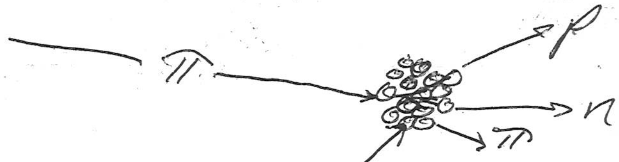
Spallation

Nuclear processes where nucleons are knocked out of the nucleus:



"intra-nuclear cascade"

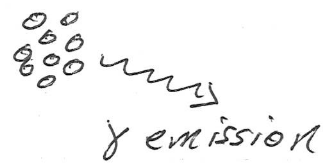
An internal series of interactions occurs.

- participating particles can escape nucleus if have sufficient energy
- composition of emitted particles

$$\frac{N_p}{N_n} \sim \frac{Z}{A-Z} \text{ of nucleus}$$

Nuclear remnant

- may be in excited state, or unstable



- fission possible for heavier nuclei

$\sigma(Z, A_S)$ maximized when $\langle A_S \rangle \sim A_T - 20$

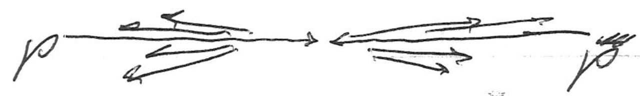
A_S: spallation product atomic weight

A_T: target nucleus atomic weight

Angular Distribution of Produced Particles

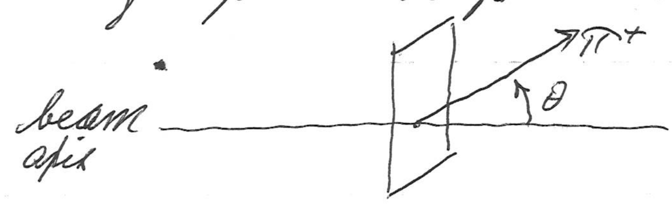
Consider interaction

- produced secondary particles tend strongly to go in beam direction in CM frame
  - carry away most of incident particle momentum



Transverse momentum

- typically around Fermi momentum (~350 MeV) for produced particles



$$p_\perp^{\pi^+} \; (= p_T^{\pi^+}) = \sqrt{p_x^{\pi^+2} + p_y^{\pi^+2}}$$

- $\langle p_T \rangle$ grows slowly with $\sqrt{s}$
- differential cross section $d\sigma/dp_T$
  - exponential fall-off for small p_T
  - increasing $\sqrt{s}$ → ~~more~~ massive virtual states
    - slower decline in $d\sigma/dp_T$ with p_T
  - true in pp, $p\bar{p}$ + e^+e^- collisions generally

Rapidity of Secondaries

A useful way to think of longitudinal momentum of secondaries in pp, pA ($p\bar{p}$ or pN) collisions

use pp collision as example

$$y = \frac{1}{2}\ln\left(\frac{E + p_{\parallel}c}{E - p_{\parallel}c}\right)$$

$$= \frac{1}{2}\ln\left(\frac{E + p_{\parallel}c}{E - p_{\parallel}c}\cdot\frac{E + p_{\parallel}c}{E + p_{\parallel}c}\right)$$

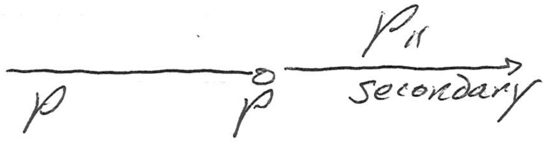
$$= \ln\left(\frac{E + p_{\parallel}c}{\sqrt{(E - p_{\parallel}c)(E + p_{\parallel}c)}}\right)$$

using $E^2 = p_{\parallel}^2c^2 + p_{\perp}^2c^2 + m_s^2c^4$

$$\boxed{y = \ln\left(\frac{E + p_{\parallel}c}{\sqrt{p_{\perp}^2c^2 + m_s^2c^4}}\right)}$$

Specific Rapidity cases

Forward case: secondary scattered in direction of incident proton



$p_{\perp} \approx 0$

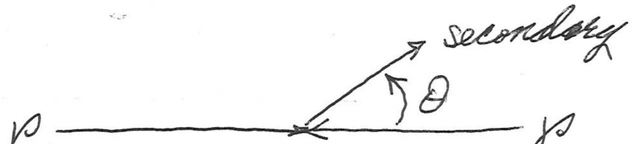
$$y_{max} = \ln\left(\frac{E + p_{\parallel} c}{m_s c^2}\right)$$

$$= \boxed{\ln(\gamma + \gamma\beta)}$$

(γ + β of incoming particle)

(a large value)

CM System:



