E' = \frac{M E}{M+2 E \sin^2(\theta/2)}$$

$$p' \sin(\theta) + p_N \sin(\phi) = 0$$

$$\alpha \sim 1/137$$ - fine structure constant [2018.6].

We have neglected $m_e^2$ terms ($0.5^2 \ll 938^2$ MeV$^2$, hydrogen nucleus) ...

mass in MeV? - Yep!, “Natural units”: $c = \hbar = 1$ and free use of $E = m c^2$. How do we measure a cross section experimentally? - easy:

$$\frac{d\sigma}{d\Omega} = C \frac{e_{\text{caught}}}{e_{\text{beam}} N_{\text{targ}} \Omega}$$
How do we guide the electrons to where we want them? - mostly with all types of electromagnets although in a few cases, permanent magnets and electrostatic filters are also used.

What kind of electromagnets are used at JLab? - both resistive (i.e. wound copper cable) and superconducting (i.e. Niobium-Titanium) are used. At JLab, the superconducting magnets are clustered in the experimental halls. Some of those magnets have iron poles others do not - e.g., the Hall B CLAS12 detector system has two iron free superconducting magnets (a Torus and a Solenoid)
Particle trajectory is a circle (no energy losses) - must balance Lorentz force ($\vec{F} = q \vec{v} \times \vec{B}$) and “centrifugal force” ($\vec{F}_c = -\frac{m v^2}{r} \hat{r}$):

$$m v = p = q B r$$

$$q/m = v/(B r)$$

Apparatus used by Thompson to measure the $e^- q/m$ ratio.
The Stanford Linear Accelerator Center (SLAC) End Station A: the 8, 1.6 (left) and 20 (back) GeV spectrometers.

See [1982.0] for further details on the design of beam transports and spectrometers.
As the $e^-$ energy is increased, its de Broglie wavelength ($\lambda = h/p$) becomes smaller $\Rightarrow$ scattering will behave as Mott predicted if the nucleus is indeed a point, and different otherwise.

If the nucleus is not a point but a sphere, then ([1948.0]),

$$\sigma = \sigma_{Mott} \left| \int_V \rho(r) e^{i\mathbf{q} \cdot \mathbf{r}} \, d\tau \right|^2 \sim \sigma_{Mott} \left[ \int_0^\infty \frac{4\pi}{q} \rho(r) \sin(qr) \, r \, dr \right]^2$$

$$= \sigma_{Mott} F^2(q)$$

$F(q)$ is called the elastic “form-factor” or “structure factor”. [1956.0]
More recently (e.g. [1993.0]),

- Nucleon correlations and short distance behavior in nuclei through \((e, e' N), (e, e'2N), \ldots (e, e'mN)\) knockout reactions to high \(q^2\).
- Study the nuclear shell structure with \((e, e' N)\) reactions and Hypernucleus ([2018.11]) spectroscopy.
Study collective excitations, giant multipole resonances and highly-distorted nucleus with large spin states via \((e, e'N)\), \((e, e'2N)\) and, \((e, e'\gamma)\) reactions.

Take a pause from \(e^-\) scattering off nuclei and go back to early 1900’s and the identified radioactive decays then: alpha, beta and gamma.

- Of the three decays, the particle ejected by an alpha decay [2018.12] could easily transmute materials (it turns out an \(\alpha\) is the nucleus of helium - 2 protons and 2 neutrons) - the shorter range of the ejected projectile meant a larger cross section/strength of interaction.
- In the 1920’s, the nucleus was imagined to be made-up of protons and electrons (to explain \(\beta\)-decay).
- Chadwick discovered the neutron in 1932 by running \(\alpha\)’s into Beryllium ([1932.0], [2018.13]).
In 1933 Fermi explained $\beta$ -decay by $n \rightarrow p + e^- + \nu$, the (electron) neutrino, a new particle [2018.14] - the nucleus was made of $p$ and $n$ without $e^-$

A new force was required to keep the protons and neutrons together - Yukawa (1935) proposed the exchange of a hypothetical new particle, the meson (discovered in 1947), like the photon in quantum electrodynamics ([1935.0], [2018.15]).

