Hard light meson production in (anti)proton-hadron collisions and charge-echange reactions

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Hadron Electromagnetic Form factors

An extension of the QED 'return to resonance' mechanism to light meson emission (π, ρ) in (anti)proton collisions with a hadronic target (nucleon or nucleus) is proposed. The cross section and the multiplicity distributions are calculated. The collinear emission (along the beam direction) of a charged meson may be used to produce high energy (anti)neutron beams.

Possible applications at existing and planned facilities are considered.

- Production of anti-neutron beams (PANDA,Fair)
- Explanation of high hadron multiplicities in pp collisions (Protvino)

"Return to resonance" mechanism

- The emission of a hard real photons by electron (positron) beams at e^+e^- colliders enhances the cross section when the energy loss from one of the incident particles lowers the total energy up to the mass of a resonance.
- In the case of creation of a narrow resonance this mechanism appears through a radiative tail : it is the characteristic behavior of the cross section which gradually decreases for energies exceeding the resonance mass (effective method for studying narrow resonances like J/Ψ).
- For emission along the directions of the initial (final) particles, the emission probability has a logarithmic enhancement, increasing with the energy of the "parent" charged particle.
- In frame of QED this mechanism is called as "quasi-real electron" mechanism (QRE).

Motivation

- First indication of charge-exchange reactions in $\pi^- p$ and in pp scattering from cosmic rays detected with proportional chambers :

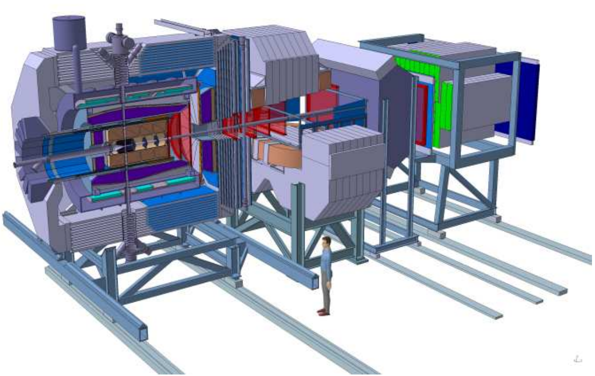
$$p + p \to n + \pi^+ + p + N_\pi,$$

- QRE mechanism is applied to the collinear emission of a light meson from a (anti)proton beam and the cross section for single and multi pion production (neutral or charged) is calculated.

Emission of a charged light meson-(π, ρ) in pp or $\bar{p}p$ collisions $\to$ conversion of high energy (anti)proton beam into (anti)neutron

This effect is observed in accelerator physics (V. Nikitin).

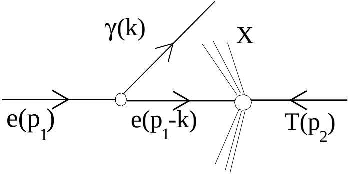
High energy antineutron beams at PANDA ?



- In PANDA good detection of hard pion and ρ mesons, produced by the antiproton beam.
- Deviation of charged meson by 2T magnet,
- Large production of anti-neutrons, $\rightarrow$ secondary high energy beam ?

Quasi-real electron method

$$e(p_1) + T(p_2) \to e(p_1 - k) + \gamma(k) + X$$



- The virtual electron after the hard (collinear) photon emission is almost on mass shell.

$$\mathcal{M}_\gamma(p_1, p_2) = e\overline{T}(p_2)\frac{\hat{p_1} - \hat{k} + m}{-2p_1 k}\hat{\varepsilon}(k)u(p_1).$$

- Factorization of the matrix element

$$\sum |\mathcal{M}_\gamma|^2 = e^2\left[\frac{E_p^2 + E^2_{\vec{p}-\vec{k}}}{\omega(E_p - \omega)(kp)} - \frac{m^2}{(kp)^2}\right]\sum |\bar{T}(p_2)u(p_1 - k)|^2$$

$\sum |\bar{T}(p_2)u(p_1 - k)|^2$: Born matrix element squared with shifted argument.

