Dilepton radiation from nucleon-nucleon collisions

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We calculate the dilepton spectrum arising from hadronic bremsstrahlung and from the radiative decay of the delta in nucleon-nucleon collisions. Comparison is made with the recent p + Be data at 4.9 GeV obtained by the DLS Collaboration at the Bevalac. We argue that dileptons constitute a valuable probe of nuclear dynamics.

Our understanding of the properties of strongly interacting systems at high density and temperature is still quite incomplete. Such physical conditions are thought to have existed immediately after the Big Bang and are likely to be attained in supernovae and neutron stars. In the laboratory, we attempt to recreate this environment by colliding heavy nuclei at high energies. One hope is to be able to extract some information about the nuclear equation of state from such data.[1-4] The manifestation of the nuclear equation of state is only one facet of the relativistic nuclear many-body problem; there are many others. In particular, little is known about the interactions of pions with the hot and dense nuclear medium. What is observed experimentally is an asymptotic signal where the pionic excitations have either been absorbed or moved on shell. We have recently argued[5,6] that the only direct means of observing the clothed pion propagator in hot and dense matter was through the observation and study of the dilepton signal in high-energy heavy ion collisions. We have shown that if the pion dispersion relation in dense nuclear matter flattens out or has a minimum because of the strong coupling to delta-hole states, there will be a peak in the dilepton spectrum originating from two-pion annihilation at an invariant dilepton mass of $M=2\omega_{\min}$, where $\omega_{\min}$ is the pion energy at the dip. A lowering of the threshold for $\pi^+\pi^-\to e^+e^-$ below $2m_\pi$, where m_π is the pion mass, would also be a clear signature of the softening of the pion dispersion relation. However, along with heavy systems, one must obtain measurements in light ion and nucleon-nucleon reactions. This information is an important prerequisite to the unambiguous extraction of a genuine many-body signature. The dilepton spectrometer (DLS) Collaboration has undertaken a program of measuring direct dilepton pair production in nucleon-nucleon, p-nucleus, and nucleus-nucleus collisions at the Lawrence Berkeley Bevalac. The first experimental results for dielectron production in p + Be collisions at 4.9 GeV have recently been obtained.[7] It is the purpose of this paper to theoretically address those first results.

Since Be is a relatively small system, one would not expect the formation of hot and dense equilibrated nuclear matter in a reaction induced by a 4.9 GeV proton. We shall therefore restrict our discussion to dilepton pairs arising from nucleon-nucleon processes. We consider the bremsstrahlung contribution and the radiative decay of the delta into a nucleon and a virtual photon which internally converts to an electron-positron pair.

The hadronic bremsstrahlung piece can be calculated in the soft photon approximation.[8] In this limit the radiated photon has $\omega\to 0$, radiation from the external legs of a diagram dominate the bremsstrahlung amplitude, and only the classical characteristics of the electromagnetic current are important. Also in this limit, the proton-proton rate is negligible compared to the proton-neutron one. Analytically continuing from a soft real photon spectrum to a soft real dilepton spectrum,[9] we obtain

$$\frac{d\sigma_{np}^{e^+e^-}}{dy\,d^2\mathbf{p}_T dM}=\frac{\alpha^2}{6\pi^3}\frac{\bar{\sigma}(s)}{ME^2}\left[\frac{R_2(\sqrt{s_2};m_N,M)}{R_2(\sqrt{s};m_N,0)}\right]. \quad (1)$$

In the above, m_N is the nucleon mass, $\bar{\sigma}(s)$ is the momentum transfer weighted cross section,

$$\bar{\sigma}(s)=\int_{-(s-4m_N^2)}^{0}dt\left[\frac{-t}{m_N^2}\right]\frac{d\sigma_{np}}{dt}, \quad (2)$$

and the factor in the large parentheses is introduced to partially correct the soft photon approximation. It represents the relative Lorentz invariant phase space[10] available to the two-nucleon system in the cases of the emission of a dilepton of invariant mass M and energy E and no dilepton emission. For the above cases, the energy of the two-nucleon system is, respectively, $s_2=s+M^2-2\sqrt{s}E$ and s. For Eq. (2) we use the parametrization developed in Ref. 5.

