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Volume Emission of Pions in Relativistic Heavy-Ion Collisions*

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Abstract

We consider the possibility of volume emission of pions by the $\Delta(1232)$ decay in a hot compressed projectile-target residue. We calculate the momentum distribution of the pions created by the two-body $\Delta(1232)$ decay. Reabsorption is taken into account assuming a quasi-deuteron model. We argue that low energy pions created deep inside the hot zone are likely to escape and contribute to the pion inclusive spectrum.

Recently the Rasmussen and Nakai groups in Berkeley[1] have measured low energy pion inclusive spectra for the reaction Ne + NaF $\rightarrow \pi^+$ plus anything at an incoming energy of 800 MeV per nucleon. They have observed that very low energy pions (CM energies 30-50 MeV) are emitted isotropically in the CM frame. Pions emitted from the surface of a hot zone by the mechanism of massive radiation has been suggested earlier.[2] In this letter we would like to discuss another possible mechanism for pion emission: that of the decay of the $\Delta(1232)$ resonances in flight over the entire region of the hot zone and with subsequent emission (or eventual absorption) of pions. We argue that the reabsorption mechanism is such that low energy pions are likely to escape even though they are created far inside the hot zone.

To be explicit, let $f(\vec{p}_\Delta)$ denote the momentum distribution of the $\Delta(1232)$ resonances inside the matter. It is well known[3] that the partial decay mode of the resonance is $\Delta \rightarrow N + \pi$ almost complete (99.4%). It is now an easy task to find the momentum distribution of the pions $g(\vec{p}_\pi)$ created by the Δ two-body decay:

$$g(p_\pi) = \frac{m_\Delta{}^2}{2\pi\sqrt{x(m_\Delta{}^2, m_N{}^2, m_\pi{}^2)}E_\pi} \int d^3p_\Delta f(\vec{p}_\Delta) \int \frac{d^3p_N}{E_N} \delta^4(p_\Delta - p_\pi - p_N) \qquad (1)$$

Here we use units $\hbar = c = k_{Boltzman} = 1$ and $x(m_\Delta{}^2, m_N{}^2, m_\pi{}^2) = [m_\Delta{}^2-(m_\pi + m_N)^2][m_\Delta{}^2-(m_N-m_\pi)^2]$ is the usual relativistic factor involving the rest masses of the delta (Δ) the nucleon (N), and the pion (π) respectively. Here, $\delta^4(p_\Delta-p_\pi-p_N) = \delta(E_\Delta-E_\pi-E_N)\delta^3(\vec{p}_\Delta-\vec{p}_N-\vec{p}_\pi)$ and E_π, E_N, E_Δ are total relativistic energies. Assuming $f(\vec{p}_\Delta)$ to be normalized so that $\int f(p_\Delta)d^3p_\Delta = 1$, we get

$$g(p_\pi) = \frac{m_\Delta{}^2}{\sqrt{x}} \frac{1}{E_\pi p_\pi} \int p_\Delta f(p_\Delta) dp_\Delta \qquad (2)$$

where the integration limits are $|E_\pi\sqrt{x} \pm p_\pi\sqrt{n}|/2m_\pi^2$ and $\sqrt{n}$ is given by $\sqrt{n} = m_\Delta^2 + m_\pi^2 - m_N^2$.

Equation 2 allows us to calculate the momentum distribution of pions if a model for $f(\vec{p}_\Delta)$ is provided with the assumption of no reabsorption during the pions course outwards. Since the experimental data are taken for charged pions (π^+) we have to consider six different decay channels for the Δ

$$\Delta^{++} \to \pi^+ + p$$
$$\Delta^+ \to \pi^+ + n$$
$$\Delta^+ \to \pi^0 + p$$
$$\Delta^0 \to \pi^0 + n$$
$$\Delta^0 \to \pi^- + p$$
$$\Delta^- \to \pi^- + n$$

