PHYSICAL REVIEW C VOLUME 51, NUMBER 1 JANUARY 1995

Baryon resonances: A primary $\rho \to l^+l^-$ source in $p+p$ and $p+d$ at 4.9 GeV

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(Received 2 August 1994)

Dilepton spectra for $p+p$ and $p+d$ reactions at 4.9 GeV are calculated. We consider electromagnetic bremsstrahlung also in inelastic reactions. N^* and Δ^* decays present the major contributions to the ρ and ω meson yields. Pion annihilation yields only $\sim 1.5\%$ of all ρ's in $p+d$. The ρ mass spectrum is strongly distorted due to phase space effects, populating dominantly dilepton masses below 770 MeV. It is found that inclusive production cross sections of ρ, ω, and η mesons in $p+p$ are 3–4 times higher than the (measured) exclusive cross sections for pp+meson. This prediction could be checked by measuring the decays of ρ, ω, and η mesons into photons.

PACS number(s): 13.75.Cs, 14.20.Gk, 14.40.Aq, 14.40.Cs

Data for dilepton production in $p+p$ and $p+d$ at beam energies at 4.9 GeV have recently been analyzed by the DLS Collaboration [1]. This is the highest energy available at the Bevalac. Hence, the most massive baryon resonances are excited. All sources for dileptons relevant for light systems at lower energies are present. Furthermore, the highest statistics are achieved as compared to previously measured systems [2]. An understanding of dilepton sources in light systems is a prerequisite for the discovery of in-medium effects in heavy ion experiments [2,3]. It also serves as a check for the input of theoretical models [4–8]. In this paper we consider all hadronic sources based on events which we generated with the relativistic quantum molecular dynamics model (RQMD) [7].

The data in the low mass region ($M_{l^+l^-} < 600$ MeV) can be explained by Daltiz decays (η,Δ) and electromagnetic bremsstrahlung [5,7,8]. Electromagnetic bremsstrahlung from arbitrary reactions can be calculated via the soft photon approximation [9] according to

$$d\sigma_{ab}^{Xe^+e^-} = \frac{\alpha^2}{12\pi^3}|\epsilon \cdot J|^2 \frac{R_2(\bar{s})}{R_2(s)} \frac{d^3q}{q^0} \frac{dM^2}{M^2} d\sigma_{ab}^{X} . \quad (1)$$

M is the invariant mass of the pair with four momentum q. The dipol current of the in- and outgoing particles is given by

$$J^\nu = \sum_{i=1}^{n} Q_i \frac{p_i^\nu}{p_i \cdot q} - Q_a \frac{p_a^\nu}{p_a \cdot q} - Q_b \frac{p_b^\nu}{p_b \cdot q} . \quad (2)$$

Here p_i and $Q_i e$ are momentum and charge of particle i. The extension to higher photon energies is made by the phase space correction factor $R_2(\bar{s})/R_2(s)$ in Eq. (1) [4]:

$$R_2(s) = \frac{1}{16\pi}\left[\left(1-\frac{(m+m')^2}{s}\right)\left(1-\frac{(m-m')^2}{s}\right)\right]^{1/2} \quad (3)$$

with $\bar{s} = (p+p'-q)^2 = s^2 - 2\sqrt{s}q_0 + M^2$. The differential decay rate for dilepton production by bremsstrahlung $d\Gamma_a^{Xe^+e^-}$ can be given in terms of the decay rate for the process $a \to X$ by the replacement $d\sigma_{ab} \to d\Gamma_a$ and $\sqrt{s} \to m_a$. The cross section for electromagnetic bremsstrahlung with only one hadron in the final state can be calculated by time reversal symmetry in terms of the cross section for the production of a resonance $ab \to c$ by $m,m' \to m_a, m_b$ in Eq. (3). Here the squared current $|\epsilon \cdot J|^2$ carries the exact relativistic dipol structure by using the four momenta generated by RQMD. Note that all processes included in RQMD except those involving strings or constituent quarks enter into Eq. (1). Those are (i) resonance (de)excitation, $h_1h_2 \to h_3h_4$ where h_i denotes any well-established hadron or hadron resonance up to a mass of 2 GeV for baryons or up to 1.6 GeV for mesons; (ii) resonance formation or decay $h_1h_2 \leftrightarrow h_3$ (see Ref. [10]).

