Neutrons I

I.1 Meet the neutron
I.2 Low Energy Fundamental Physics
I.3 β-decay in Nuclear Physics

Adam Holley
Tennessee Technological University

36th National Nuclear Summer School, July 2024
Indiana University, Bloomington

“The Existence of a Neutron”, J. Chadwick, 1932

The Existence of a Neutron.

By J. Chadwick, F.R.S.

(Received May 10, 1932.)

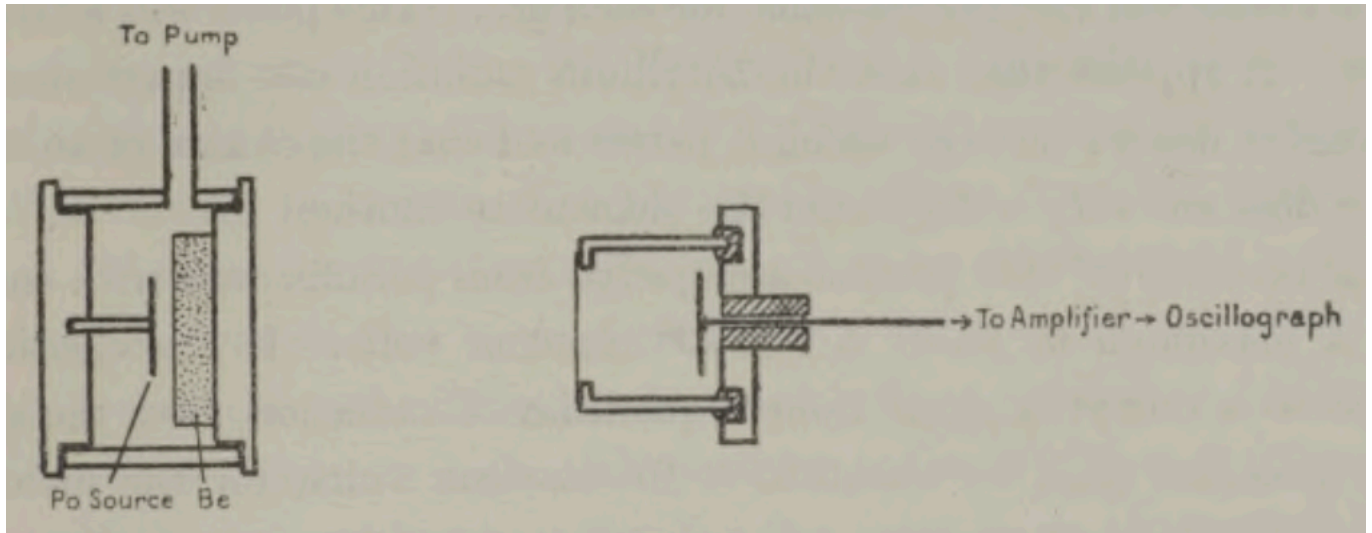


Fig. 1.

1896 Becquerel: Radioactivity
1897 Thompson: electron
1898 Rutherford: alpha rays & beta rays
1900 Villard: gamma rays
1902 Kaufmann: beta rays = electrons
1907 Royds/Rutherford: alpha rays = He ions
1913 Soddy/Fajans: isotopes
1913 Bohr Model
1914 Rutherford/Andrade: gamma rays = E&M radiation
1908 — 1913 Geiger/Marsden: Rutherford Gold Foil
1917 Rutherford: proton
1921 Harkins: “neutron” (proton/electron composite)
1930 Bothe/Giessen: penetrating radiation from α + Be/B/Li
1932 Joliot-Curie/Joliot: penetrating radion + parafin = 5 MeV protons
1932 Chadwick: neutron

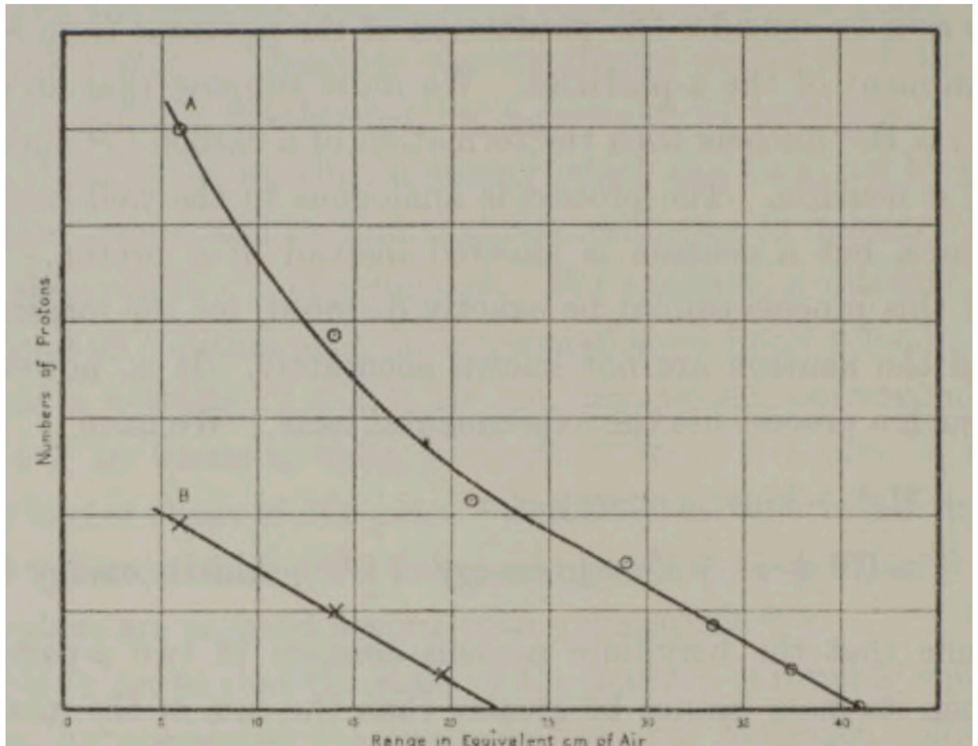
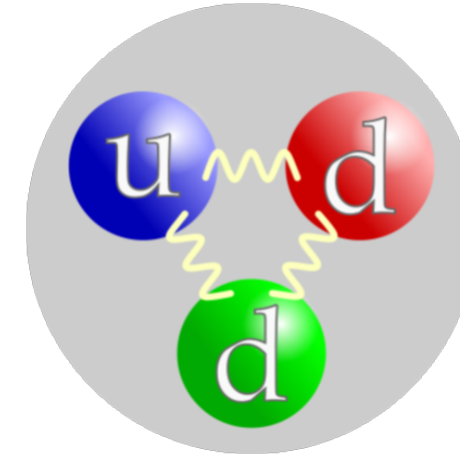


Fig. 2.

Summary.

The properties of the penetrating radiation emitted from beryllium (and boron) when bombarded by the α-particles of polonium have been examined. It is concluded that the radiation consists, not of quanta as hitherto supposed, but of neutrons, particles of mass 1, and charge 0. Evidence is given to show that the mass of the neutron is probably between 1·005 and 1·008. This suggests that the neutron consists of a proton and an electron in close combination, the binding energy being about 1 to 2 × 10^6 electron volts. From experiments on the passage of the neutrons through matter the frequency of their collisions with atomic nuclei and with electrons is discussed.



n $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

n MASS (MeV)

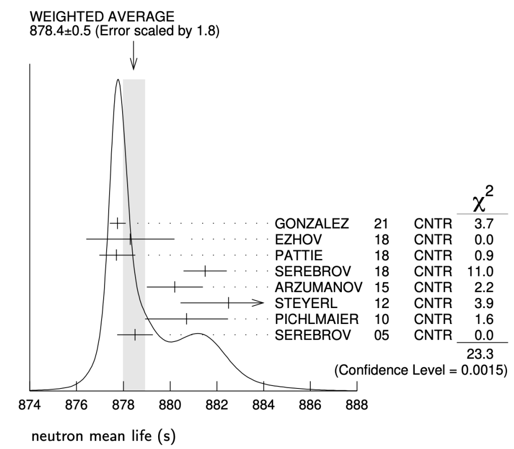
VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
939.56542052±0.00000054	TIESINGA	21	RVUE	2018 CODATA value

$m_n - m_p$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
1.29333236±0.00000046	[1] TIESINGA	21	RVUE	2018 CODATA value

n MEAN LIFE

VALUE (s)	DOCUMENT ID	TECN	COMMENT
878.4 ± 0.5 OUR AVERAGE	Error includes scale factor of 1.8. See the ideogram		



n MAGNETIC MOMENT

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−1.91304273±0.00000045	TIESINGA	21	RVUE	2018 CODATA value

n ELECTRIC DIPOLE MOMENT

VALUE (10^{-25} e cm)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.18	90	[1] ABEL	20	MRS	UCN

n CHARGE

VALUE (10^{-21} e)
− 0.2± 0.8 OUR AVERAGE

LIMIT ON $n\bar{n}$ OSCILLATIONS

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
$>4.7 \times 10^8$	90	[1] ABE	21	CNTR	n bound in oxygen
$>8.6 \times 10^7$	90	BALDO-...	94	CNTR	Reactor (free) neutrons

LIMIT ON nn' OSCILLATIONS

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>352	95	[1] ABEL	21	CNTR	UCN, scan of B field
>448	90	SEREBROV	09A	CNTR	Assumes $B' < 100$ nT

n $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

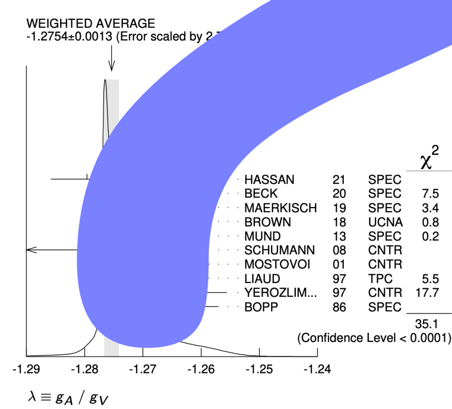
n DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p e^- \overline{\nu}_e$		100 %	
Γ_2	$p e^- \overline{\nu}_e \gamma$	[a]	$(9.2 \pm 0.7) \times 10^{-3}$	
Γ_3	hydrogen-atom $\overline{\nu}_e$		$< 2.7 \times 10^{-3}$	95%
	...ion (Q) violating mode			
Γ_4	p...		$< 8 \times 10^{-27}$	68%
	Baryon num... iolating decay			
Γ_5	...ble			

[a] This ... is for γ energ... een 0.4 and 782 keV.