To find out the branching ratios for the Δ decay into π^+ plus anything we expand the various Δ wave functions with the aid of Clebsch-Gordan coefficients[4]

$$|\Delta^{++}\rangle = |\tfrac{3}{2}, \tfrac{3}{2}\rangle = |p,\pi^+\rangle$$
$$|\Delta^+\rangle = |\tfrac{3}{2}, \tfrac{1}{2}\rangle = \frac{1}{\sqrt{3}}\left[|n,\pi^+\rangle + \sqrt{2}\,|p,\pi^0\rangle\right]$$
$$|\Delta^0\rangle = |\tfrac{3}{2}, -\tfrac{1}{2}\rangle = \frac{1}{\sqrt{3}}\left[|p,\pi^-\rangle + \sqrt{2}\,|n,\pi^0\rangle\right]$$
$$|\Delta^-\rangle = |\tfrac{3}{2}, -\tfrac{3}{2}\rangle = |n,\pi^-\rangle$$

From this argument the decay ratios of $\pi^+:\pi^-:\pi^0 = 1:1:1$ and to get the fraction of π^+ emerging we have to multiply our $g(\vec{p}\ )$ with 1/3. We will now try to incorporate reabsorption within the quasi-deuteron model. For the π^+ absorption cross section we choose the model used by Metropolis[5,6,7]

$$\sigma_{ab}(p_\pi) = \frac{A(m_\pi{}^2 + Bp_\pi{}^2)}{p_\pi m_\pi} \tag{3}$$

where A = 0.230 [Fm^2] and B = 7.14 [dimensionless]

We will now define a momentum and path dependent transparency factor by

$$\phi(p_\pi, L) = e^{-L/\lambda(p_\pi)} \tag{4}$$

Here L is the length of a straight line from the point the π was created to the surface of the hot zone, and λ is the pion mean free path. Assuming a spherical shape (for simplicity only) we can calculate an average transparency factor (averaged over all possible lengths L)

$$\Phi(p_\pi) = \frac{3}{u^4}\{[u^2 + 2u + \frac{3}{2}]e^{-2u} + u - \frac{3}{2}\} \tag{5}$$

where $u = R/\lambda = R\rho\sigma_{ab}(p_\pi)$ (6)

Here R is the radius of the hot zone (assumed to be the radius of the ions for central collisions of equal mass ions), ρ is the density of the quasi deuteron in the hot zone, (which we estimate to be 3/4 x 0.17 [Fm^{-3}] corresponding to overlap density[8] and where assuming every nucleon-nucleon pair is a quasi-deuteron, the factor 3/4 accounts for the need of at least one neutron to absorb a π^+ [5]). To transform from CM to LAB frame of the ions we now need β_{CM} and Y_{CM} (the velocity and rapidity of the center of mass of the ions) respectively:

$$\beta_{CM} = \frac{\sqrt{T^2 + 2m_N T}}{T + (\frac{A_1 + A_2}{A_1})m_N} \tag{7}$$

$$Y_{CM} = \mathrm{Arctanh}(\beta_{CM}) \tag{8}$$

In Eqs. 7-8 T is the incoming kinetic energy per nucleon. A_1 and A_2 is the mass of the projectile and target respectively. For the reaction Ne + NaF at 800 MeV/N we get β_{CM} = 0.547 and Y_{CM} = 0.614. It is often convenient

to display the cross sections in the transverse momentum versus rapidity plane. The advantage (if one uses invariant cross section) is that the transverse momentum component will not change and the rapidities are additive ($Y_{LAB} = Y^* + Y_{CM}$) so contours of cross sections just shift to the right along the rapidity axes by the transformation from CM to the LAB frame.

We now examine the π^+ spectra for two limiting cases of $f(\vec{p}_\Delta)$: first for the hard scattering model (neglecting Fermi motion) and second for a thermal equilibrium distribution. For the first case we get

$$f(\vec{p}_\Delta) = \frac{\delta(p_\Delta - p_o)}{4\pi p_o^{\,2}} \tag{9}$$

Here p_o is estimated from the first hard nucleon-nucleon scattering:

$$p_o = \frac{1}{2}\sqrt{\frac{4T^2m_N^2+4Tm_N(3m_N^2m_\Delta^{\,2})+9m_N^{\,4}+m_\Delta^{\,4}-10m_N^{\,2}m_\Delta^{\,2}}{4m_N^{\,2} + 2Tm_N}} \tag{10}$$