- if there is no $p_{\parallel}$

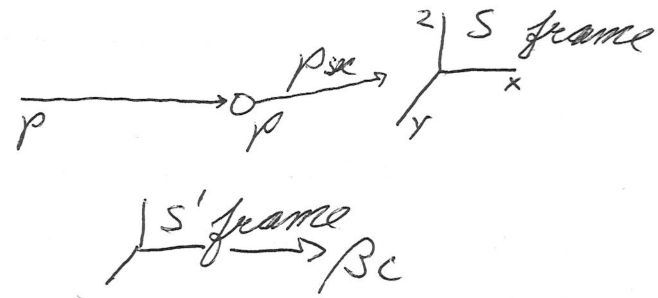
$$\underline{y_{\perp, CM}} = \ln\left(\frac{E}{E}\right) = \underline{0} \qquad (\theta = 90°)$$

- have same case of secondaries from other proton (left-moving one above)
  - a minimum rapidity occurs ~~from~~ for secondaries scattered in this direction

$$\underline{y_{min, CM} = -y_{max}}$$

Lorentz Boost & Rapidity

Frame S' moving with velocity βc in incoming particle direction



$$p_{\parallel}' c = \gamma (p_{\parallel} c - \beta E)$$
$$E' = \gamma (E - \beta p_{\parallel} c)$$
$$p_{\perp}' = p_{\perp}$$

($p_{\parallel}$ is longitudinal component of p_{sec})

The rapidity is

$$y' = \ln\left(\frac{E' + p_{\parallel}' c}{\sqrt{p_{\perp}'^2 c^2 + m_s^2 c^4}}\right)$$

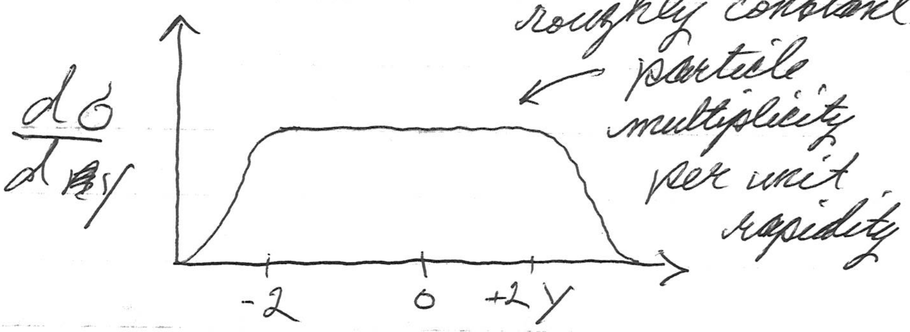
Substituting for $p_{\parallel}' c$, $p_{\perp}'$ and E' yields

$$\boxed{y' = y + \frac{1}{2} \ln\left(\frac{1-\beta}{1+\beta}\right)}$$

Shape of Rapidity Distribution

→ observed in experiments

- roughly "flat" for small values of rapidity



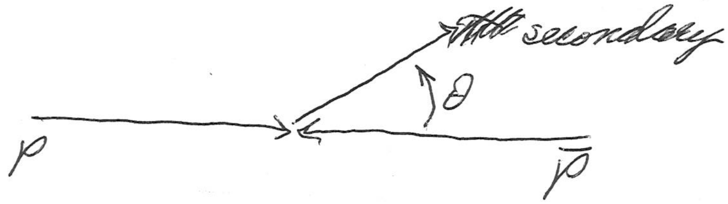
- falls rapidly for rapidities near y_{max} or $y_{min,cm}$

- this distribution is result of strong interactions

- production of massive states will have a different shape
- CAUTION: y-dist is not energy density
  → nor is it jet multiplicity per unit y

Pseudorapidity

Expand $E + p_{\parallel}c$ in terms of scattering angle, θ



$$y = \frac{1}{2}\ln\left[\frac{\cot^2\frac{\theta}{2} + \frac{m_s^2}{4p^2} + \cdots}{\sin^2\frac{\theta}{2} + \frac{m_s^2}{4p^2} + \cdots}\right]$$

In the case where m_s is negligible (i.e. $E \gg m_s c^2$):

$$y = \ln\left[\left(\frac{\cot\theta/2}{\sin\theta/2}\right)^2\right]^{1/2} = \ln(\cot\theta/2)$$

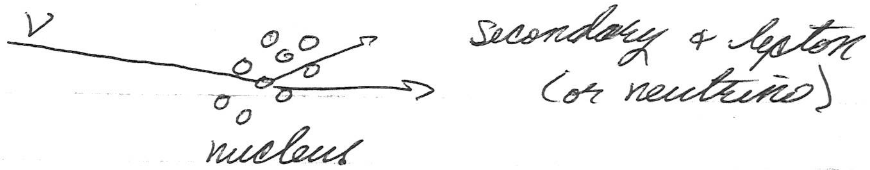
$$= \boxed{-\ln(\tan\theta/2) \equiv \eta}$$

"pseudorapidity"

Weak Interactions

Much weaker than other interactions
- only one available for ν's (and perhaps WIMPs)

Example of neutrino-nucleon (νN) scattering:



