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The possibility of significant heavy lepton production and emission from the electromagnetic field in relativistic, heavy-ion collisions was suggested several years ago by Gould [1], based on estimates of the Weizsäcker-Williams method. This technique can be derived from perturbation theory, as discussed earlier by Soff [2], for electron pair production in relativistic collisions of uranium. In such collisions, the near-zone electromagnetic becomes very large, transverse, and very sharply pulsed. Restating Gould's point, the time-like part of these pulses contains large Fourier frequency components, and hence μ-pair and τ-pair production becomes likely.

In this paper, we address the production of heavy lepton pairs out of the vacuum using nonperturbative methods. The formal details of our method have been given elsewhere [3] and result in a simple picture, in which the propagation of the vacuum is obtained by solving the time-dependent Dirac equation in the presence of the electromagnetic fields of the colliding nuclei. One-dimensional, numerical studies of this phenomenon have been reported [4] using methods [5], whose results agree with those developed by Greiner and co-workers [6], to study strong field electrodynamics in nonrelativistic collisions. In our current work, we shall apply a simple model and discuss, in detail, the

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production cross sections as a function of the transverse momentum and rapidity.

The production of lepton pairs, using the Weizsäcker-Williams methods, is given in (1),

$$\sigma_W = 2\pi \int_{2m_\ell c^2}^{\gamma m_\ell c^2} d\omega \int_{\lambda\!\!\!^{-}}^{\infty} dbb \ \Phi(b,\omega) \left(\frac{\sigma(b,\omega)}{b^2}\right), \tag{1}$$

where Φ is the flux of virtual photons and σ the cross section for photon-induced pair production. The integral requires a cutoff at small values of the impact parameter, usually taken at $b = \lambda\!\!\!^{-}$, the Compton wavelength. In the high-energy limit, (1) scales with lepton mass, m_ℓ, with the charges Z_1, Z_2, and with the bombarding energy per nucleon, γ-1, as

$$\sigma_W \sim \frac{Z_1{}^2 Z_2{}^2}{m_\ell{}^2} \ln(\gamma)^3. \tag{2}$$

Equation (2) is not entirely correct in the high-energy limit, since it violates the Froissart-bound $\sigma \sim O(\ln\gamma)^2$ [7].

Before discussing the nonperturbative calculations, it is interesting to examine a dimensionless parameter, κ, which, in simple systems, behaves as the expansion parameter for pair production via time-dependent perturbation theory [8],

$$\kappa = (\omega/m_\ell)(E/E_0). \tag{3}$$

In (3) E_0 is the critical field for a lepton of mass m_ℓ,

$$E_0 = m_\ell{}^2/e,$$

and ω is the frequency of the interacting field of strength E. We have evaluated κ for collisions of U+U at the AGS and at RHIC, and we find that $\kappa \gg 1$ for muon production at the AGS and for muon and tauon production at RHIC, suggesting that perturbative methods are inapplicable.

Accordingly, we have formulated the production of lepton pairs from the time-dependent, electromagnetic fields of the colliding nuclei in a time-dependent picture which encompasses all orders of perturbation theory. Employing the methods discussed in Ref. 3, we obtain a set of time-dependent, single-particle equations,

$$[\vec{\alpha}\cdot(\vec{P}-\vec{A}) + \beta m_\ell + A_0 - i\partial_t] \mid \psi_\lambda^{(s)}(t)\rangle = 0. \qquad (4)$$