Quasi-real electron method

- The unpolarized cross section for $e(p_1) + T(p_2) \to e + \gamma + T$ can be factorized (CMS), :

$$d\sigma_{\gamma}^{eT\to eT\gamma}(s,x) = d\sigma(\bar{x}s)dW_{\gamma}(x),\ s=(p_1+p_2)^2,\ \bar{x}=1-x,$$

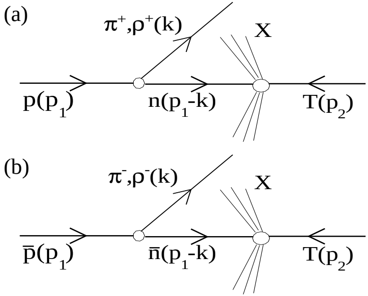
$$dW_{\gamma}(x) = \frac{\alpha}{\pi}\frac{dx}{x}\left[(1-x+\frac{1}{2}x^2)\ln\frac{E^2\theta_0^2}{m_e^2} - (1-x)\right],$$

$x = \frac{\omega}{E},\ \theta < \theta_0 \ll 1,\ \frac{E\theta_0}{m_e} \gg 1,$

- The initial electron transforms into an electron (energy fraction $1-x$) and a hard photon(x), emitted at $\theta < \theta_0$
- $\bar{x}s > s_{thr}$, where s_{thr} is the threshold energy of process without photon emission.
- Logarithmic enhancement originates from the small values of the mass of the intermediate electron, which is almost on mass shell.
  This justifies also the name of Quasi Real Electron (QRE) method.

QRE method in hadron physics

$$p + T \to n + T + h^+; \ \bar{p} + T \to \bar{n} + T + h^-$$



$h = \rho$ or π, T any target (p, n, nucleus..).
The matrix element for collinear $\pi(\rho)$ emission is :

$$\mathcal{M}^{h_+}_{pT}(p_1,p_2)) = \mathcal{M}_{nT}(p_1-k,p_2) T^{pn}_{h_+}(p_1,p_1-k);$$

$$\mathcal{M}^{h_-}_{\bar{p}T}(p_1,p_2)) = \mathcal{M}_{\bar{n}T}(p_1-k,p_2) T^{\bar{p}\bar{n}}_{h_-}(p_1,p_1-k).$$

$$T^{pn}_h = \frac{g}{m_h^2 - 2p_1k}\bar{u}_n(p_1-k)\gamma_5(\hat{\epsilon})u_p(p_1).$$

QRE method in hadron physics

- The cross sections are :

$$\begin{aligned} d\sigma^{pT\to h_+X}(s,x) &= \sigma^{nT\to X}(\bar{x}s)dW^{h_+}(x), \\ d\sigma^{\bar{p}T\to h_+X}(s,x) &= \sigma^{\bar{n}T\to X}(\bar{x}s)dW^{h_-}(x), \\ d\sigma^{pT\to h_0X}(s,x) &= \sigma^{pT\to X}(\bar{x}s)dW^{h_0}(x). \end{aligned}$$

- Following the QED result :

$$\begin{aligned} \frac{dW^i_\rho(x)}{dx} &= \frac{g^2}{4\pi^2}\frac{1}{x}\sqrt{1-\frac{m_\rho^2}{x^2E^2}}\left[\left(1-x+\frac{1}{2}x^2\right)L-(1-x)\right] \\ L &= \ln\left(1+\frac{E^2\theta_0^2}{M^2}\right), \rho^i=\rho^+,\rho^-,\rho^0, \end{aligned}$$

Pion hard photon emission

$$\frac{dW^{\pi}}{dx}=\sum|\mathcal{M}_{pn}(p_1,p_1-k)|^2\frac{d^3k}{16\omega\pi^3},$$

with

$$\sum|\mathcal{M}_{pn}(p_1,p_1-k)|^2=\frac{g^2}{[m_\pi^2-2(p_1k)]^2}Tr(\hat{p}_1-\hat{k}+M)\gamma_5(\hat{p}_1+M)\gamma_5$$
$$=\frac{4(p_1k)g^2}{[m_\pi^2-2(p_1k)]^2},$$

.

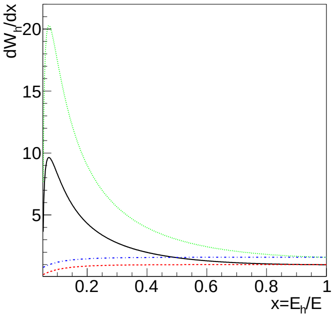
$$p_1k)=E\omega(1-bc),1-b^2\approx\frac{m_\pi^2}{\omega^2}+\frac{M^2}{E^2}$$