which gives us $p_o \simeq 279$ [MeV/c] for T = 800 [MeV] for symmetric ion-ion collisions. We now estimate a typical statistical temperature T_o be given by

$$3T_o/2 = \sqrt{s}/2 - m_N \tag{11}$$

Here $\sqrt{s}$ is the invariant mass of the colliding nucleons in the ions. For T_o we obtain 122 MeV which is sufficiently high to allow a Maxwellian form for $f(\vec{p}_\Delta)$ which becomes in the limit of thermal equilibrium

$$f(\vec{p}_\Delta) = (2\pi Tm_\Delta)^{-3/2}\, e^{-(p_\Delta^{\,2}/2Tm_\Delta)} \tag{12}$$

We have so far neglected Coulomb effects, which can be included in a more rigorous treatment.

In Fig. 1 we show contours for the invariant double differential cross section $\frac{Ed^2\sigma}{p^2dpd\Omega}$ for the pions calculated per unit cross section of the Δ

formation. The contours are given in CM-frame of the ions. Of particular interest is the rather low energy ridge due to the distribution $g(\vec{p}_\pi)$ and the subsequent absorption profile. The ridge is roughly consistent with recent experimental findings (Rasmussen et al.). However, it should be emphasized that hydrodynamical flow models can also account for such a ridge[10] (peak).

In conclusion we have shown that if a high energy central collision populates the $\Delta(1232)$ resonances sufficiently it is likely that some of the pions created by the decay of the Δ (and especially the very low-energy pions) can escape to the exterior even though they have been created far inside the projectile-target residue.