The label s = +,- denotes states which evolve from single lepton or single anti-lepton states, and λ denotes all of the other necessary quantum numbers. The solution to (4), for particular field configurations, yields the inclusive number of negatively charged leptons as,

$$N = \sum_{\lambda,\mu} \left| \langle \psi_\lambda^{(+)}(-\infty) \mid \psi_\mu^{(-)}(+\infty)\rangle \right|^2, \qquad (5)$$

where the summation on λ and μ, respectively, are over all of the available positive- and negative-energy, single-particle states. The emission of leptons from the projectile and target nuclei is incoherent, in part due to the classical motion of the heavy ions, and in part due to the time scales for the emission. Thus, we can work in a reference frame at rest in one of the nuclei (target) and only consider the time-varying fields due to the other nucleus (projectile). In this frame, the total, inclusive, singles cross section can be written as,

$$\sigma = 2\pi \int_0^\infty bdb\ [2\ N(b)], \qquad (6)$$

where the states in (5) are now restricted to those of the target atom, and where we shall only consider symmetric projectile and target combinations. These equations are evaluated using a local equivalent field approximation, which we shall not discuss but which is treated in Ref. 9.

The results of calculations for colliding beams of U+U are shown in Fig. 1 for the e^-, μ^-, and τ^-, inclusive singles cross sections. The dot-dashed curve is the e-pair cross section evaluated using the Weizsäcker-Williams method, (1), which we include for comparison purposes. There are several important features in Fig. 1. At low energies, the e^- cross section is approximately the same as the Weizsäcker-Williams result. However, near energies per nucleon of about 100 GeV, these differ by about a factor of 100. Although we estimate that the

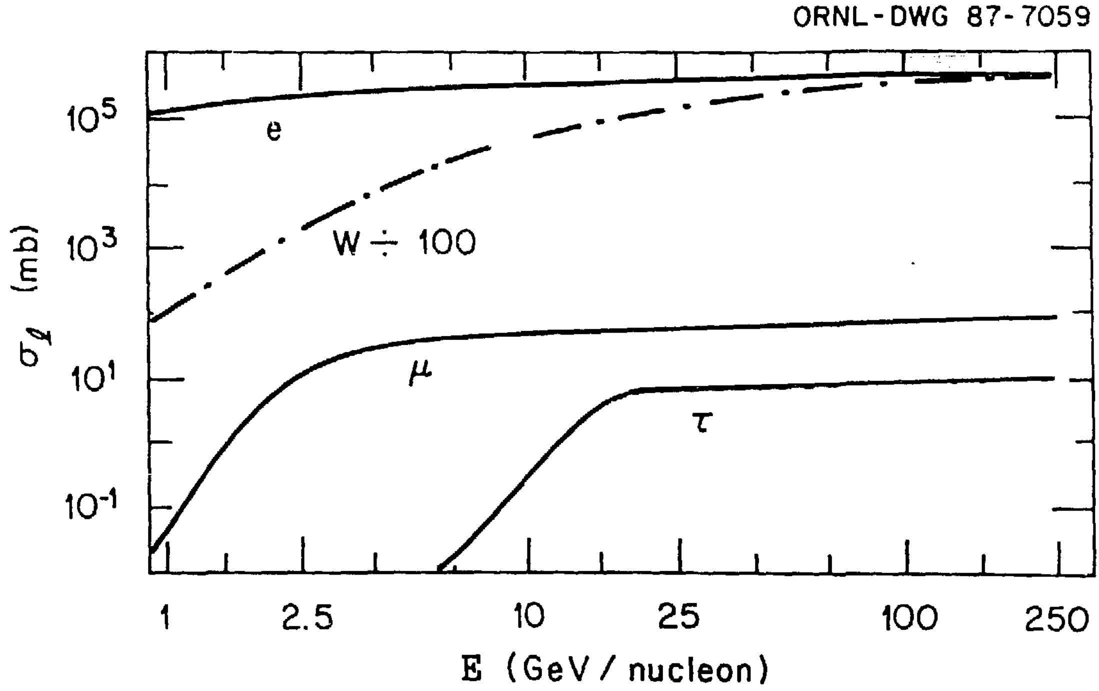

Fig. 1

local field approximation may have errors of as much as a factor of two at these energies, this is essentially due to the unphysical $\ell n^3(\gamma)$ energy dependence of the perturbative method. Note that the μ and τ cross sections, for sufficiently high energies, increase as $\ell n(\gamma)$ and thus satisfy the Froissart limit, whereas the perturbative result does not. Also note that the muon and tauon cross sections are large; at energies per nucleon of 100 GeV they are, respectively, 100 and 10 mb.