$\lambda \equiv g_A / g_V$

VALUE
−1.2754 ±0.0013 OUR AVERAGE



e^- ASYMMETRY PARAMETER A

VALUE
−0.11958±0.00021 OUR AVERAGE

$\overline{\nu}_e$ ASYMMETRY PARAMETER B

VALUE
0.9807±0.0030 OUR AVERAGE

PROTON ASYMMETRY PARAMETER C

VALUE
−0.2377±0.0010±0.0024

TRIPLE CORRELATION COEFFICIENT D

...UE (units 10^{-4})
...1.2 ± 2.0 OUR AVERAGE

e-$\overline{\nu}_e$ ANGULAR CORRELATION COEFFICIENT a

VALUE
−0.1049 ±0.0013 OUR AVERAGE

FIERZ INTERFERENCE TERM b

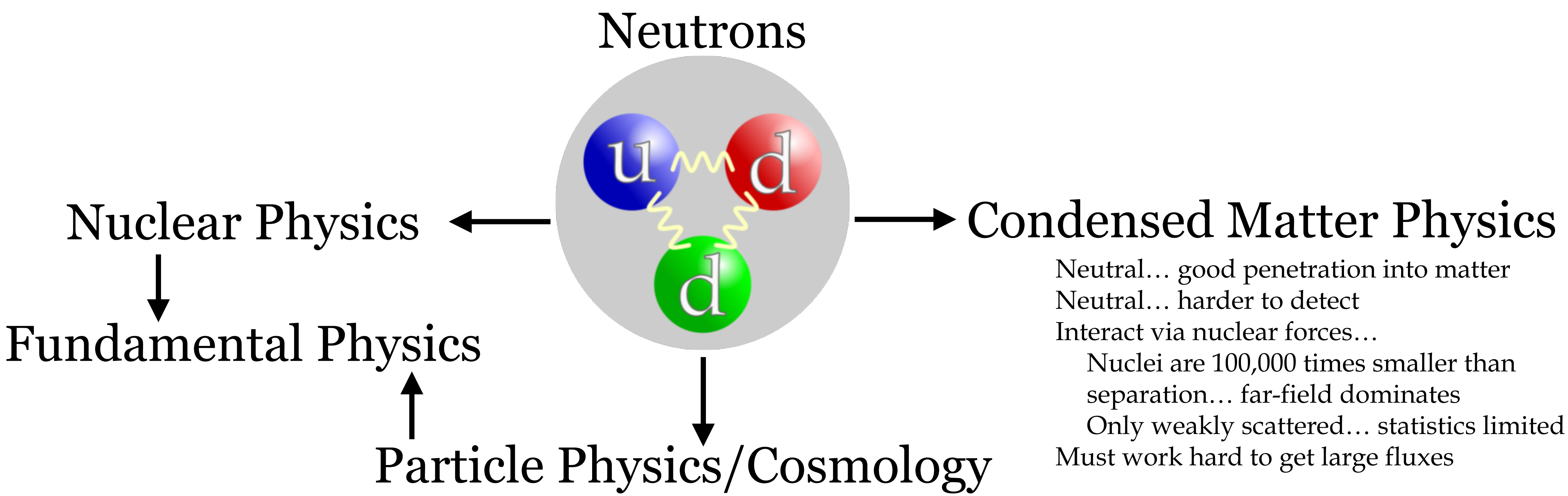
VALUE
0.017±0.020±0.003

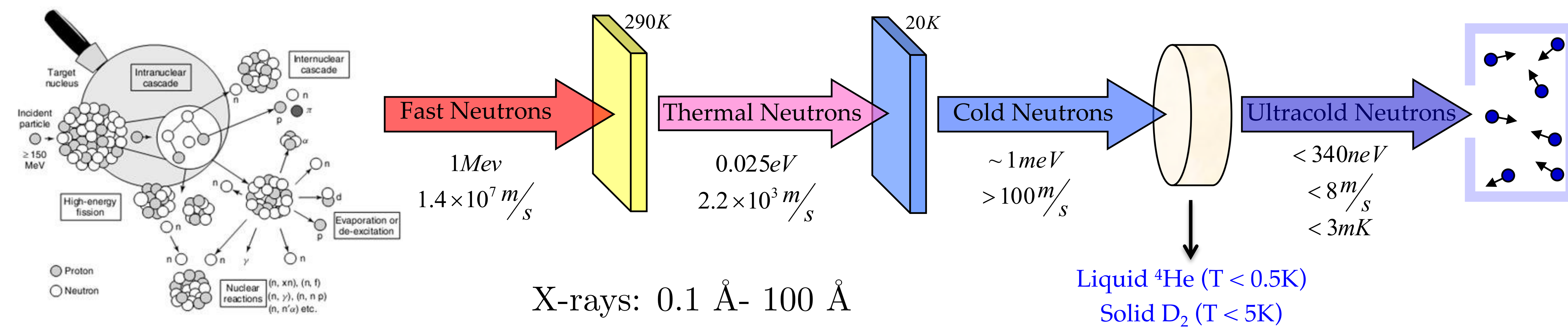
ϕ_{AV}, PHASE OF g_A RELATIVE TO g_V

VALUE (°)
180.017±0.026

TRIPLE CORRELATION COEFFICIENT R

VALUE
+0.004±0.012±0.005





X-rays: 0.1 Å- 100 Å

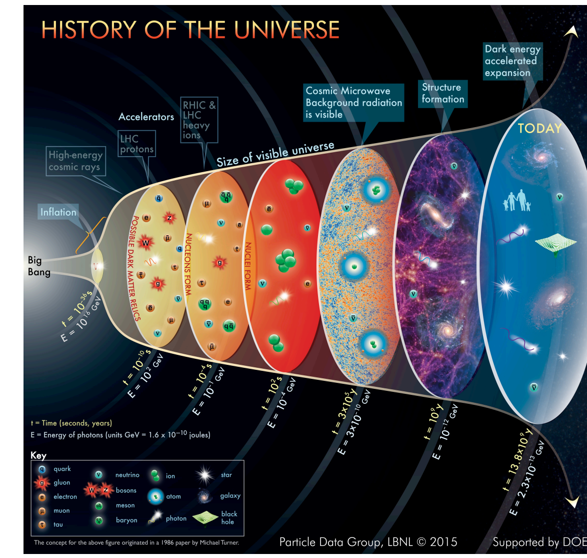
visible photons: 3900 Å- 7500 Å

Designation	Energy [eV]	Speed [m/s]	Wavelength [Å]
Fast	100×10^{3} - 10×10^{6}	4.37×10^{6} - 4.37×10^{7}	9.05×10^{-4} - 9.05×10^{-5}
Slow	$\sim 1\times10^{3}$	$\sim 4.37\times10^{5}$	$\sim 9.05\times10^{-3}$
Epithermal	~ 1	$\sim 1.38\times10^{4}$	~ 0.286
Hot	100×10^{-3} - 500×10^{-3}	4.37×10^{3} - 9.77×10^{3}	0.905 - 0.405
Thermal	10×10^{-3} - 100×10^{-3}	1.38×10^{3} - 4.37×10^{3}	2.86 - 0.905
Cold	0.1×10^{-3} - 10×10^{-3}	138 - 1.38×10^{3}	28.62 - 2.86
Ultracold	$< 400\times10^{-9}$	< 8.74	> 452.5

Fundamental Physics

Can’t predict the production of light elements in the early universe.

Big Bang Nucleosynthesis



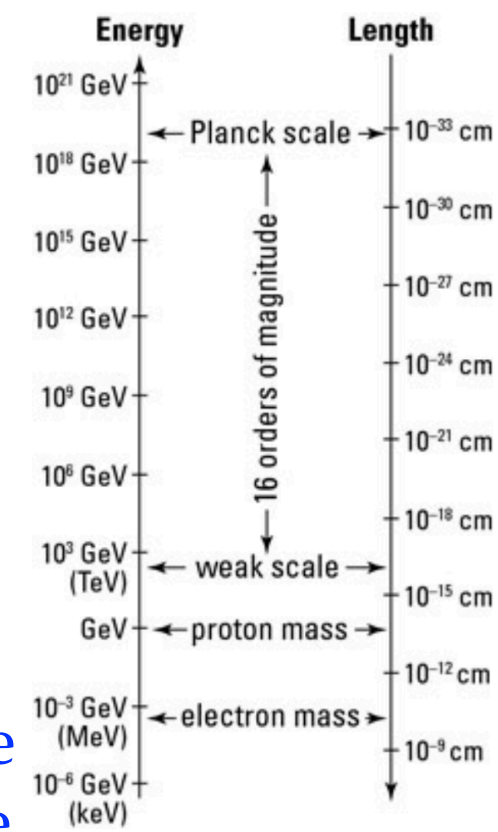
Particle Data Group at Lawrence Berkeley National Lab

Doesn’t explain why there is so little antimatter.

Baryogenesis and CP violation

Requires ad hoc inputs.

Neutrino mass
Particle masses and couplings
Parity Violation
Hierarchy problem



Chien-Yeah Seng, DNP 2021

Doesn’t explain a **lot** of what seems to make up the universe.

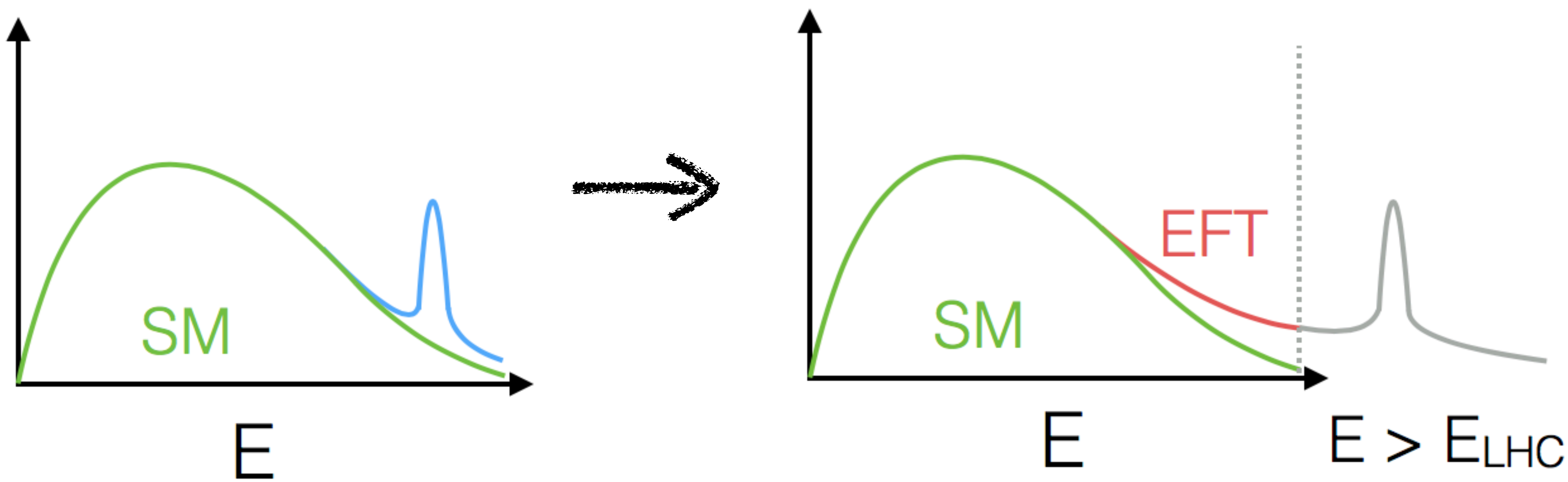
Dark Matter = 27% of the universe
Dark Energy = 68% of the universe
What we (mostly) understand = 5%

Fundamental Physics

$$\frac{1}{(p/c)^2 - M^2} \xrightarrow{M^2 \gg (p/c)^2} \frac{1}{M^2}$$

direct production — precision

We are entering a "precision era":



Ken Mimasu, 2018 HEP Summer Solstice Meeting

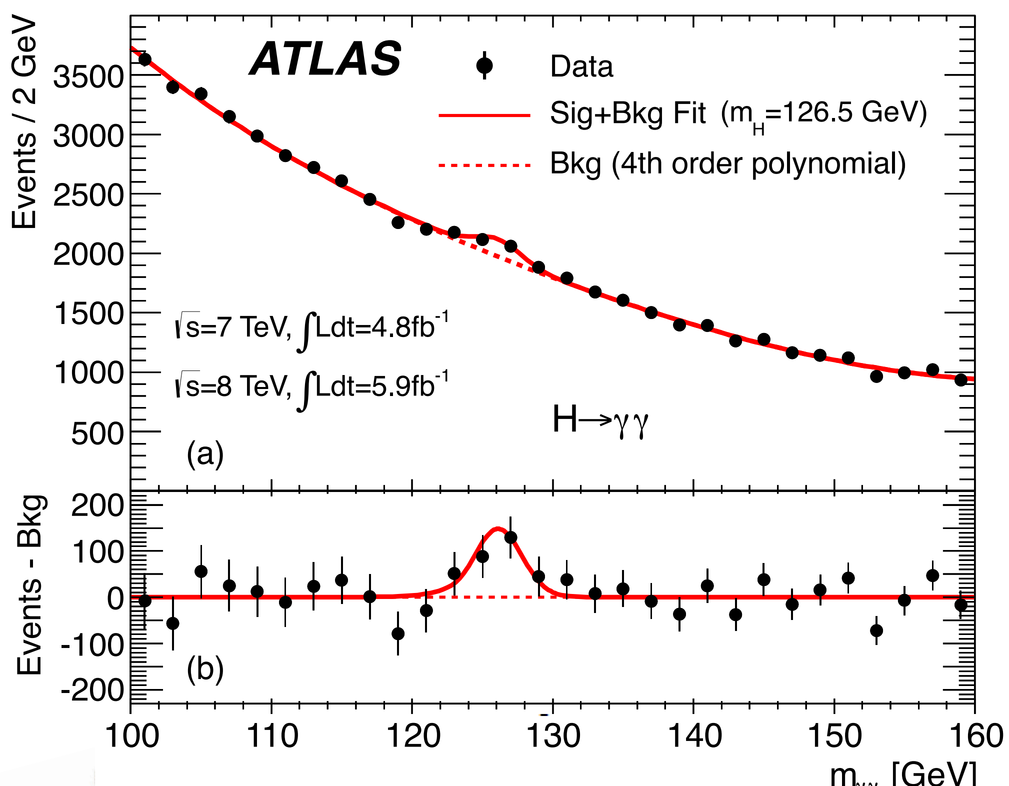
Instead of "more energy", we now want "more precision".