Angular integration for $1-(\theta_0^2/2)<c<1,\ c=\cos(\vec{k},\vec{p}_1)$:

$$\frac{dW^i_\pi(x)}{dx}=\frac{g^2}{8\pi^2}\sqrt{1-\frac{m_\pi^2}{x^2E^2}}\left[L+\ln\frac{1}{d(x)}+\frac{m_\pi^2}{xd(x)M^2}\right],$$
$$x=\frac{E_\pi}{E}>\frac{m_\pi}{E},\ d(x)=1+\frac{m_\pi^2\bar{x}}{M^2x^2},\quad \bar{x}=1-x,$$

$g=g_{\rho pp}=g_{\pi pp}\approx 6$ is the strong coupling constant.

dW_h/dx for ρ- and π-meson production- not normalized probability



$\theta_0 = 10^\circ$ *for* ρ*- meson*

$\theta_0 = 10^\circ$ *for* π*-meson*

$\theta_0 = 20^\circ$ *for* ρ*- meson*

$\theta_0 = 20^\circ$ *for* π*-meson*

Integrated probabilities

$$W_i = \int_{x_t^i}^{1} \frac{dW_i}{dx} dx$$

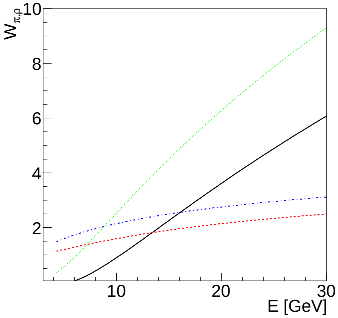
$x_t^i = E_{th}^i/E$, E_{th} is the threshold value of the energy of the detected particle, $i = \rho, \pi$:

$$\begin{aligned} W_i &= \frac{g^2}{4\pi^2}(A^i L + B^i), \\ A^\rho &= I_0(x_t^\rho) - I_1(x_t^\rho) + \frac{1}{2} I_2(x_t^\rho),\ B^\rho = -I_0(x_t^\rho) + I_1(x_t^\rho), \\ A^\pi &= \frac{1}{2} I_1(x_t^\pi);\ B^\pi = I_1(x_t^\pi), \end{aligned}$$

with $I_n(z) = \int\limits_z^1 \frac{dx}{x} x^n \sqrt{1 - \left(\frac{z}{x}\right)^2}$

$$\begin{aligned} I_0(z) &= \frac{1}{2} \ln \frac{1+r}{1-r} - r,\ I_1(z) = r + z \arcsin(z); \\ I_2(z) &= \frac{1}{2} r - \frac{z^2}{4} \ln \frac{1+r}{1-r}; \end{aligned}$$

Integrated probabilities



$\theta_0 = 10^\circ$ *for* ρ*- meson*

$\theta_0 = 10^\circ$ *for* π*-meson*

$\theta_0 = 20^\circ$ *for* ρ*- meson*

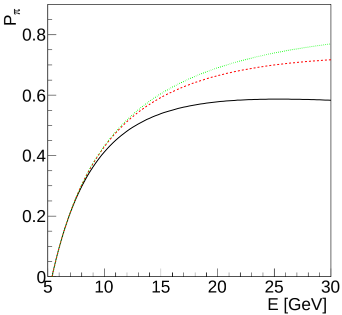
$\theta_0 = 20^\circ$ *for* π*-meson*

- The integrated quantities W_i, $i = \rho, \pi$ may exceed unity, violating unitarity.
- Virtual correction for the probability of emission of n "soft" photons (emission and absorption of the off-mass shell meson).
- Poisson formula for n soft photons : $W_n = (a^n/n!)e^{-a}$ (a : probability of emission of a single soft photon).

Renormalization factor

A general factor $P_\pi = e^{-W_\pi}$, takes into account virtual corrections.

$$\sigma(s) \to \sigma(s) \times P_\pi \sum^{k=n} \frac{W_\pi^k}{k!}, W_\pi = \frac{g^2}{8\pi^2} L,$$



Probability of emission of 2, 3, 4 pions, for $\theta_0 = 10^\circ$

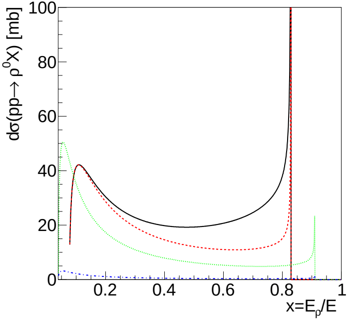
From experiment $P_\pi \approx 0.5$: the fraction of protons in the final state of proton-proton collisions is approximately 1/2.
$\to$ charge exchange reactions change protons into neutrons.