In Fig. 2 the cross section at one energy per nucleon, 100 GeV, is given as a function of the lepton mass, m_ℓ. This figure illustrates the effects of a number of assumptions: In (a), both the positive- and negative-energy continuum states of the target are assumed to be plane waves, in effect assuming a coherent field over the entire nucleus. In (b), Coulomb distortion factors are included and averaged over the nuclear volume, yielding fields which are coherent over distances the size of nucleons. In (c), these factors are treated without any averaging, yielding a field which is approximately coherent over distances comparable with the impact parameter. The result, (d), is for point

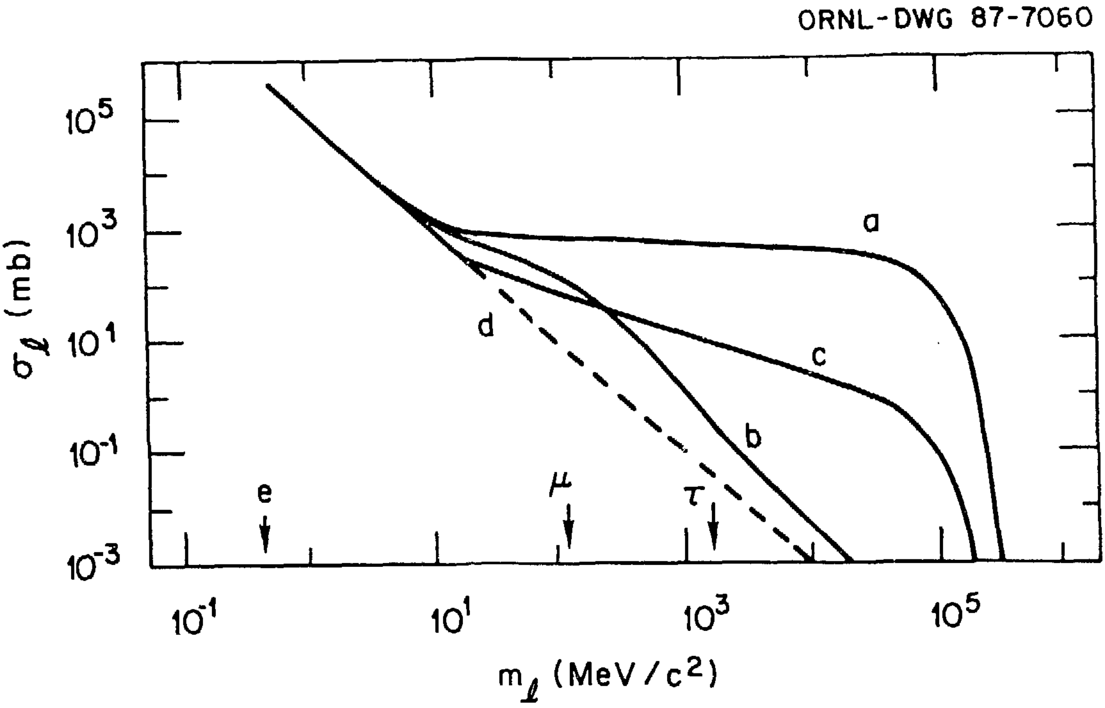

Fig. 2

charge nuclei with none of the above effects treated, and this case scales as m_ℓ^{-2}.