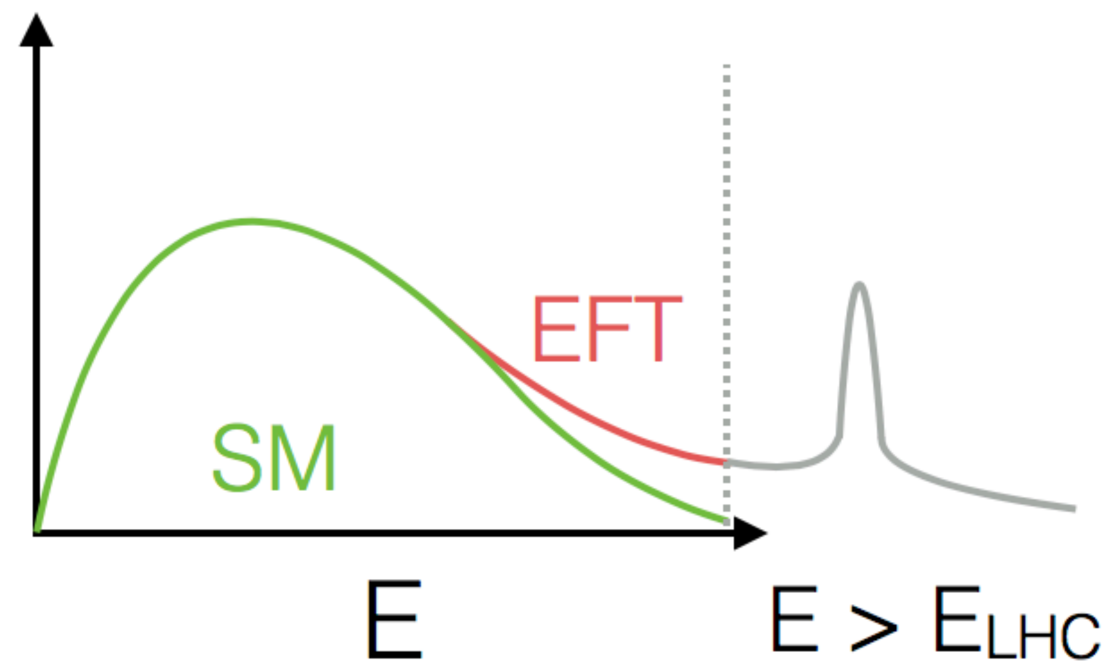
Fundamental Physics

$$\frac{1}{(p/c)^2 - M^2} \xrightarrow{M^2 \gg (p/c)^2} \frac{1}{M^2}$$

direct production → precision

We are entering a "precision era":





Ken Mimasu, 2018 HEP Summer Solstice Meeting

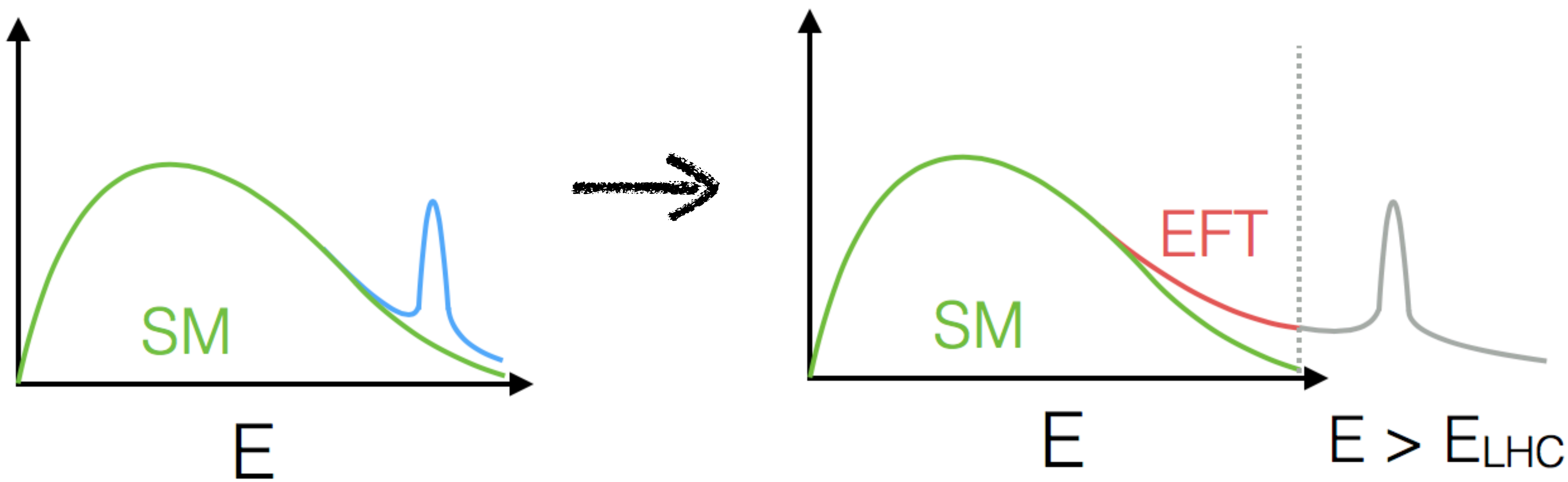
Instead of "more energy", we now want "more precision".

Fundamental Physics

$$\frac{1}{(p/c)^2 - M^2} \xrightarrow{M^2 \gg (p/c)^2} \frac{1}{M^2}$$

direct production → precision

We are entering a "precision era":



Ken Mimasu, 2018 HEP Summer Solstice Meeting

Instead of "more energy", we now want "more precision".

Fundamental Physics

$$\frac{1}{(p/c)^2 - M^2} \xrightarrow[M^2 \gg (p/c)^2]{} \frac{1}{M^2}$$

direct production — precision

A Race to find Anomalies

We hope for an experimental result that **disagrees** with the Standard Model, an **anomaly**.

We also look for **puzzles**: Two experiments that disagree, but shouldn't.

The Standard Model Right Now

$$\frac{|Experiment - Theory|}{Theory} < 0.1\%$$

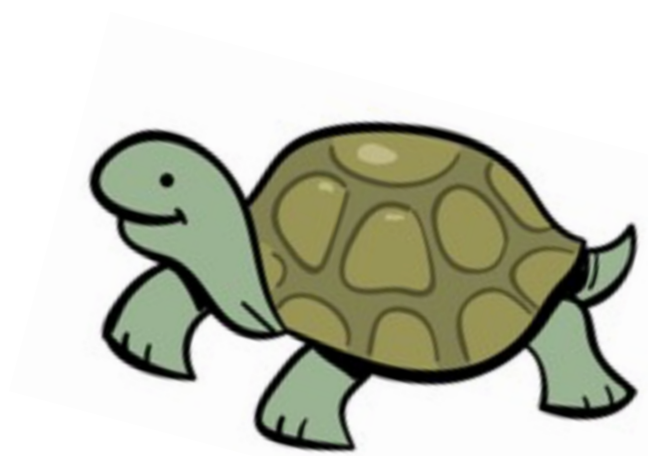
"Significance" Level

Assuming the Standard Model is correct, chance the observation is a statistical fluctuation.

$1\sigma \sim 1/10$

$3\sigma \sim 1/1000$ "Interesting"

$5\sigma \sim 1/4{,}000{,}000$ "Discovery"

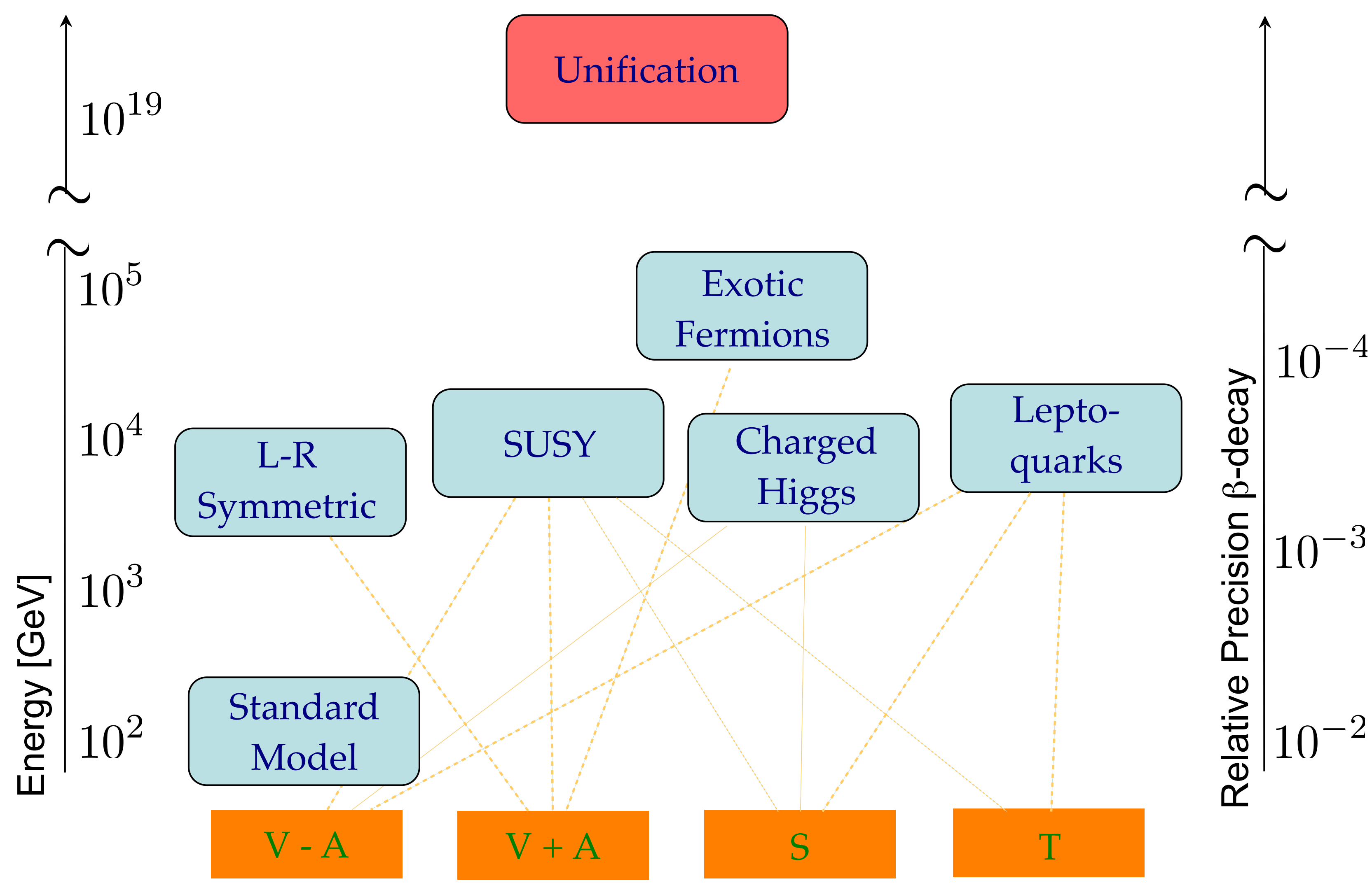


Fundamental Physics

$$\frac{1}{(p/c)^2 - M^2} \xrightarrow{M^2 \gg (p/c)^2} \frac{1}{M^2}$$

direct production — precision: model independent tests (EFT)

- Baryon Asymmetry
- B and L conservation
- CKM Unitarity
- Dark Matter
- Dark Energy
- Inflation
- Nature of the neutrino
- Neutrino mass
- Nature of the Higgs
- Nature of Gravity
- New Interactions
- QCD at Low Energy
- τ_n Problem



Adapted from Gertrud Konrad and Vincenzo Cirigliano

New physics is expected, but elusive. The field of fundamental neutron physics is characterized by an exciting assortment of experiments and techniques.