The meson exchange nuclear force is no longer considered fundamental (because of QCD) but still best model to understand effective N-N potential and how nuclei are put together.
In general, unpolarized [1/2,1/2], 1-photon, elastic ([1963.0]) and inelastic ([1964.2]) scattering (note the two form-factors in each xsection),

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \left[ A(Q^2) + B(Q^2) \tan^2(\theta/2) \right]
\]

\[
\frac{d^2\sigma}{d\Omega \, dE'} = \sigma_{NS} \left[ W_2(x, Q^2) + 2 \, W_1(x, Q^2) \tan^2(\theta/2) \right]
\]

\[
\sigma_{NS} = 4 \alpha^2 (E')^2 \, Q^{-4} \, \cos^2(\theta/2)
\]
\( ^3 \)He nucleus: 2p+1n, spin 1/2

\[
A(Q^2) = \frac{F_C^2(Q^2) + \mu^2 \tau F_M^2(Q^2)}{1 + \tau} \\
B(Q^2) = 2 \tau \mu^2 F_M^2(Q^2) \\
\tau = \frac{Q^2}{4M}
\]

\( A(Q^2) \) and \( B(Q^2) \) are the “charge” and “magnetic” form factors.

\( \mu = \) magnetic moment

Separating \( F_C \) and \( F_M \) requires at least two measurements of the cross section at the same \( Q^2 \) but different \( \theta \) (Rosenbluth separation):

\[
F_{\text{exp}} = (1 + \tau) \left( \frac{d\sigma}{d\Omega} \right) \frac{1}{\left( \frac{d\sigma}{d\Omega} \right)_M} \\
= F_C^2 + \mu^2 \tau F_M^2 [1 + 2(1 + \tau) \tan^2(\theta/2)]
\]

\( \epsilon^{-1} \)
Locations of diffraction minima and strength of $F_{C,M}$ coming out of the minima sensitive to meson exchange currents (MECs) ($1 \text{ fm}^{-2} = 0.0389 \text{ GeV}^2$).
Another example: elastic electron - proton scattering

Same elastic scattering machinery than before, form factor names are a bit different,

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left[ G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2) \right] \left( \frac{1}{1 + \tau} \right)
\]

and separate \( G_E \) and \( G_M \) by changing the angle in \( \epsilon \) while keeping \( Q^2 \) constant (as before).

However, with intense, highly polarized, electron beams, we can measure the reaction: \( \vec{e}p \rightarrow e\bar{p} \) to get to \( G_E \) and \( G_M \). In the one-photon exchange,

\[
\frac{G_E}{G_M} = -\frac{P_t}{P_I} \frac{(E + E')}{2M} \tan(\theta/2)
\]

\( P_t \) and \( P_I \) are proton recoil polarization transverse (parallel) to the proton momentum.
Another example: elastic electron - proton scattering (II)

.. and one gets something completely different ?!

The difference could be explained by two photon exchange but ... not everything has fallen into place. The fall with $Q^2$ will indicate a depletion of charge towards the center of the proton.
The discovery of the neutron opened the doors to the production of many radioactive isotopes.

The first particle accelerators appeared by the 1930’s,

- Cockcroft and Walton made a positive ion accelerator (protons and $H_2^+$, $E_{\text{max}} \sim 0.7 \text{ MeV}$) and used it to disintegrate Li ([1932.1], [1932.2]).
- The Van de Graaff electrostatic accelerator
- The betatron (to accelerate electrons)
- The cyclotron

Using particles subject to the nuclear force, by the late 1950’s and early 1960’s, there was a zoo of “new” particles (actually, many did not survive the test of time and many were nuclear resonances instead of particles).

There could not be so many elementary particles - multiple ideas to organize the particle zoo were being explored.

Two particular ones: Gell-Mann ([1961.0], [1964.3]) and Zweig ([1964.1], [1980.0]) - both made use of hypothetical new particles (“quarks” for Gell-Mann, “aces” for Zweig).
No much progress until ....

Inelastic electron-proton scattering at $10^\circ$ and $7 \leq E \leq 17$ GeV. See [2014.0]

- Data taken with the SLAC 20 GeV/c spectrometer. Extended to larger angles with the 8 GeV/c spectrometer in 1972.
- Cross section ratio for $W \geq 3$ GeV is $\sim$constant $\Rightarrow$ electrons are bouncing off something that looks like a point.
- Feynman realized this quickly and called those points “partons”. Bjorken and Paschos worked out the machinery [1969.1]
Quarks carry more quantum numbers that spin and electric charge - e.g. the strange quark has strangeness quantum number $+1$. More importantly, they carry a “color charge” responsible for the strong force holding them together.