It is well known that the delta has a radiative decay channel $\Delta\to\gamma N$. The measured branching ratio for this process is 0.6%. We can analytically continue the expression for photon emission from the decay of the delta to a pair of soft leptons. We now consider the process $NN\to\Delta X\to e^+e^-X'$. We can then write

$$\frac{d\sigma^{e^+e^-}}{dy\, d^2\mathbf{p}_T dM}=\frac{\alpha}{\pi}\frac{\sigma_\Delta(s)|F_\pi(M)|^2}{M}\int_{m_N+m_\pi}^{\sqrt{s}-m_N}\int_{-1}^{1} dm_\Delta dz_\Delta P_1(m_\Delta)P_2(z_\Delta)B_\gamma(m_\Delta)\left[\frac{R_2(m_\Delta,m_N,M)}{R_2(m_\Delta,m_N,0)}\right]\frac{d^3N^{e^+e^-}}{dy\, d^2\mathbf{p}_T dM} . \quad (3)$$

Here $P_1(m_\Delta)$ is the probability of forming a delta of mass m_Δ and is a normalized Breit-Wigner distribution with a mass-dependent width. $P_2(z_\Delta)$ is the normalized delta angular distribution, taken from data,[11] where $z_\Delta=\cos\theta_\Delta$. $B_\gamma(m_\Delta)$ is the mass-dependent branching ratio of a delta into a real photon. We approximate this by the relative partial widths in the γ and π channels: $B_\gamma(m_\Delta)=\Gamma_\gamma(m_\Delta)/\Gamma_\pi(m_\Delta)$. This approximation will hold for m_Δ not too close to its π channel threshold value. This region will contribute to low dilepton masses, below the domain we are interested in. The following parametrizations ensure the proper threshold behavior of the decay widths:

$$\Gamma_\pi(m_\Delta)=k_1\left[\frac{k_\pi}{\omega_\pi}\right]^3 , \quad \Gamma_\gamma(m_\Delta)=k_2\left[1-\left[\frac{m_N}{m_\Delta}\right]^2\right] , \quad (4)$$

where k_π and ω_π are the pion momentum and energy in the rest frame of the delta. The parameters k_1 and k_2 are chosen so that $\Gamma_\pi(m_0)=0.115$ GeV and $B_\gamma(m_0)=0.006$, for $m_0=1.232$ GeV. We infer the isospin-averaged cross section for delta formation, $\sigma_\Delta(s)$, from the experimental data. At 4.9 GeV we use $\sigma_\Delta=9$ mb, a number midway between the limits associated with exclusive single delta production[12] and the total nucleon-nucleon inelastic cross section. Notice that Eq. (3) is also phase space corrected.

The Lorentz invariant dilepton distribution appearing on the right side of Eq. (3) is easily deduced in the rest frame of the delta

$$\frac{d^3N^{e^+e^-}}{dy\, d^2\mathbf{p}_T}=\frac{1}{4\pi p_0}\delta(E-E_0) , \quad (5)$$

where p_0 is the recoil momentum of the nucleons and E is the dilepton energy. Note that $m_\Delta=(\mathbf{p}_0^2+m_N^2)^{1/2}+E_0$. One can show that Eq. (3) is in agreement with a derivation from first principles[13] up to, of course, the delta structure functions. These are not known. In the spirit of the vector dominance model,[14] we let the photon transform into a ρ meson before coupling to the delta. We thus included a factor $\frac{3}{2}|F_\pi(M)|^2$ in Eq. (3) and used the parametrization of Ref. 5. Before a direct comparison with experiment is made an important point must be stressed. The DLS apparatus has an acceptance which only sees part of the kinematically accessible phase space. Our production cross sections therefore have to be corrected by this filter. In our acceptance calculation we do not include a 50 MeV/c cut on the individual electron and positron momenta. However, this only affects the low mass bins.

The two components of the dilepton invariant mass spectrum and the effect of the acceptance cutoff are displayed in Fig. 1. The filter plays an important role for low invariant masses, where high p_T and high y drive the dileptons out of the acceptance. The ρ peak is clearly visible and constitutes a contribution of the delta decay to the net spectrum. This observation points to dileptons

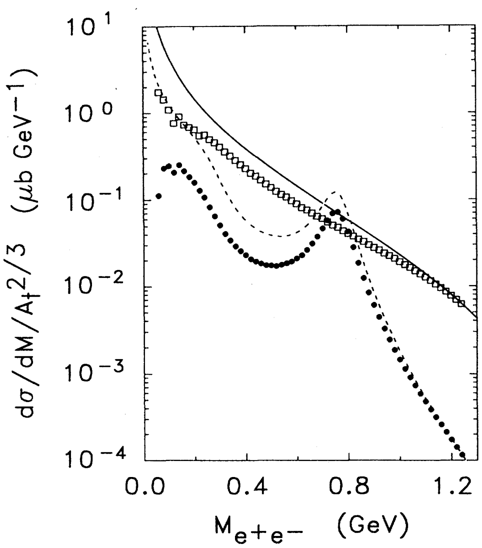

FIG. 1. The dilepton invariant mass distribution. Shown separately are the bremsstrahlung (solid line) and the delta decay (dashed line) contributions. The acceptance-corrected bremsstrahlung (open squares) and delta decay (filled circles) spectra are plotted to illustrate the effect of the acceptance filter.