https://www.jigidi.com/user/okieclem/

Cold Neutrons

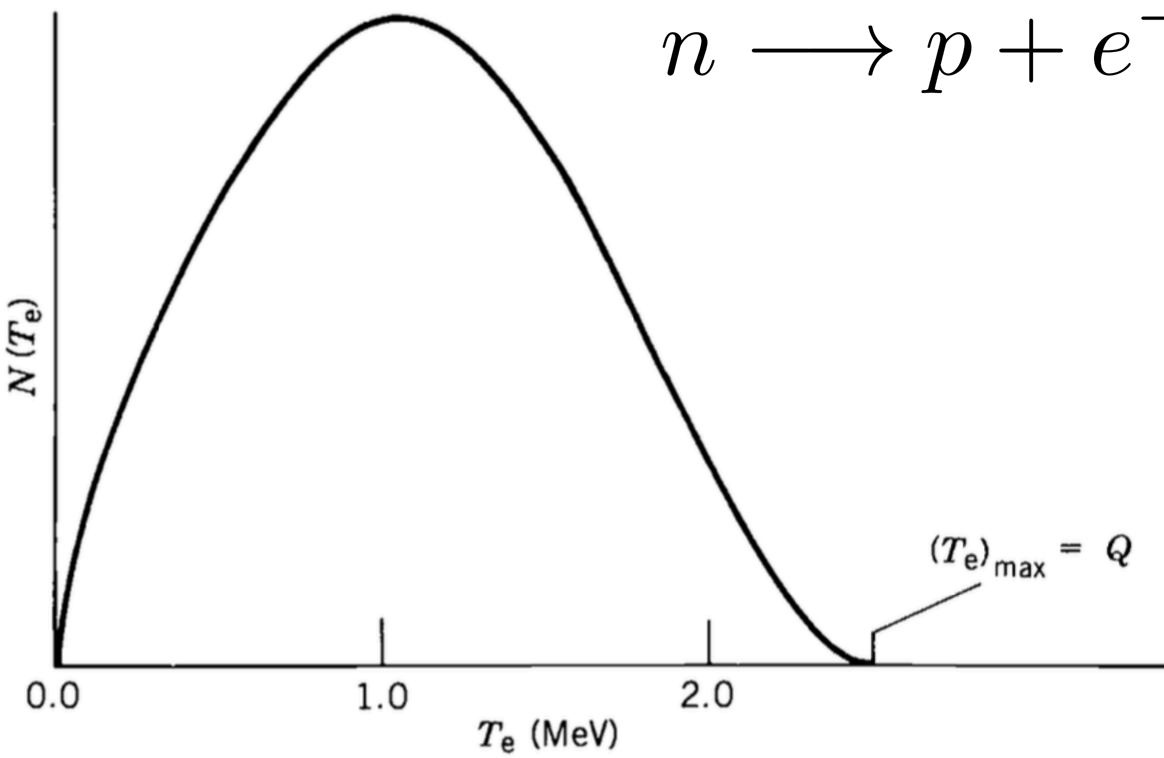
Ultracold Neutrons

Decay Experiments

Non-Decay Experiments

β-Decay "Nuclear Physics"

K. Krane, Introductory Nuclear Physics



$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$

$$m_n - m_p = 1.29 \text{ MeV}$$

$$m_e = 0.51 \text{ MeV}$$

$$m_\nu \approx 0$$

$$Q = m_n - (m_p + m_e + m_\nu) = 1.29 \text{ MeV} - 0.51 \text{ MeV} - 0 = 0.78 \text{ MeV} = 780 \text{ keV}$$

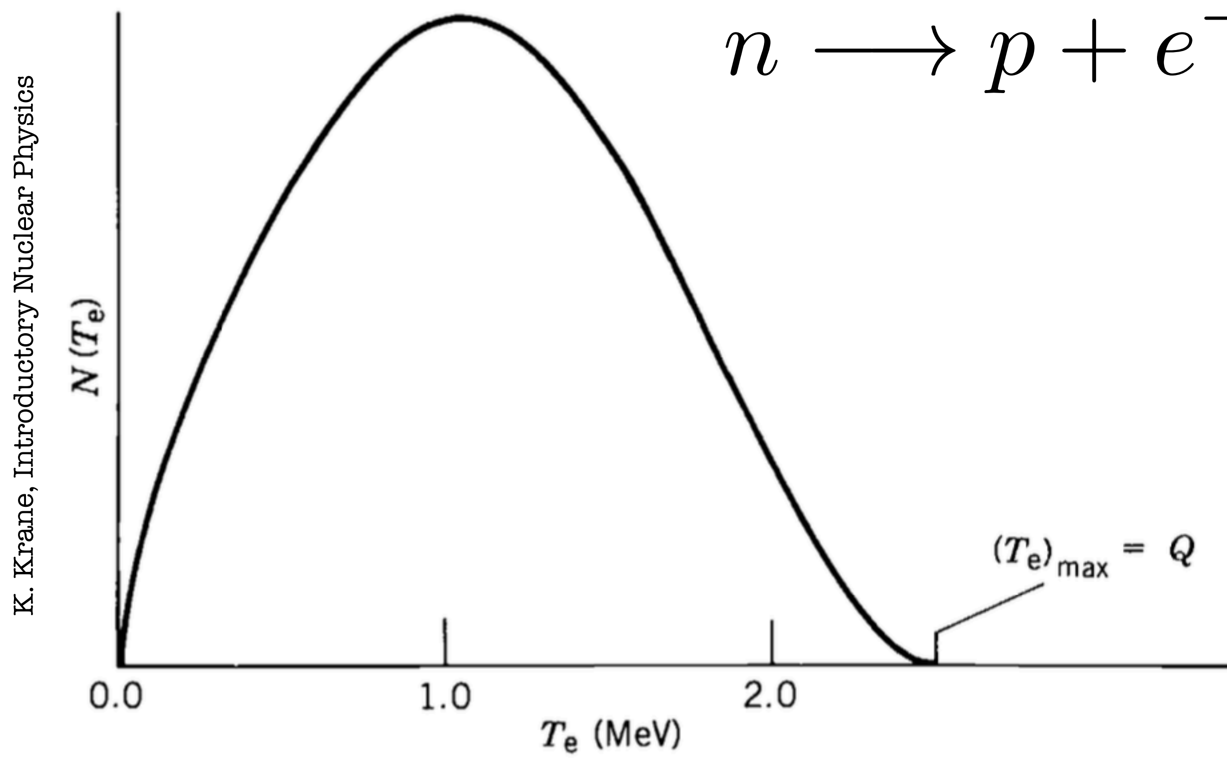
$$T_e^{\max} \approx \frac{Q}{1 + \frac{m_e}{m_p}}$$

$$T_p^{\max} = Q - T_e^{\max}$$

$$T_p^{\max} \approx Q \frac{m_e}{m_p}$$

"Recoil" Order

β-Decay "Nuclear Physics": Spectrum Shape



$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$

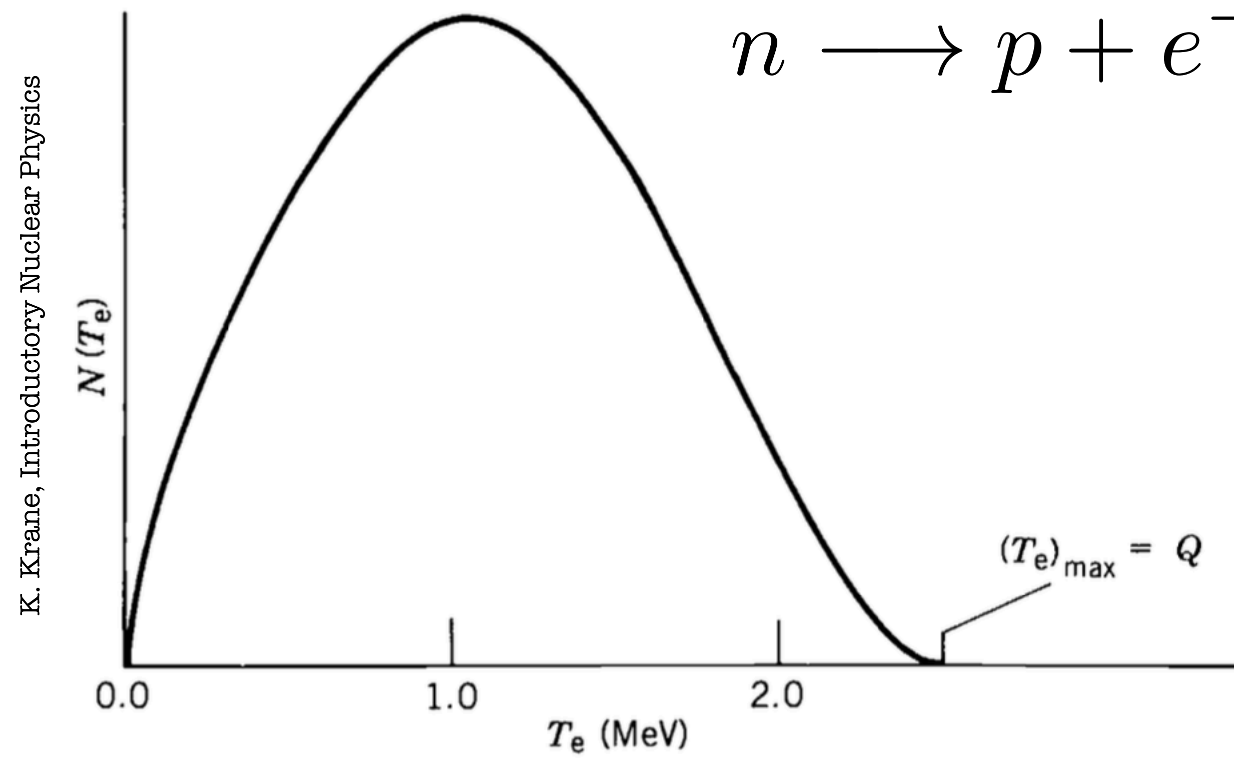
$$m_n - m_p = 1.29 \text{ MeV}$$

$$m_e = 0.51 \text{ MeV}$$

$$m_\nu \approx 0$$

$$\lambda = \frac{2\pi}{\hbar} \left| g \int \mathrm{d}V \, \left(\psi_p^* \, \phi_e^* \, \phi_\nu^*\right) \widehat{O} \, \psi_n \right|^2 \rho(E_f)$$ ← Fermi's Golden Rule

β-Decay "Nuclear Physics": Spectrum Shape



$$n \longrightarrow p + e^- + \overline{\nu}_e$$

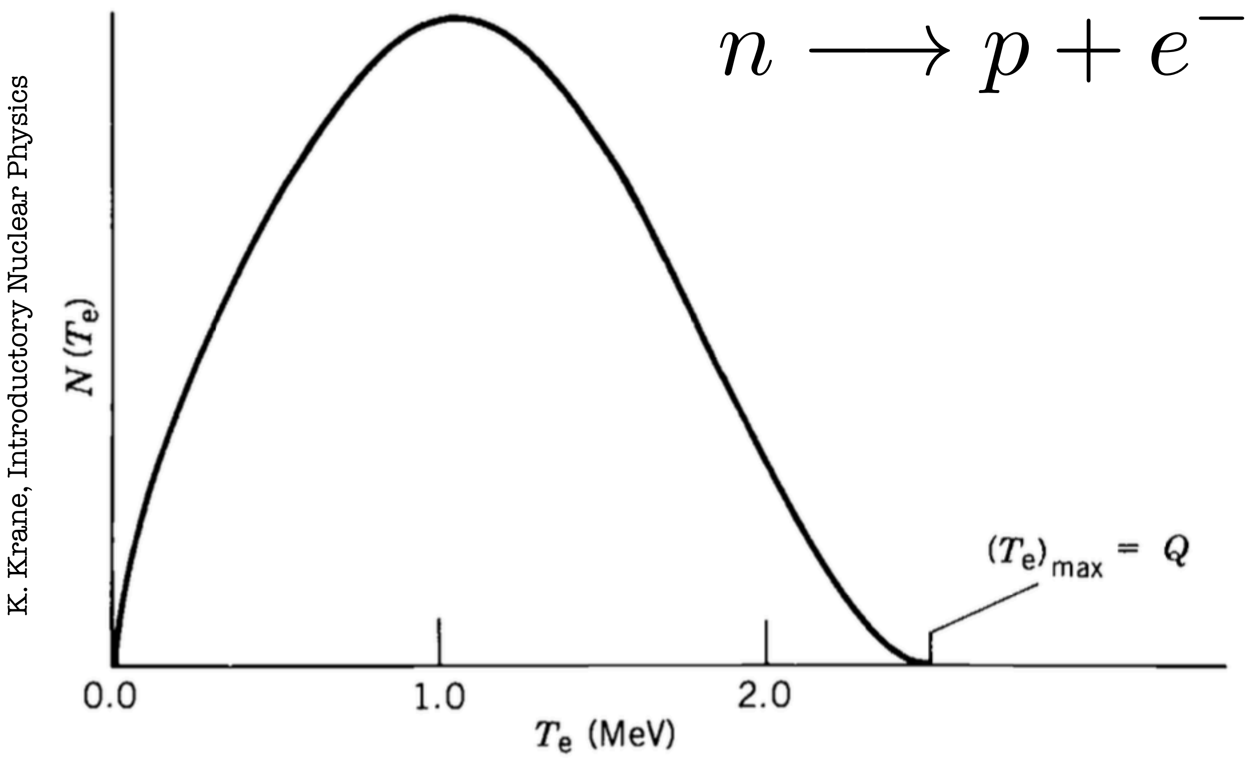
$$m_n = 939.56 \text{ MeV}$$
$$m_n - m_p = 1.29 \text{ MeV}$$
$$m_e = 0.51 \text{ MeV}$$
$$m_\nu \approx 0$$