The differential cross sections, in terms of transverse momentum and rapidity, can be obtained from (6) by

$$\sigma = \int_{-\infty}^{\infty} dY \int_0^{\infty} dP_\perp \frac{d\sigma}{dYdP_\perp}, \tag{7}$$

where

$$Y = \frac{1}{2} \ln\left(\frac{P_0+P_\parallel}{P_0-P_\parallel}\right), \tag{8}$$

and where $P = (P_0, \vec{P})$ is the four vector associated with the positive energy continuum state, λ, in (5). The vector $\vec{P}$ is decomposed into parts which are transverse, $\vec{P}_\perp$, and longitudinal, $P_\parallel$, to the beam direction. The transverse part is averaged over the azimuthal angle in order to simplify the calculations needed in (7). The resulting e^- differential cross section is shown in Fig. 3 for the fixed target

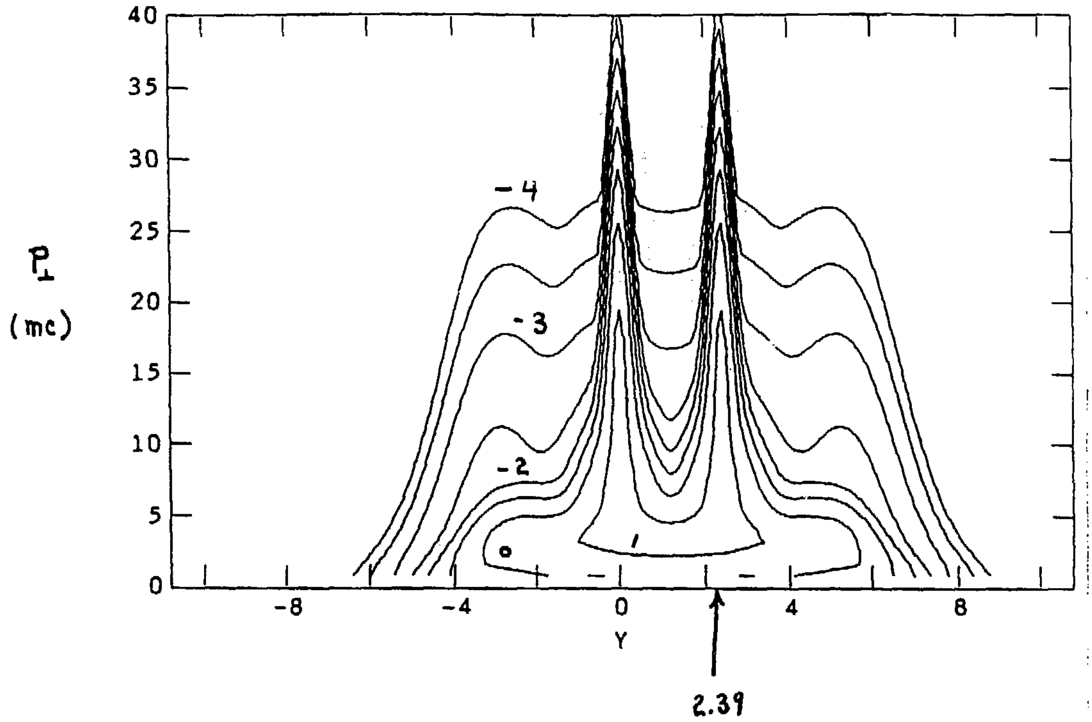

Fig. 3

collision of Au+Au at an energy per nucleon of 4.2 GeV. These are contours of the cross section in (7), as a function of the transverse momentum, $P_\perp$, in units of $m_\ell c$, and of the rapidity. The cross section is given in units of mb/$m_\ell c$, and the contours are labeled by the exponent to the base 10. In this collision, the projectile rapidity is approximately 2.4, as indicated in the figure. Note the sharp side peaking at the projectile and target rapidity, reflecting the transverse character of the fields producing the pairs. Also, note that the distribution is a maximum for values of $P_\perp$ near the Compton momentum, κ, and has a broad distribution which decreases by three orders of magnitude by $P_\perp \sim 20\ m_\ell c$.