Annihilation into two pions $\bar{p}+p\to\pi^{+}+\pi^{-}+X$

$$
\begin{aligned}
d\sigma^{p\bar{p}\to\rho^0 X} &= 2\frac{dW_\rho(x)}{dx}\sigma^{p\bar{p}\to X}(\bar{x}s)\times P_\rho, \\
P_\rho &= e^{-W_\rho};\;\; W_\rho=\int_{x_t}^{1}\frac{dW_\rho}{dx}; \qquad (2)
\end{aligned}
$$

- The factor of two takes into account the emission along each of the initial particles.
- P_ρ is a survival factor which takes into account virtual radiative corrections.

Annihilation into two pions $\bar{p} + p \to \pi^+ + \pi^- + X$



$E = 10$ *GeV and* $\theta_0 = 10^\circ$

$E = 10$ *GeV and* $\theta_0 = 20^\circ$

$E = 20$ *GeV and* $\theta_0 = 10^\circ$

$E = 20$ *GeV and* $\theta_0 = 20^\circ$

The characteristic peak at $x = x_{max}$ *is known in QED :* $e^+ + e^- \to \mu^+ + \mu^- + \gamma$ *: threshold effect, corresponding to the creation of a muon pair, where* $x_{max} = 1 - 4M_\mu^2/s$, M_μ *is the muon mass.*

Annihilation into three pions $\bar{p}+p\to\pi^{+}+\pi^{-}+\pi^{0}+X$

Three pion production,assuming that the process occurs through a $\pi^0\rho^0$ initial state emission :

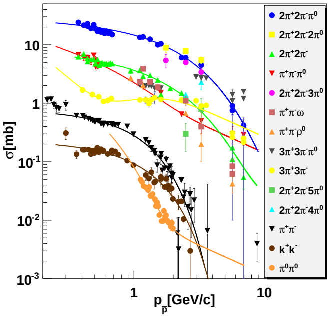
$$d\sigma(p,\bar{p})^{p\bar{p}\to\pi\rho X}=$$

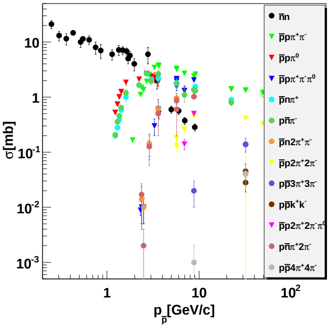
$$dW_{\rho}^{0}(x_{\rho})dW_{\pi}^{0}(x_{\pi})[d\sigma(p-p_{\rho},\bar{p}-p_{\pi})^{p\bar{p}\to X}+$$

$$d\sigma(p-p_{\pi},\bar{p}-p_{\rho})^{p\bar{p}\to X}]P_{\pi}P_{\rho},$$

implying the subsequent decay $\rho^0\to\pi^+\pi^-$.

Predictions for cross sections





- The cross sections for the interaction of high energy (anti)neutron beams with hadrons can be derived by (anti)proton, with the emission of the charged meson.

$$\sigma^{nT\to X}(\bar{x}s) = \frac{d\sigma^{pT\to h^+X}/dx}{dW_+(x)/dx},$$

- Total cross section for $\bar{n}p \to X$ from the total cross section of $\bar{p}p \to \bar{n}h\_p \approx 1$ mb,

$$W_\pi(E_1,\theta_0)\sigma^{\bar{n}p\to X}(E-E_1) = \sigma^{\bar{p}p\to X}(E),$$

Conclusion

- The QRE method has been extended to light meson emission from an (anti)proton beam. Cross section for multi-pion emission have been predicted for present and planned hadron facilities.
- Collinear light meson emission for producing secondary (anti)neutron beams, at a high energy (anti)proton accelerator.
- The gluon dominance model predicts the ratio of inelastic CE to total inelastic cross section in pp scattering $\approx 40\%$, in reasonable agreement with the experimental data.
- Collinear light meson emission in (anti)proton-proton collisions is a source of high multiplicities pion events. The emission of hadrons in initial as well as in final states must be taken into account.
- Probabilities to create a π or ρ-meson by a proton, in infinite momentum reference frame (Altarelli,1977).
- Emission of (polarized) ρ-meson by quark and the ρ meson production in quark-antiquark annihilation (Teryaev, 1982).