$$\lambda = \frac{2\pi}{\hbar} \left| g \int_{\text{nuclear volume}} \mathrm{d}V \, \left(\psi_p^* \, \phi_e^* \, \phi_\nu^*\right) \widehat{O} \, \psi_n \right|^2 \rho(E_f)$$ ⟵ Fermi's Golden Rule

$$\phi_e(\vec{r}) = \frac{e^{i\frac{\vec{p}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = 1 + \frac{i\vec{p}\cdot\vec{r}}{\hbar} + \cdots$$
$$\phi_\nu(\vec{r}) = \frac{e^{i\frac{\vec{q}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = 1 + \frac{i\vec{q}\cdot\vec{r}}{\hbar} + \cdots$$

$$E^2 = p^2c^2 + m^2c^4$$
$$p = \frac{\sqrt{E^2 - (mc^2)^2}}{c} = \frac{\sqrt{(0.74 \text{ MeV})^2 - (0.511 \text{ MeV})^2}}{c} = \frac{0.54 \text{ MeV}}{c}$$
$$\frac{p}{\hbar} = \frac{0.54 \text{ MeV}}{(3\times10^8 \text{ m/s})\,(6.582\times10^{-22} \text{ MeV}\cdot\text{s})} = 0.003 \text{ fm}^{-1}$$

β-Decay "Nuclear Physics": Spectrum Shape



$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$

$$m_n - m_p = 1.29 \text{ MeV}$$

$$m_e = 0.51 \text{ MeV}$$

$$m_\nu \approx 0$$

$$\lambda = \frac{2\pi}{\hbar} \left| g \int \mathrm{d}V \; (\psi_p^* \; \phi_e^* \; \phi_\nu^*) \; \widehat{O} \; \psi_n \right|^2 \rho(E_f)$$ ← Fermi's Golden Rule

"Forbidden"

$$\phi_e(\vec{r}) = \frac{e^{i\frac{\vec{p}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = \boxed{1} + \frac{i\vec{p}\cdot\vec{r}}{\hbar} + \cdots$$

$$\phi_\nu(\vec{r}) = \frac{e^{i\frac{\vec{q}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = \boxed{1} + \frac{i\vec{q}\cdot\vec{r}}{\hbar} + \cdots$$

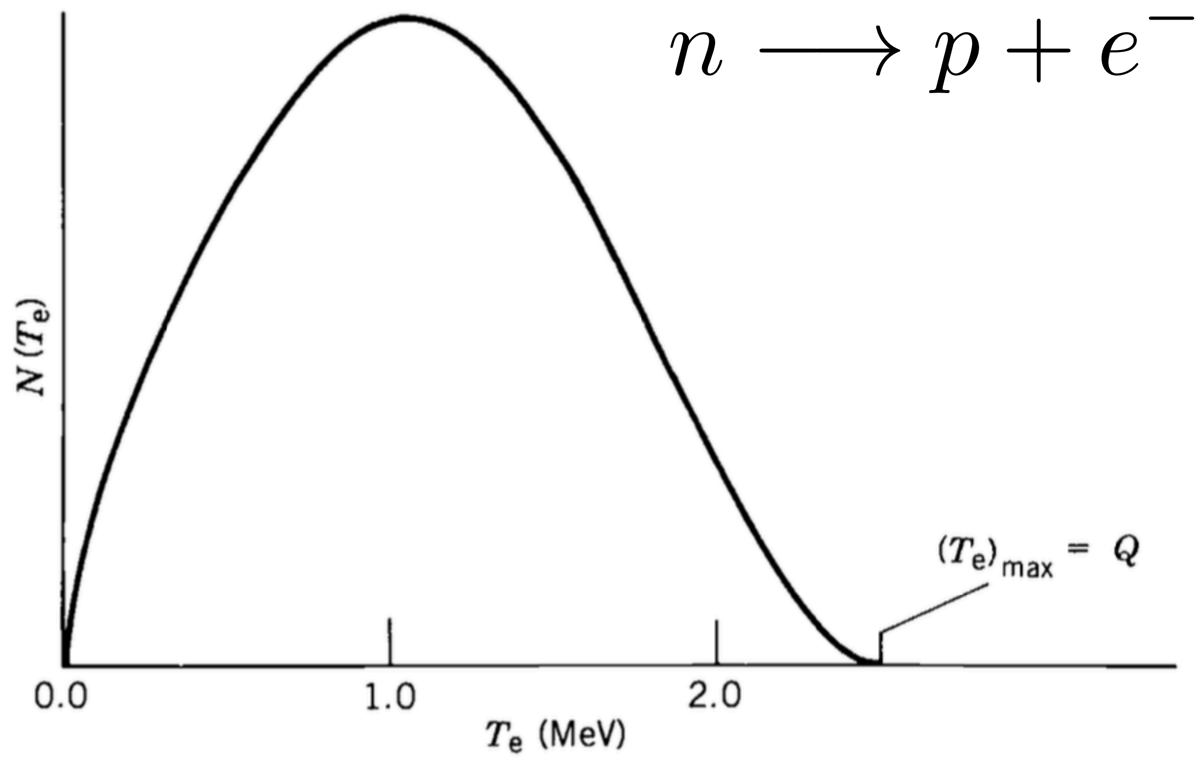
Allowed

$$E^2 = p^2c^2 + m^2c^4$$

$$p = \frac{\sqrt{E^2 - (mc^2)^2}}{c} = \frac{\sqrt{(0.74 \text{ MeV})^2 - (0.511 \text{ MeV})^2}}{c} = \frac{0.54 \text{ MeV}}{c}$$

$$\frac{p}{\hbar} = \frac{0.54 \text{ MeV}}{(3 \times 10^8 \text{ m/s})\,(6.582 \times 10^{-22} \text{ MeV}\cdot\text{s})} = 0.003 \text{ fm}^{-1}$$

β-Decay "Nuclear Physics": Spectrum Shape



K. Krane, Introductory Nuclear Physics

$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$

$$m_n - m_p = 1.29 \text{ MeV}$$

$$m_e = 0.51 \text{ MeV}$$

$$m_\nu \approx 0$$

$$\lambda = \frac{2\pi}{\hbar} \left| g \int \mathrm{d}V \; (\psi_p^* \; \phi_e^* \; \phi_\nu^*) \; \widehat{O} \; \psi_n \right|^2 \rho(E_f)$$

← Fermi's Golden Rule

"Forbidden"

$$\phi_e(\vec{r}) = \frac{e^{i\frac{\vec{p}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = \boxed{1} + \frac{i\vec{p}\cdot\vec{r}}{\hbar} + \cdots$$

$$\phi_\nu(\vec{r}) = \frac{e^{i\frac{\vec{q}\cdot\vec{r}}{\hbar}}}{L^{3/2}} = \boxed{1} + \frac{i\vec{q}\cdot\vec{r}}{\hbar} + \cdots$$

Allowed

$$E^2 = p^2c^2 + m^2c^4$$

$$p = \frac{\sqrt{E^2 - (mc^2)^2}}{c} = \frac{\sqrt{(0.74 \text{ MeV})^2 - (0.511 \text{ MeV})^2}}{c} = \frac{0.54 \text{ MeV}}{c}$$

$$\frac{p}{\hbar} = \frac{0.54 \text{ MeV}}{(3 \times 10^8 \text{ m/s})\,(6.582 \times 10^{-22} \text{ MeV} \cdot \text{s})} = 0.003 \text{ fm}^{-1}$$

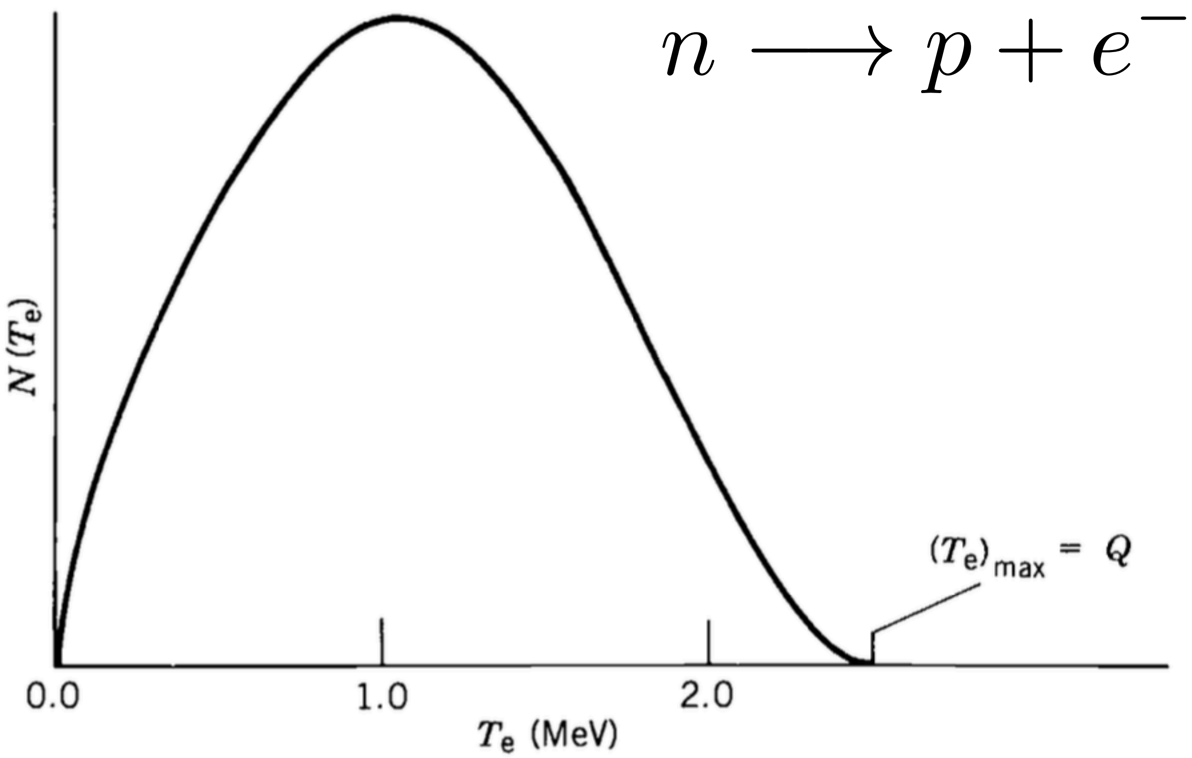
Statistical Factor from density of final states

Shape differences from (p,q) dependence. Unity in the Allowed approximation.

$$N(p) = \frac{g^2}{2\pi^3\hbar^7c^3} \left[p^2(Q - T_e)^2\right] F(Z', p) \; |M_{fi}|^2 \; S(p, q)$$

Fermi Function accounts for distortion of the spectral shape due proton's Coulomb potential.
(Use wave function for free particle in Coulomb potential for electron wave function.)