These same features are apparent in colliding beams of Au+Au at an energy per nucleon of 100 GeV as shown in Fig. 4. The transverse momentum and rapidity distribution is very broad in rapidity, reflecting the extreme violence of the collision. However, the cross section still has a maximum for $P_\perp$ near the Compton momentum and decreases by about three orders of magnitude at about $P \sim 20\ m_\ell c$. In this

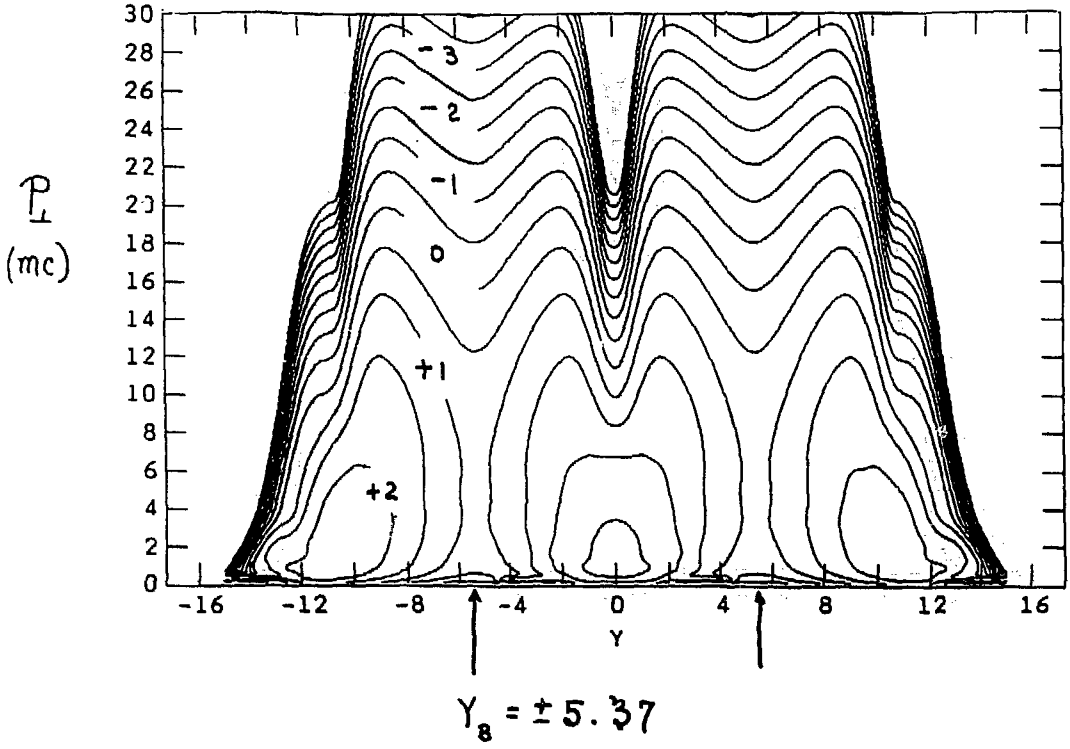

Fig. 4

particular case, the rapidities of the two beams are at -5.4 and +5.4, and the total cross section yield is about 1260 b.

We have also studied these distributions for the production of muons and tauons:

i) The production of heavy leptons occurs mainly within the interior of the nuclei and is sensitive to details of the nuclear charge distribution. Because of the relatively small Compton sizes of the μ and τ, it is probably important to give the nuclear charge form factor in terms of the quark distributions in the nucleus.

ii) The cross section yields for muons and tauons are large compared to those predicted by the Weizsäcker-Williams process, due to the coherence developed during the time evolution in the interior of the nucleus. The differential cross sections are strongly peaked at the projectile and target rapidity, and in the transverse momentum variable, about the Compton momentum of the produced lepton.

In conclusion, we should like to emphasize that other particles should readily be produced by this mechanism, including the J/ψ, W^+-W^- pairs, and possibly even pairs of magnetic monopoles [10]. There is some evidence that in central collisions, heavy ions in this energy range will undergo tremendous deceleration forces. If this is the case, then the production of leptons, as we have discussed, will be substantially enhanced.

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