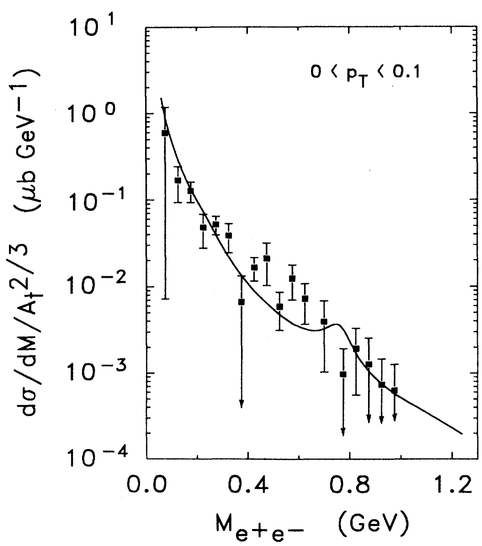

FIG. 2. The acceptance-corrected invariant mass spectrum for $0<p_T<0.1$ GeV/c as obtained from Eqs. (1) and (3), compared to the DLS data (filled squares). The bin width is 50 Mev, unless specified by a horizontal error bar.

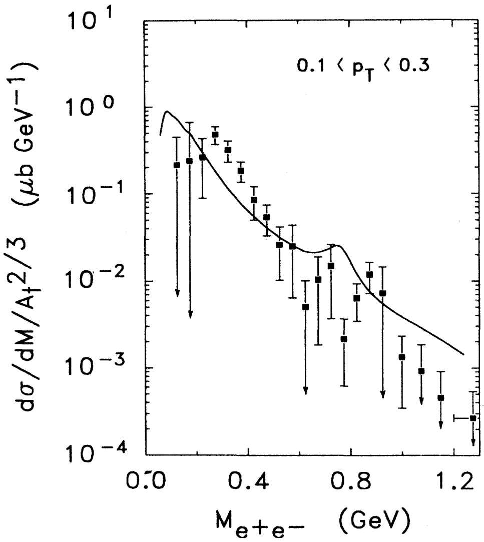

FIG. 3. Same caption as Fig. 2, with $0.1 < p_T < 0.3$ Gev/c.

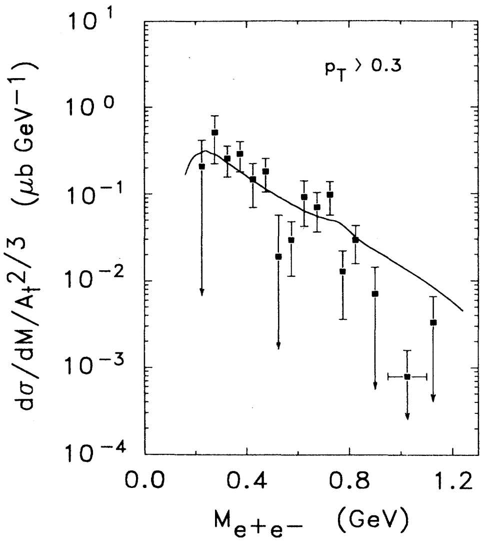

FIG. 4. Same caption as Fig. 2, with $p_T > 0.3$ GeV/c.

as precious tools in the study of the Δ structure functions. Also notice that high invariant masses are bremsstrahlung dominated. In Fig. 2, we show the acceptance-corrected net spectrum for low values of the dilepton transverse momentum. Comparing with the "nucleon-nucleon" DLS data,[7] we obtain a good fit over the entire measured mass range. For intermediate p_T's, Fig. 3, we underestimate by roughly a factor of 2 at $M \approx 2m_\pi$. There might be some amount of pion-pion annihilation, even for this small system. We are currently investigating this. We attribute the overestimation at high masses to the soft photon approximation in the hadronic bremsstrahlung sector. At high p_T's the contribution from the delta decay is less apparent, as seen from Fig. 4. Here again the calculation has the right magnitude and lies somewhat higher than the experimental data for large masses. The overall fit is quite satisfactory.

We conclude that the hadronic bremsstrahlung is the most important contribution, although the delta channel leads to a non-negligible contribution to the dilepton spectrum and therefore should be included in future interpretations of experimental data. We believe that several features of the current set of Bevalac DLS measurements can be accounted for in terms of nucleon-nucleon interactions, although the structure in $d\sigma/dM$ around twice the pion mass is not fully reproduced. We are presently considering a possible scenario of double pion production and annihilation. However, our present calculation suggests that the magnitude of this specific contribution is not large. In future works we plan to go beyond the soft photon and on-shell approximations by evaluating the Feynman diagrams for dilepton emission, using meson exchange theory for the nucleon-nucleon interaction. This is a formidable task which we have begun and will report on elsewhere. The results from this study should pin down how much of the overshooting at high M's and p_T's is actually due to the soft γ approach. Nevertheless, the present results show that the dilepton signal emitted at the nucleon level is of the right magnitude, has the right trends, and is not inconsistent with the set of data considered here.

Note added in proof. Since this paper was written, one of us (J.K.) has been involved in such calculation.[15]

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