β-Decay "Nuclear Physics": Kurie Plot



K. Krane, Introductory Nuclear Physics

$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$

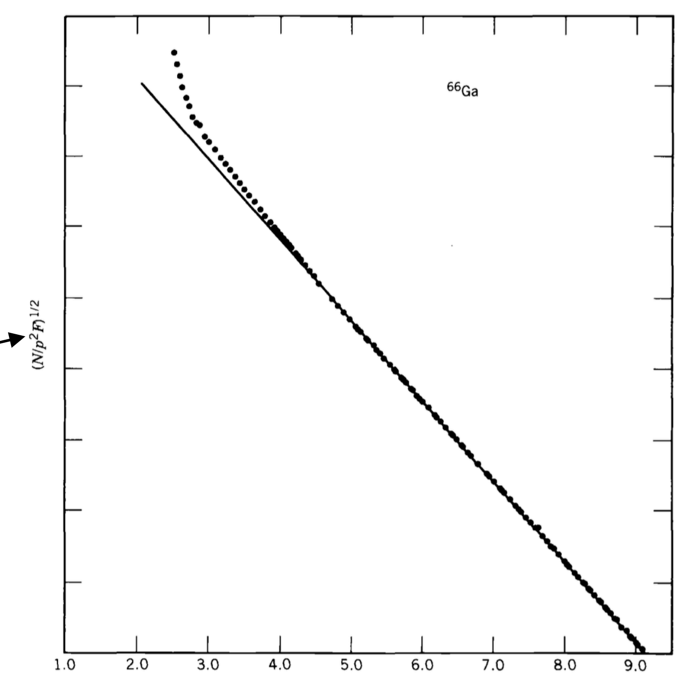
$$m_n - m_p = 1.29 \text{ MeV}$$

$$m_e = 0.51 \text{ MeV}$$

$$m_\nu \approx 0$$

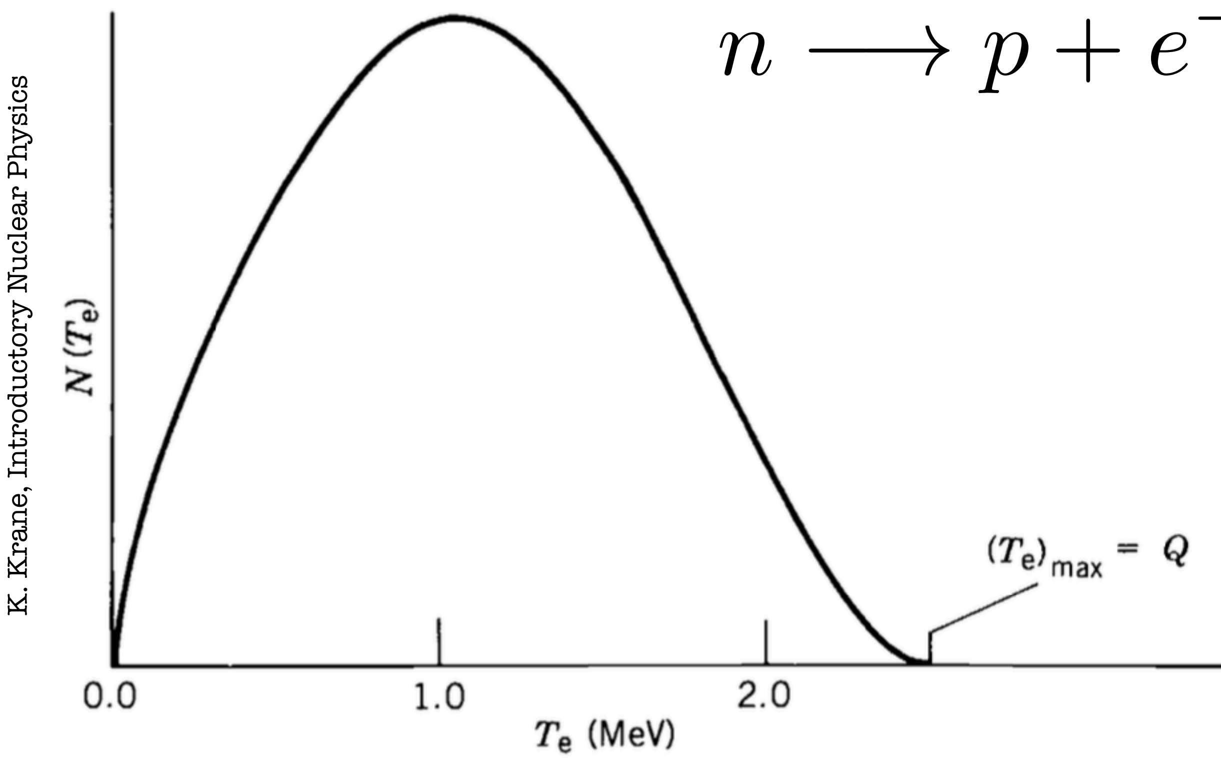
$$N(p) = \frac{g^2}{2\pi^3\hbar^7c^3}\left[p^2(Q-T_e)^2\right]F(Z',p)\,|M_{fi}|^2\,S(p,q)$$

$$(Q - T_e) \propto \frac{1}{|M_{fi}|}\sqrt{\frac{N(p)}{p^2F(Z',p)S(p,q)}}$$



K. Krane, Introductory Nuclear Physics

β-Decay "Nuclear Physics": ft Value



$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$m_n = 939.56 \text{ MeV}$$
$$m_n - m_p = 1.29 \text{ MeV}$$
$$m_e = 0.51 \text{ MeV}$$
$$m_\nu \approx 0$$

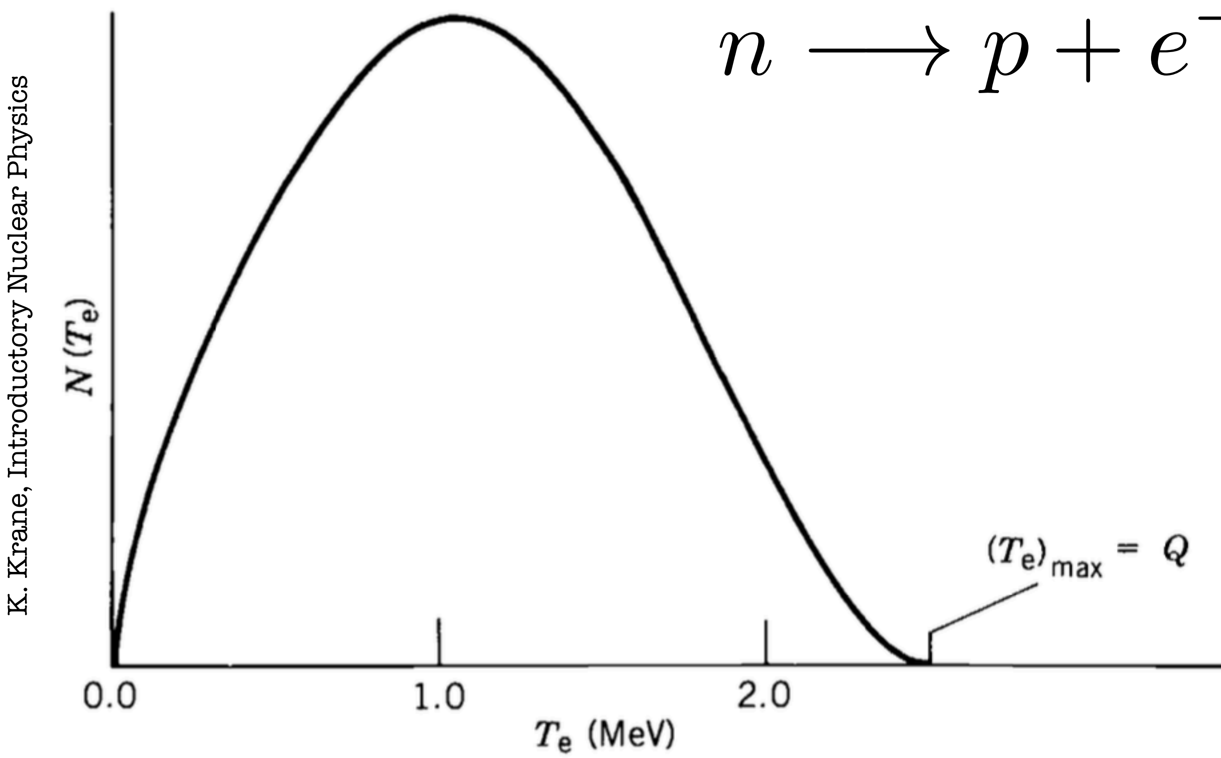
$$N(p) = \frac{g^2}{2\pi^3\hbar^7c^3}\left[p^2(Q-T_e)^2\right] F(Z',p)\,|M_{fi}|^2\,S(p,q)$$

↓ Allowed Approximation

$$\lambda = \frac{g^2|M_{fi}|^2}{2\pi^3\hbar^7c^3}\int_0^{p_{\max}} \mathrm{d}p\, F(Z',p)p^2(Q-T_e)^2$$

$$f(Z',E_e^{\max}) \equiv \frac{1}{(m_ec)^3(m_ec^2)^2}\int_0^{p_{\max}} \mathrm{d}p\, F(Z',p)p^2(E_e^{\max}-E_e)^2$$

β-Decay "Nuclear Physics": ft Value



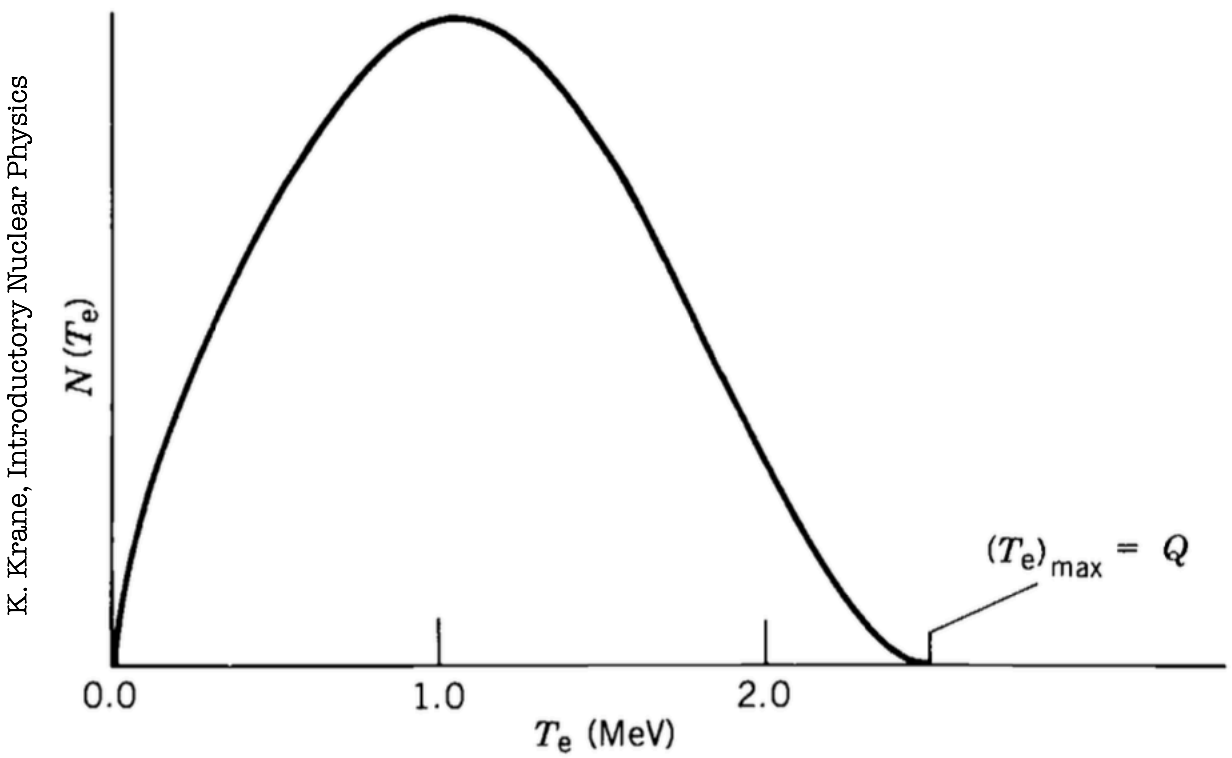
$$n \longrightarrow p + e^{-} + \overline{\nu}_e$$

$$\lambda = \frac{g^2 |M_{fi}|^2}{2\pi^3 \hbar^7 c^3} \int_0^{p_{\max}} \mathrm{d}p \; F(Z', p) p^2 (Q - T_e)^2$$

$$f(Z', E_e^{\max}) \equiv \frac{1}{(m_e c)^3 (m_e c^2)^2} \int_0^{p_{\max}} \mathrm{d}p \; F(Z', p) p^2 (E_e^{\max} - E_e)^2$$

$$f t_{1/2} \equiv 0.693 \frac{2\pi^3 \hbar^7}{g^2 m_e^5 c^4 |M_{fi}|^2}$$ "Comparative Half-Life"