The inclusion of inelastic bremsstrahlung into our calculation as shown in Fig. 1 does not change our conclusion in Ref. [7] obtained without inelastic breamsstrahlung: η and Δ Dalitz decays dominate the low mass region, since it is about 1 order of magnitude above the contribution of bremsstrahlung including inelasticities. The bremsstrahlung from elastic pp and pn collisions is much lower than bremsstrahlung including inelasticities. This is in accord with the results given in Ref. [8]. The bremsstrahlung contribution due to inelasticities is slightly lower here as compared to Ref. [8]. This is caused by a different treatment of inelastic pp collisions. In RQMD the two nucleons excite each other and form baryon resonances as described in Ref. [10]. These resonances then decay with final lifetimes according to experimental branching ratios if available by meson radiation, i.e., for resonance masses below 2 GeV:

$$\Delta^*, N^* \to N\pi, N\sigma, \Delta\pi, N\rho, N\omega, YK. \quad (4)$$

This model yields significantly less bremsstrahlung since the phase space open for electromagnetic bremsstrahlung is reduced as compared to a model were the charge is directly decelerated into their final state (pions and nucleons) as in Ref. [8]. On the other hand, there only the exclusive η production channel $pp \to pp\eta$ is considered, while in our model the inclusive cross section is about 5 times higher. A measurement of the inclusive η production cross section via its decay into photons, for example with the TAPS spectrometer [11] at a future 5 GeV proton beam at SIS, could help to verify our result.

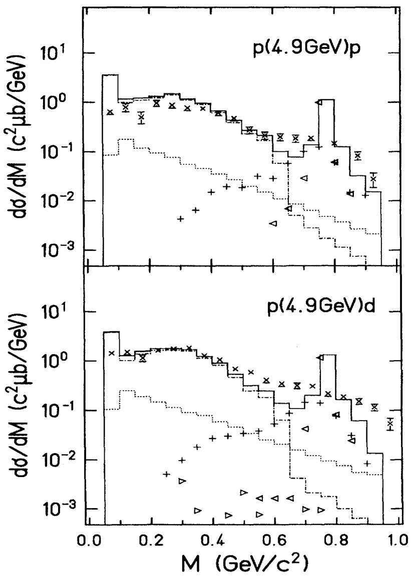

FIG. 1. The differential cross section for dielectron emission for $p+p$ and $p+d$ at 4.9 GeV vs invariant mass of the dielectron is compared to experimental data [2] ($\times$). The dash-dotted line refers to the sum of all Dalitz decays. The plusses (+) refer to decays of ρ mesons. The dotted lines give the sum of all contributions from the electromagnetic bremsstrahlung, including inelasticities. The solid line is the sum of all. The calculation is corrected with the DLS filter V2.0. Note the strong reduction especially in the low mass region as compared to our prediction [7] made with the DLS filter V1.6. Our calculation shows a slightly stronger peak structure in the ρ/ω mass region. In $p+d$ only 1.5% of all ρ mesons are formed via dynamical annihilation of co-moving pions ($\triangleright$). The ω-decay contribution is labeled by $\triangleleft$.

Let us now turn to the higher mass region. It has been shown [1] that the exclusive direct ρ contribution $pp \rightarrow pp\rho$, measured by pion correlation (see Table I), cannot fill up the ρ peak. This may indicate that inclusive ρ

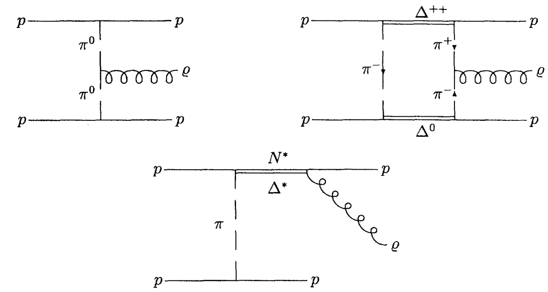

FIG. 2. Elementary graphs for exclusive ρ meson production ($pp \rightarrow pp\rho$) via pion annihilation (top) and heavy baryon resonance decays (bottom). The lowest order graph for pion annihilation (top left) does not contribute, since the Clebsch Gordan coefficient appearing at the $\pi^0\pi^0-\rho$ vertex is zero. Pion annihilation in $p+p$ is only possible via a two step process as shown in the top right diagram.

meson production is much higher than the cross section for exclusive production. Furthermore, the enhancement at intermediate masses (400–700 MeV) observed in the $p+p$ and $p+d$ dielectron data at 4.9 GeV [1] deserves attention. Calculations considering a ρ pole in the Δ Dalitz decay form factor [4] or pion annihilation [8] claim to explain the data for light systems up to $p+\mathrm{Be}$ [2] at these energies. Here we consider the contribution of heavy resonance excitation which is the mechanism for multipion production in the few GeV region. However, pion annihilation in $pp \rightarrow pp\rho$ as shown in Fig. 2 is forbidden in lowest order, due to the vanishing Clebsch Gordan coefficient at the $\pi^0\pi^0-\rho$ vertex. In next order, annihilation of π^+ and π^- in $pp \rightarrow pp\rho$ can only occur by a two step process via charge exchange between the proton lines in the initial state, e.g., $pp \rightarrow \Delta^{++}\Delta^0$ (Fig. 2). This would allow the Δ's to emit oppositely charged pions, which then could annihilate. For inclusive ρ meson production in $p+p$ reactions, the pion annihilation contribution should increase quadratically with the pion multiplicity (it is proportional to the squared pion density). However, such a behavior is not observed in the