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REFERENCES

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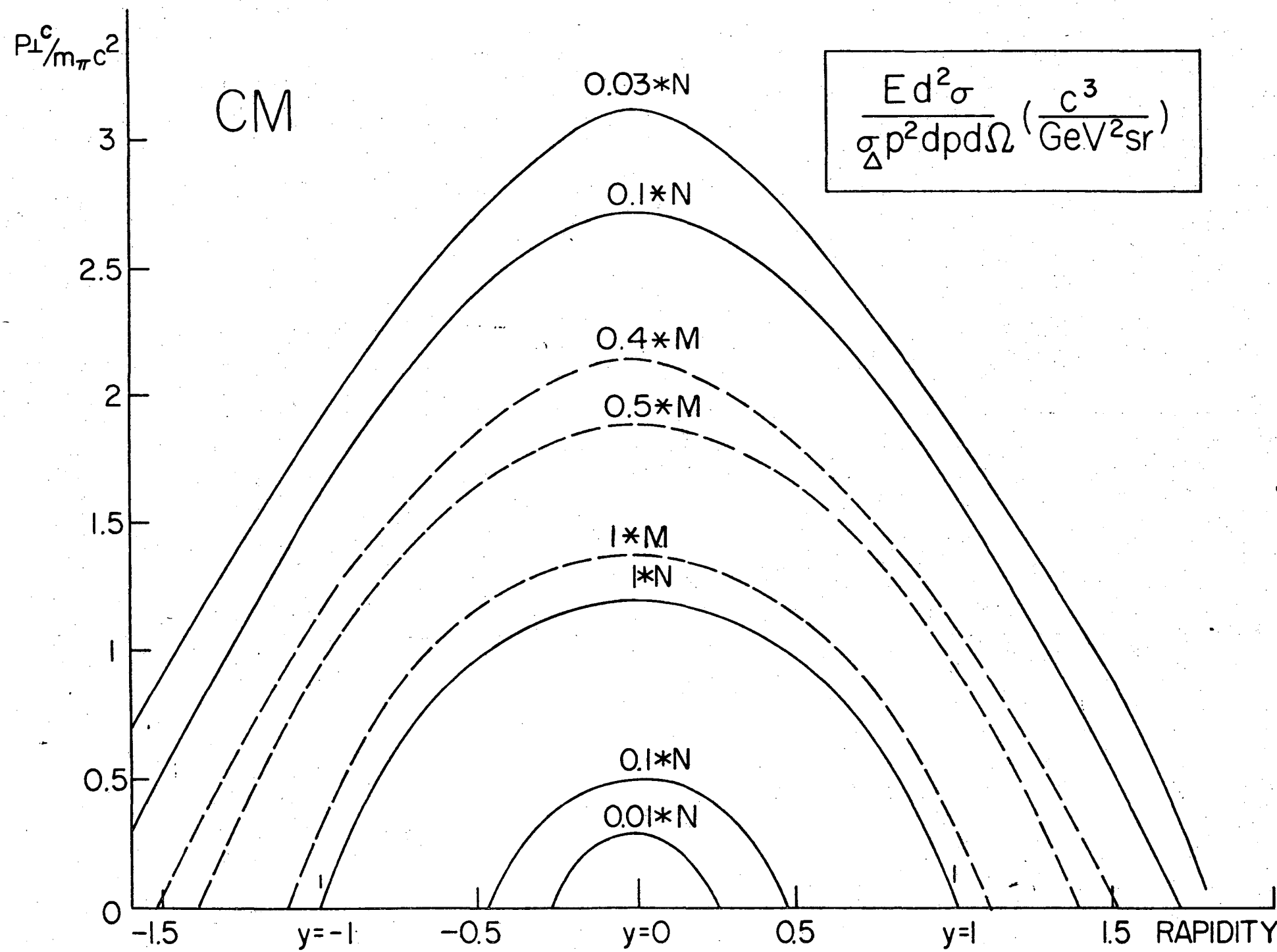
1. S. Nagamiya, I. Tanihata, S. Schnetzer, L. Anderson, W. Bruckner, O. Chamberlain, G. Shapiro, and H. Steiner, LBL-6770, August 1977.
2. Y. Karant, N. K. Glendenning, Private communication.
3. Particle properties data booklet, April 1978; Available from LBL and CERN.
4. Elementary Particle Physics, G. Källen (Addison-Wesley Publ. Comp. Inc.) 1964.
5. N. Metropolis, R. Bivins, M. Storm, J. M. Miller, G. Friedlander and A. Turkevich, Phys. Rev. 110 (1957) 204.
6. K. A. Brueckner, R. Serber, and K. M. Watson, Phys. Rev. 84 (1951) 262.
7. R. M. Frank, J. L. Gammel, and K. M. Watson, Phys. Rev. 101 (1956) 891.
8. J. Hüfner, Pions Interact with nuclei, Max Plank Inst. für Kernphysik, Heidelberg, W. Weise, Acta Phys. Austriaca, Supp. XVIII, 677-726 (1977).
9. G. D. Westfall, J. Gosset, P. J. Johansen, A. M. Poskanzei, W. G. Meyer, H. H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. 37 (1976), 1202.
10. P. J. Siemens and J. O. Rasmussen, LBL-8383 (Preprint) 1978.

Figure Caption

Figure 1. Calculated pion inclusive spectra for 800 MeV/N Ne on NaF. The figure shows contours in the rapidity transverse momentum plane. For the Δ momentum distribution a Maxwellian form was chosen with a statistical temperature of 122 MeV (solid line) and a delta distribution with p_o = 279 MeV (dotted line). The calculations are performed in the CM frame of the ions. To transform to the LAB frame just shift the contours to the right on the rapidity axis by an amount Y_{CM}. To get actual double differential cross section multiply with the scale factors (either N = 0.227 or M = 0.509) and by the cross section for the formation of the Δ resonances. The ridges are located at the contours marked 1 · N and 1 · M.


$P_\perp c/m_\pi c^2$
CM
$\frac{E\,d^2\sigma}{\sigma_\Delta p^2 dp d\Omega}\left(\frac{c^3}{GeV^2 sr}\right)$
0.03*N
0.1*N
0.4*M
0.5*M
1*M
1*N
0.1*N
0.01*N
3
2.5
2
1.5
1
0.5
0
-1.5
y=-1
-0.5
y=0
0.5
y=1
1.5
RAPIDITY

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