→ at 10 GeV, $\underline{\sigma_{\nu N} \sim 7 \times 10^{-38}\ \text{cm}^2/\text{nucleon}}$
- varies approximately linearly with energy
- compare $\sigma_{strong} \sim 4 \times 10^{-26}\ \text{cm}^2$ (40 mb)

Probability of interaction in some amount of matter:

$$R = \sigma N_A / g \; (d) \; (\rho)$$

thickness — density — grams

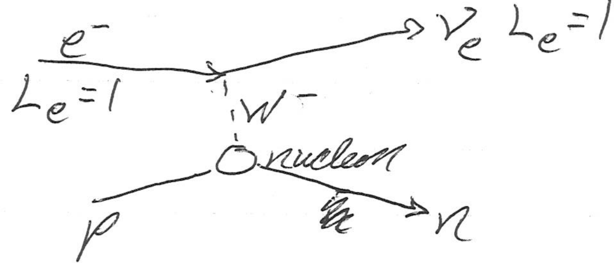
In 10 m of iron

$$\underline{\underline{R}} = 7 \times 10^{-38}\ \text{cm}^2 \left(\frac{6.02 \times 10^{23}}{g}\right)(10^3\ \text{cm})\left(7.6 \frac{g}{\text{cm}^3}\right) = \underline{\underline{3 \times 10^{-10}}}\ !$$

Extremely unlikely for interaction, even in 10 m of iron

Neutrino Production

Charged current can give



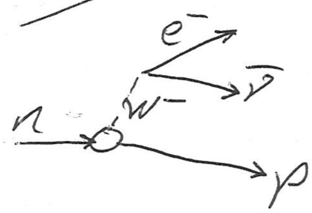
- electron capture
- lepton # conserved

$$p + e^- \rightarrow n + \nu_e$$

Energies ~ MeV

Nuclear β decay:

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Hadron decay:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$K^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\hookrightarrow \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Sources of Neutrinos

In stars such as Sun

$p + p \to d + e^+ + \nu_e$ (β^+ decay)

${}^7Be + e^- \to {}^7Li + \nu_e$ (electron capture)

${}^8B \to {}^8Be + e^+ + \nu_e$

→ energies range from keV to ~ 15 MeV

Atmospheric neutrinos

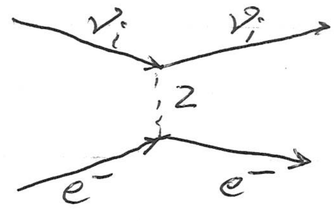
- cosmic ray nuclei incident on atmosphere
- π's + K's produced in resulting shower
- subsequent hadron decays give ν's
  - can be ~ GeV

Neutrino Interactions

Neutral Current Interaction

$\nu_i + e^- \to \nu_i + e^-$ $(i = e, \mu, \tau)$

atomic e^-

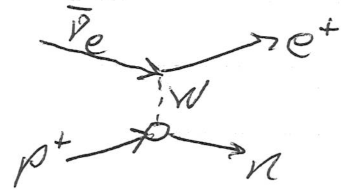


- Can measure presence of ν_i because some of its energy transferred to e^-
- Can also have $\nu p \to \nu p$ or $\nu n \to \nu n$ interactions

Charged current interaction:

$\bar{\nu}_e + p \to n + e^+$ (inverse β decay)

1.8 MeV threshold



also $\bar{\nu}_\mu + p \to \mu^+ + n$
$\bar{\nu}_\tau + n \to \tau^- + p$ } and all charge conjugate cases

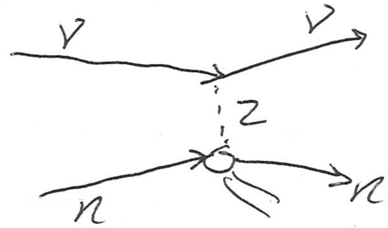
- lepton appearance facilitates inference of neutrino

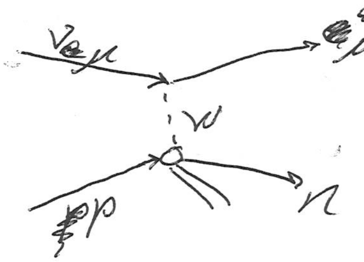
Particle Production

Consider again νN scattering
(- important because it is one way to understand structure of the nucleon)

As energy transfer W increases

$$\boxed{\langle N_{charged} \rangle \propto \ln W}$$





Angular dependence
of outgoing lepton (μ)

CM frame

- in a quark model of nucleon

if $(1-y) = \frac{1}{2}(1+\cos\theta^*)$

$$\left.\frac{d\sigma}{dy}\right|_{\bar{\nu}N\,scatt.} \propto \underline{\underline{(1+\cos\theta^*)^2}} \left(\propto (1-y)^2\right)$$

$$\rightarrow \left.\frac{d\sigma}{dy}\right|_{\nu N\,scatt} \sim \text{constant}$$