There are 3 color charges: red, blue and green - the opposite color charges are anti-red, anti-blue and anti-green (like the opposite of the $+$ electrical charge is $-$ and vice versa)

There are nine possible mediators of the color force, each carrying a color-anticolor combination - these are the gluons.

Reminder - in the electromagnetic case there is only one carrier, the photon, which carries no charge. In Quantum Electrodynamics (QED) $\gamma - \gamma$ coupling only possible in the presence of very high fields to create virtual $e^-$, $e^+$ pairs and couple through them - theory is linear. Gluons, because they carry color, couple to each other (besides quarks) - theory is non-linear.
• The theory that describes the color interaction is called Quantum Chromodynamics.

• Single quarks have not been found (there have been many searches...) - we require that states have to be singlets - i.e. no net color like \((r\bar{r} + b\bar{b} + g\bar{g})/\sqrt{3}\).

• Particles made up of quarks (like \(p\), \(n\) and \(\pi\)-mesons) are called hadrons - they are subject to the strong force. Leptons do not carry any color force.

• ..but, much work, many puzzling questions remain - e.g.,
  - QCD breaks CP but none has been detected - the “strong CP” puzzle. A possible solution: a new particle (the Axion) - not found so far. The neutron would have an electric dipole moment (charge separation).
  - We are still working on showing the theory actually confines - e.g. creates a proton.
Examples,

- Invariance under space translations $\Rightarrow$ conservation of linear momentum.
- Invariance under time translations $\Rightarrow$ conservation of energy.
- Invariance under rotations $\Rightarrow$ conservation of angular momentum.
- Gauge invariance of the electromagnetic field $\Rightarrow$ conservation of electric charge.

The above can be put on solid “theoretical” footing using Noether’s theorem [2018.7]. Others are “forced” on - if an invariance is obeyed in Nature, it imposes a constraint on the form of the interaction.

Consider the requirement that a system be invariant under reversal of an odd number of space coordinates (e.g. $\vec{x} \rightarrow -\vec{x}$) - i.e. under parity inversion - It turns out that both the strong and the electromagnetic interactions we have talked about are invariant under this operation!
... so, the suggestion by Lee and Yang (1956) that the weak interaction responsible for $\beta$-decay [2018.9] (e.g. $n \rightarrow e^- \nu_e p$) did not conserve parity was surprising but confirmed experimentally by Wu et al. (1957) [2018.8].

By the late 1960’s, Salam [1959.0] and Weinberg [1967.0] had proposed independently a gauge theory [2018.17] that could unify the weak and electromagnetic interactions.

These ideas required three new bosons to act as the mediators of the weak force and the existence of a new a neutral current interaction. The neutral current was observed in the Gargamelle bubble chamber at CERN [1973.0] ($\nu_\mu/\bar{\nu}_\mu + N \rightarrow \nu_\mu/\bar{\nu}_\mu + \text{hadrons}$)

It had been suggested by Zel’dovich in 1957 that if a neutral component of the weak decay existed, parity violating effects in electron scattering and in atomic spectra may be observable.
SLAC experiment [1978.0]
\[ e^- + d \rightarrow (e^-)' + X \]
\[ 16.2 \leq E \leq 22.2 \text{ GeV, } \theta = 4^\circ \]
\[ 1 < Q^2 < 2 \ (\text{GeV/c})^2 \]
Asym = \(10^{-4}Q^2\)

Asymmetry produced by interference between \(\gamma\) and \(Z\) exchange (both neutral). Note GaAs to produce polarized \(e^-\) - precursor to the polarized JLab gun. Well established theory now - use it, for example, to measure the neutron skin of nuclei, important for astrophysics.
Thanks for your time ......


References II


References III


[http://inspirehep.net/record/187522/files/slac-r-075.pdf].

[https://dx.doi.org/10.1016/0375-9474(93)90630-G].


[https://physics.aps.org/articles/v7/81].

[https://dx.doi.org/10.1142/S0217751X14300737].


References IV