TABLE I. Cross sections of baryon resonances and mesons by $p+p$ collisions in RQMD at $E_l=4.9$ GeV are compared to experimental data [12] at 4.6 GeV(I) and 5.1 GeV(II). Strong evidence for heavy resonance production is observed. RQMD predicts factors of 3–5 higher inclusive cross sections for meson production as compared to the measured exclusive channels. In case of the ρ meson the cross section for the complete phase space modified mass distribution and the symmetric Breit Wigner part is shown separately for our model, while in the experiments only the Lorenzian component is considered and phase space modified ρ's are excepted.

Channel	RQMD	I	II
$\Delta_{1232}\, p$	1.3	1.47 ± 0.13	0.38 ± 0.08
$N^*_{1440}\, p$	0.8	1.16 ± 0.22	0.65 ± 0.18
$N^*_{1520}\, p$	0.17	0.44 ± 0.2	0.45 ± 0.09
$N^*_{1680}\, p$	0.07	0.54 ± 0.22	0.5 ± 0.1
ωpp	0.27	0.122 ± 0.02	0.18 ± 0.05
ρpp	0.18/0.11	$\cdots/0.07\pm0.05$	$\cdots$
ηpp	0.15	0.08 ± 0.04	0.07 ± 0.05
$\omega+X$	0.84	$\cdots$	$\cdots$
$\rho+X$	0.66/0.38	$\cdots/\cdots$	$\cdots/\cdots$
$\eta+X$	0.72	$\cdots$	$\cdots$

experimental data [12]. Therefore, additional sources of ρ mesons are required in order to understand the energy dependence of the ρ meson production.

Such an additional source of ρ mesons can be decays of heavy baryon resonances: These are (in RQMD) excited in inelastic reaction between the initial particles. Here the inclusive cross section is about 4 times higher as compared to the exclusive process (similar to the case of the η meson). A compilation of cross sections for baryon resonance and meson production is shown in Table I.

The cross section for ρ meson production cannot be directly compared to the di-pion correlation data used to extract the cross section for $pp \rightarrow pp\rho$ [12]. The experimental cross section is obtained via the symmetric Lorentz component in the di-pion mass spectrum. However, the ρ mesons from RQMD show strong deviation from a (symmetric) Lorenzian distribution in their mass spectrum. This is due to the missing phase space in B^* decays. This yields nearly a factor of 2 difference between a symmetric component around the peak mass of $m_\rho = 770$ MeV and all ρ mesons (i.e., phase space modified ρ mesons are excepted in the data). Those deform the mass spectrum towards lower masses as shown in the ρ decay contribution in Fig. 1 and are partially responsible for the intermediate mass enhancement mentioned above.

At higher masses a sharp ω peak can be observed on top of the broad ρ bump (Fig. 1). The N^*_{1990} resonance here includes a decay into ωN (as compared to our previous calculation [7,10]) to fit the $pp \rightarrow pp\omega$ cross section at $\sqrt{s} = 3.074$ [12]. Again, the inclusive cross section is more than 3 times higher than the exclusive, a result that could also be checked by TAPS via the ω decay into 3 photons. However, the remaining disagreement between our calculation and the data due to the stronger peak structure at the ρ/ω mass is caused by the mass resolution of 15%, which is not yet included in the present DLS filter V2.0.

In conclusion, "inelastic" bremsstrahlung and ω production has been included into the calculation of the dielectron mass spectrum for $p+p$ and $p+d$ at 4.9 GeV. The electromagnetic bremsstrahlung including inelasticities does not suffice to explain the low mass region. Measured cross sections for exclusive production of η's, ρ's, and ω's are given in Ref. [12]. In Ref. [1] it was shown that dilepton production calculations based on these data underestimate the measured dilepton cross sections. In the present model we find that elementary cross sections for *inclusive* meson production (i.e., η's, ρ's, and ω's) are factors 3–5 times higher than the measured *exclusive* channels used in Ref. [1]. Hence, in our calculation these mesons fill up the experimentally observed yields. This prediction could be checked by measuring the decays of η's and ω's into photons. The dominant contribution to the ρ meson sources are decays of heavy baryon resonances. Pion annihilation as considered in Ref. [4] yields only ~1.5% of all ρ's in $p+d$ in the present model.

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