β-Decay "Nuclear Physics": ft Value



$0^+ \longrightarrow 0^+$ Superallowed ft-values

Decay	ft (s)
$^{10}C \rightarrow {}^{10}B$	3100 ± 31
$^{14}O \rightarrow {}^{14}N$	3092 ± 4
$^{18}Ne \rightarrow {}^{18}F$	3084 ± 76
$^{22}Mg \rightarrow {}^{22}Na$	3014 ± 78
$^{26}Al \rightarrow {}^{26}Mg$	3081 ± 4
$^{26}Si \rightarrow {}^{26}Al$	3052 ± 51
$^{30}S \rightarrow {}^{30}P$	3120 ± 82
$^{34}Cl \rightarrow {}^{34}S$	3087 ± 9
$^{34}Ar \rightarrow {}^{34}Cl$	3101 ± 20
$^{38}K \rightarrow {}^{38}Ar$	3102 ± 8
$^{38}Ca \rightarrow {}^{38}K$	3145 ± 138
$^{42}Sc \rightarrow {}^{42}Ca$	3091 ± 7
$^{42}Ti \rightarrow {}^{42}Sc$	3275 ± 1039
$^{46}V \rightarrow {}^{46}Ti$	3082 ± 13
$^{46}Cr \rightarrow {}^{46}V$	2834 ± 657
$^{50}Mn \rightarrow {}^{50}Cr$	3086 ± 8
$^{54}Co \rightarrow {}^{54}Fe$	3091 ± 5
$^{62}Ga \rightarrow {}^{62}Zn$	2549 ± 1280

K. Krane, Introductory Nuclear Physics

$$\lambda = \frac{g^2|M_{fi}|^2}{2\pi^3\hbar^7c^3}\int_0^{p_{\max}} \mathrm{d}p\; F(Z',p)p^2(Q-T_e)^2$$

"Superallowed" => Short lifetime
(100% nuclear wave function overlap)

$$f(Z',E_e^{\max}) \equiv \frac{1}{(m_ec)^3(m_ec^2)^2}\int_0^{p_{\max}} \mathrm{d}p\; F(Z',p)p^2(E_e^{\max}-E_e)^2$$

$$ft_{1/2} \equiv 0.693\frac{2\pi^3\hbar^7}{g^2m_e^5c^4|M_{fi}|^2}$$ "Comparative Half-Life"

β-Decay "Nuclear Physics": Gamow-Teller

Lee/Yang 1956 ($\tau\theta$ puzzle)
C. S. Wu, P-violation in ^{60}Co decay, 1957

$$\widehat{P}\,\psi_p(x, y, z) = \psi(-x, -y, -z)$$

$$\widehat{P}\vec{p} = -\vec{p}$$

$$\widehat{P}\vec{B} = +\vec{B}$$

$$\widehat{P}\vec{S} = +\vec{S}$$

β-Decay "Nuclear Physics": Gamow-Teller

Lee/Yang 1956 ($\tau\theta$ puzzle)
C. S. Wu, P-violation in ^{60}Co decay, 1957

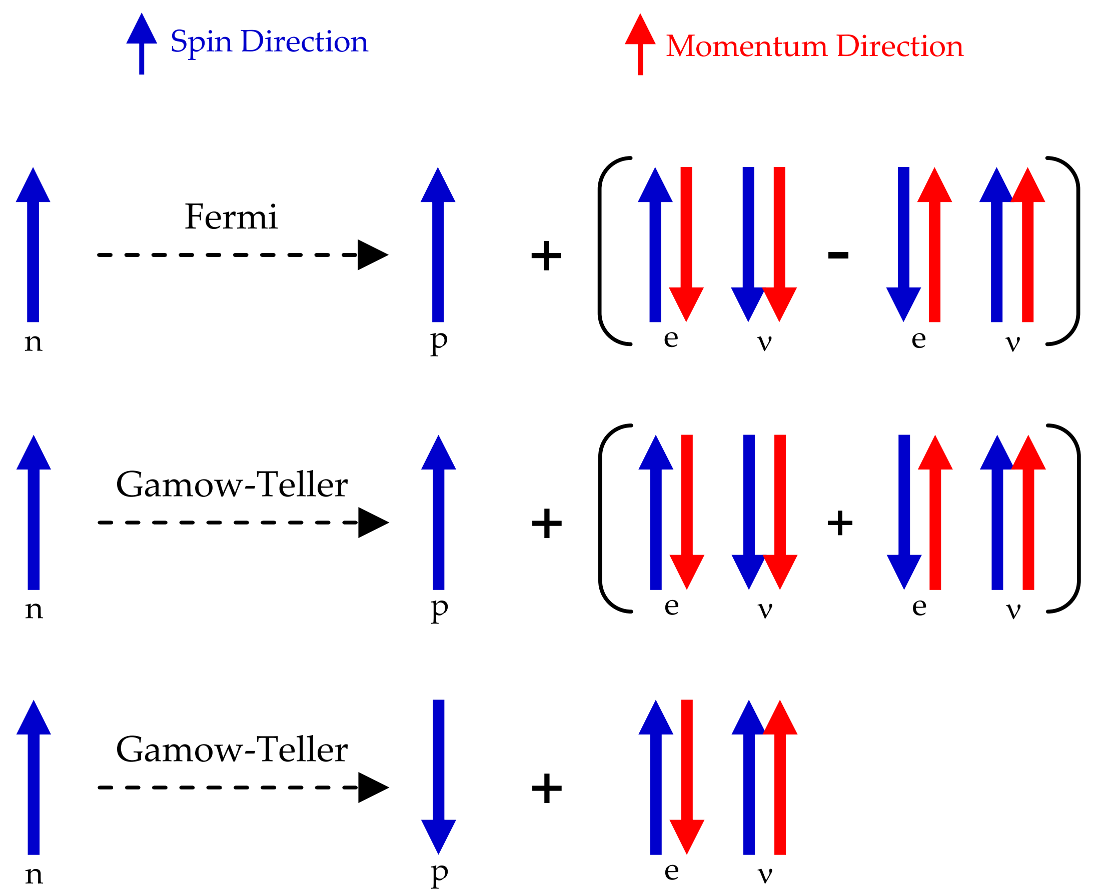
$$\widehat{P}\ \psi_p(x,y,z) = \psi(-x,-y,-z)$$

$$\widehat{P}\vec{p} = -\vec{p}$$

$$\widehat{P}\vec{B} = +\vec{B}$$

$$\widehat{P}\vec{S} = +\vec{S}$$

$$\vec{J}_n = \vec{J}_p + (\vec{L}_e + \vec{L}_\nu) + (\vec{S}_e + \vec{S}_\nu)$$



Allowed β-decay

$$\Delta I = 0$$

"Fierz Interference" quantum interference between these two affecting shape of β spectrum.

$$\Delta I = 0, 1 \quad (\text{no } 0 \rightarrow 0)$$

β-Decay "Nuclear Physics": Gamow-Teller

Lee/Yang 1956 ($\tau\theta$ puzzle)
C. S. Wu, P-violation in ^{60}Co decay, 1957

$$\vec{J}_n = \vec{J}_p + (\vec{L}_e + \vec{L}_\nu) + (\vec{S}_e + \vec{S}_\nu)$$

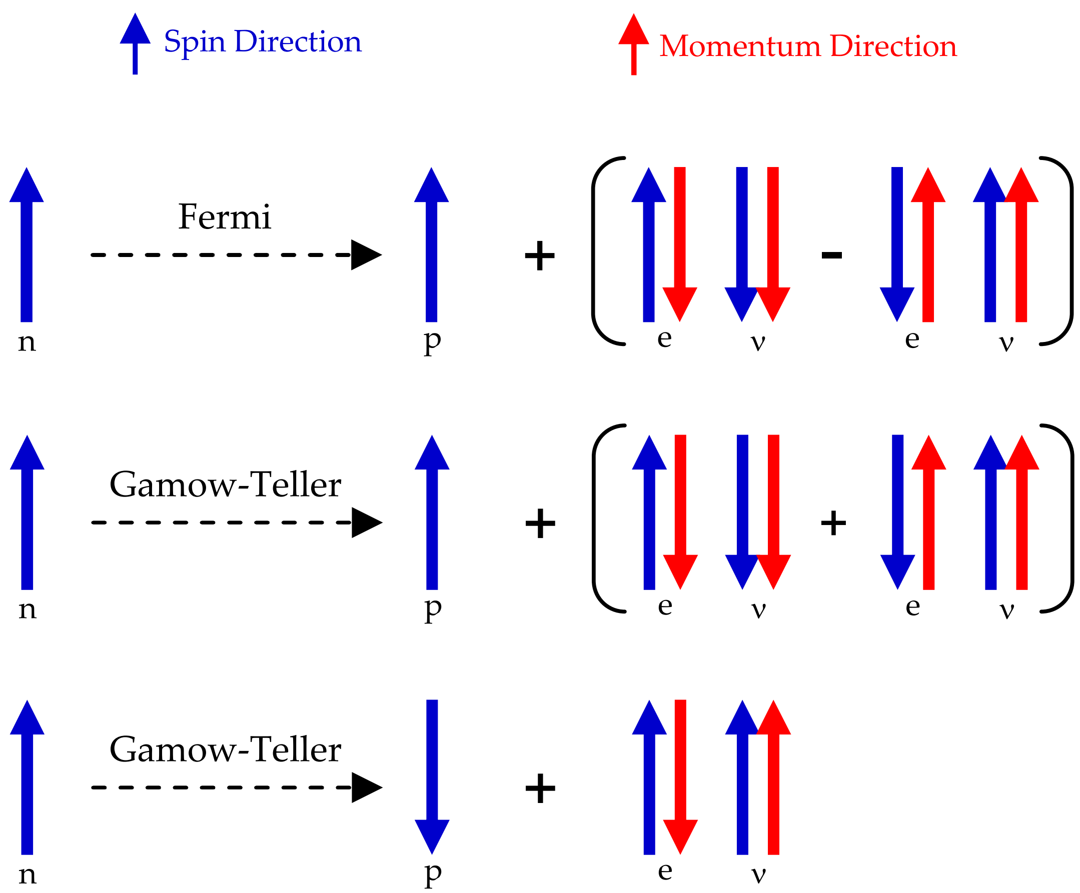
0 (Allowed Approximation)

$$\widehat{P}\,\psi_p(x,y,z) = \psi(-x,-y,-z)$$

$$\widehat{P}\vec{p} = -\vec{p}$$

$$\widehat{P}\vec{B} = +\vec{B}$$

$$\widehat{P}\vec{S} = +\vec{S}$$



Allowed β-decay

$$\Delta I = 0$$

"Fierz Interference" quantum interference between these two affecting shape of β spectrum.

$$\Delta I = 0, 1 \quad (\text{no } 0 \rightarrow 0)$$

β-Decay "Nuclear Physics": Gamow-Teller

Lee/Yang 1956 (τθ puzzle)
C. S. Wu, P-violation in ^{60}Co decay, 1957

$$\widehat{P}\,\psi_p(x,y,z) = \psi(-x,-y,-z)$$

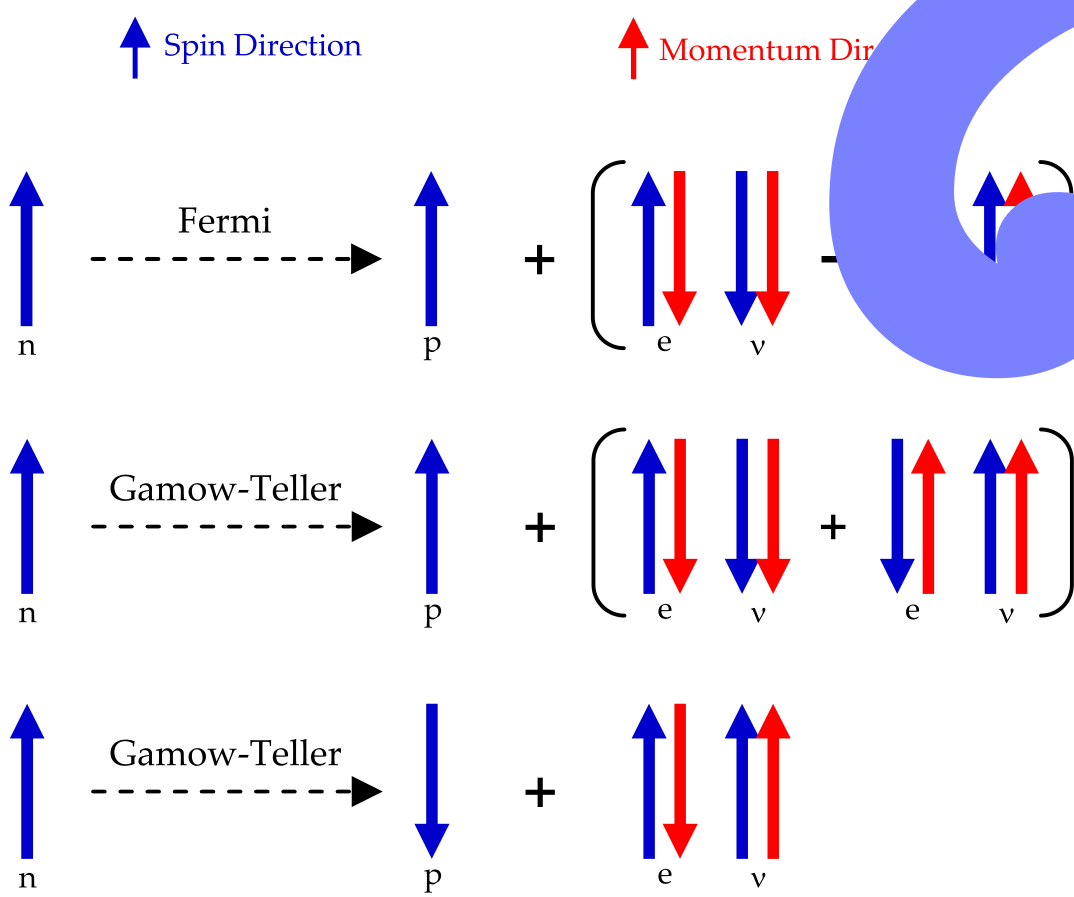
$$\widehat{P}\vec{p} = -\vec{p}$$

$$\widehat{P}\vec{B} = +\vec{B}$$

$$\widehat{P}\vec{S} = +\vec{S}$$

0 (Allowed Approximation)

$$\vec{J}_n = \vec{J}_p + (\vec{L}_e + \vec{L}_\nu) + (\vec{S}_e + \vec{S}_\nu)$$



Allow -decay

Δ 0

"Fier quantum interference between these two affecting shape of β spectrum.

$\Delta I = 0, 1$ (no 0 → 0)

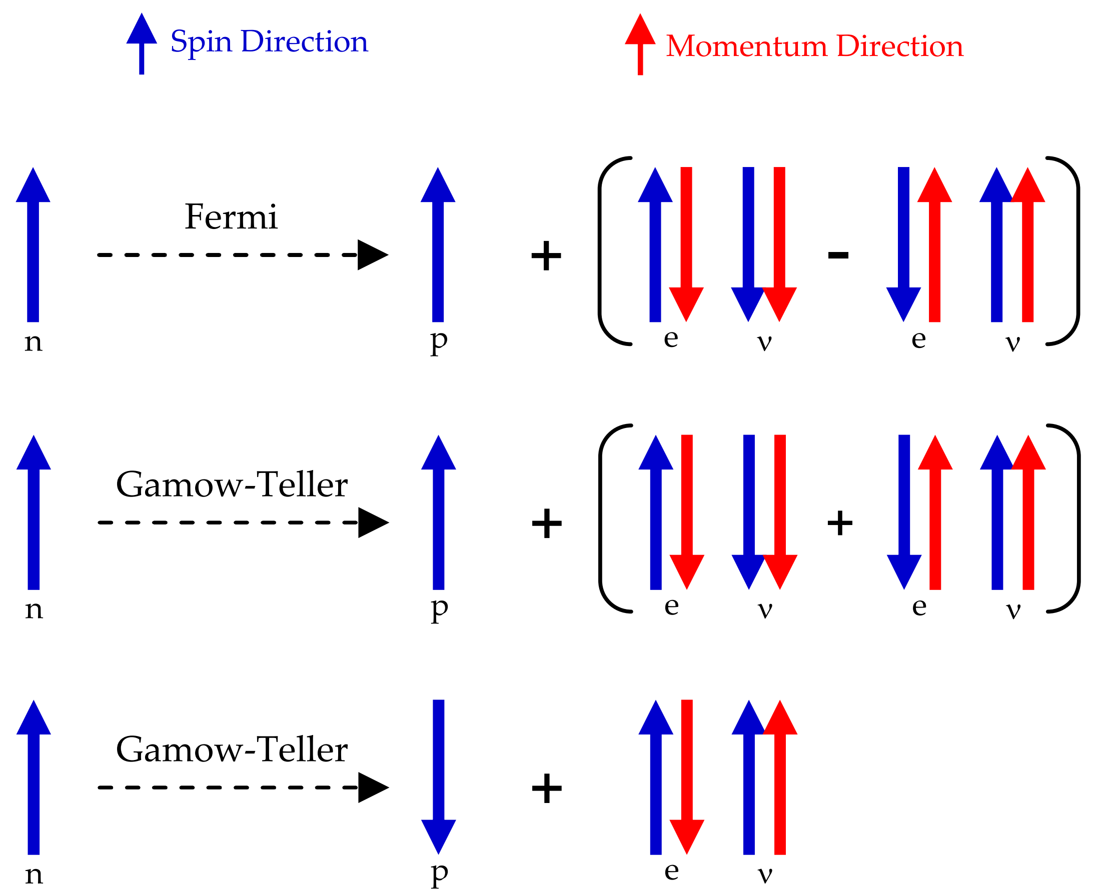
Superallowed 0+ —> 0+ is pure Fermi and has easy nuclear matrix element: $M_{if} = \sqrt{2}$
For neutron decay (a *mirror* transition) $M_{if} = 1$

Since the wave functions are the same, the isospin lowering operator is the only contribution to the nuclear matrix element. ("Isobaric Analog States")

$$I_3^{(p)} = +\frac{1}{2} \qquad I_3^{(n)} = -\frac{1}{2} \qquad \widehat{I}_\pm = \sqrt{I(I+1) - I_3(I_2 \pm 1)}$$

β-Decay "Nuclear Physics": Gamow-Teller

$$\vec{J}_n = \vec{J}_p + (\vec{L}_e + \vec{L}_\nu) + (\vec{S}_e + \vec{S}_\nu)$$



Allowed β-decay

$$\Delta I = 0$$

"Fierz Interference" quantum interference between these two affecting shape of β spectrum.

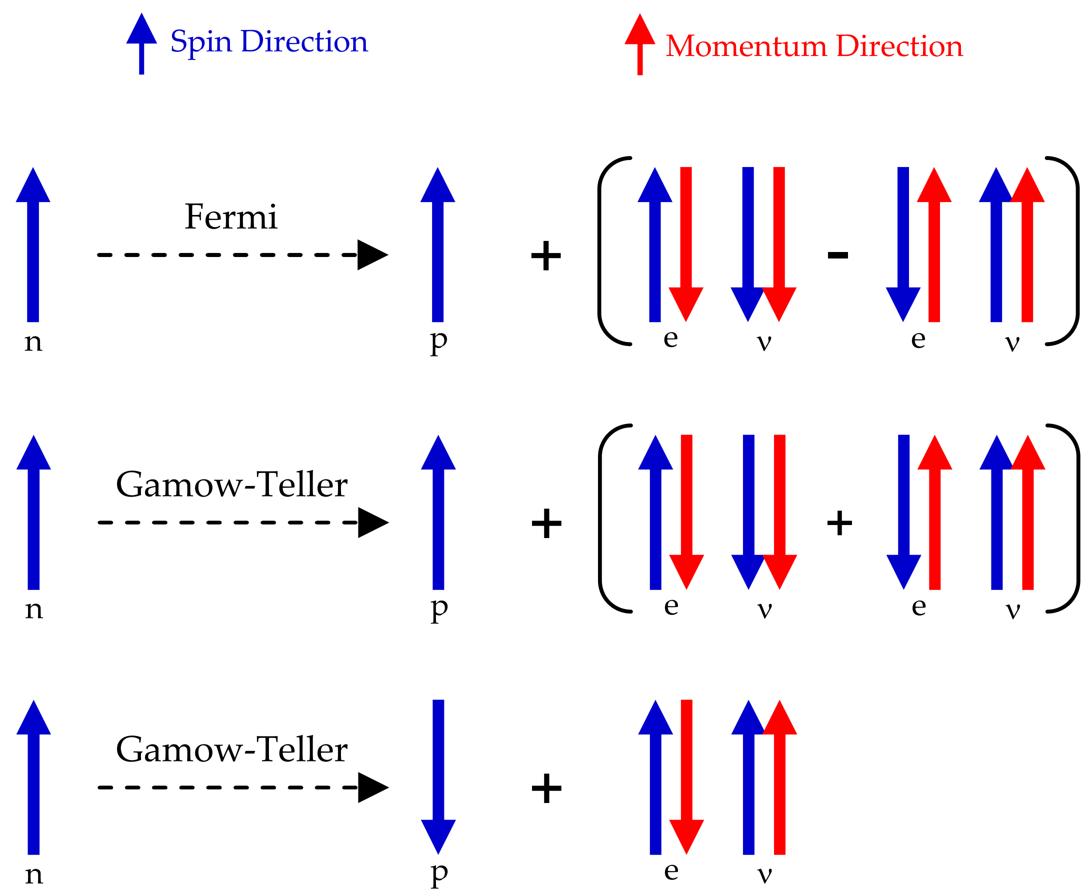
$$\Delta I = 0, 1 \quad (\text{no } 0 \rightarrow 0)$$

$$g^2 |M_{fi}|^2 \longrightarrow g_{\mathrm{F}}^2 |M_{\mathrm{F}}|^2 + g_{\mathrm{GT}}^2 |M_{\mathrm{GT}}|^2$$

determined by 0^+ —> 0^+ superallowed decays

β-Decay "Nuclear Physics": CVC

$$\vec{J}_n = \vec{J}_p + (\vec{L}_e + \vec{L}_\nu) + (\vec{S}_e + \vec{S}_\nu)$$



Allowed β-decay

$$\Delta I = 0$$

"Fierz Interference" quantum interference between these two affecting shape of β spectrum.

$$\Delta I = 0, 1 \ \ (\text{no } 0 \rightarrow 0)$$

$$g^2 |M_{fi}|^2 \longrightarrow g_{\mathrm{F}}^2 |M_{\mathrm{F}}|^2 + g_{\mathrm{GT}}^2 |M_{\mathrm{GT}}|^2$$

<u>Conserved Vector Current</u> (CVC): Fermi interaction unaffected by the nuclear environment.

$0^+ \longrightarrow 0^+$ Superallowed ft-values

Decay	*ft* (s)
$^{10}C \rightarrow {}^{10}B$	3100 ± 31
$^{14}O \rightarrow {}^{14}N$	3092 ± 4
$^{18}Ne \rightarrow {}^{18}F$	3084 ± 76
$^{22}Mg \rightarrow {}^{22}Na$	3014 ± 78
$^{26}Al \rightarrow {}^{26}Mg$	3081 ± 4
$^{26}Si \rightarrow {}^{26}Al$	3052 ± 51
$^{30}S \rightarrow {}^{30}P$	3120 ± 82
$^{34}Cl \rightarrow {}^{34}S$	3087 ± 9
$^{34}Ar \rightarrow {}^{34}Cl$	3101 ± 20
$^{38}K \rightarrow {}^{38}Ar$	3102 ± 8
$^{38}Ca \rightarrow {}^{38}K$	3145 ± 138
$^{42}Sc \rightarrow {}^{42}Ca$	3091 ± 7
$^{42}Ti \rightarrow {}^{42}Sc$	3275 ± 1039
$^{46}V \rightarrow {}^{46}Ti$	3082 ± 13
$^{46}Cr \rightarrow {}^{46}V$	2834 ± 657
$^{50}Mn \rightarrow {}^{50}Cr$	3086 ± 8
$^{54}Co \rightarrow {}^{54}Fe$	3091 ± 5
$^{62}Ga \rightarrow {}^{62}Zn$	2549 ± 1280