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Contribution of π^0 and η Dalitz decays to the dilepton invariant-mass spectrum in 1*A* GeV heavy-ion collisions

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The Dalitz-decay contributions of π^0 and η mesons to the di-electron invariant-mass spectrum at 1*A* GeV have been obtained from a systematics of inclusive meson production cross sections measured for the collision systems ^{12}C+^{nat}C and ^{40}Ar, ^{40}Ca+^{nat}Ca in the bombarding-energy range of 0.8–2.0 *A* GeV. These results are compared with the recently published di-electron mass spectra of the DLS collaboration. Systematic errors and angular-distribution effects are discussed. We conclude that the low-mass part of the DLS data cannot be explained by the Dalitz decays of light neutral mesons only. [S0556-2813(97)50612-1]

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Particle production is generally considered to be a sensitive probe of the dynamics of relativistic and ultrarelativistic heavy-ion collisions, as well as of the properties of the hot and compressed nuclear matter produced in such reactions [1–3]. Although most experimental effort has concentrated so far on the study of meson emission, it has nonetheless early been realized that interaction-free probes like bremsstrahlung photons and dileptons offer potentially a more direct and cleaner view of the relevant phenomena. Experiments of this kind have indeed been performed at CERN by the HELIOS-3, CERES, and NA50 collaborations, and surprisingly large dilepton yields have been reported [4–6], fostering intensive theoretical investigations. In the few-GeV regime, pioneering work has been done by the Dilepton Spectrometer (DLS) collaboration [7] at the BEVALAC, who has investigated di-electron emission in a series of experiments, both on light-ion and heavy-ion collisions for a range of bombarding energies [8–13].

In a recent publication [13] the DLS group reports on their latest results obtained for Ca+Ca, C+C, α+Ca, and d+Ca collisions at a beam energy close to 1 *A* GeV. In their paper they present inclusive di-electron invariant-mass spectra in the mass range of 0.05–0.9 GeV/c^2 and compare them, in the case of the Ca+Ca system, with the contributions expected from the Dalitz decay of neutral pions and η mesons produced in the collision. In order to estimate these contributions, they make use of inclusive π^0 and η cross sections published by the Two Arm Photon Spectrometer (TAPS) Collaboration [14,15]. However, the TAPS collaboration has meanwhile greatly improved and extended their data base of π^0 and η production cross sections, and consequently such a comparison can now be put on a much firmer footing. Hence, in the following we present an evaluation of the Dalitz contributions to the di-electron mass spectra in Ca+Ca and C+C collisions, based on our most recently measured meson-production cross sections, as well as estimates for α+Ca and d+Ca collisions, obtained from scaled meson yields.

We have investigated neutral-meson production in relativistic heavy-ion collisions in two series of experiments at the heavy-ion synchrotron SIS at GSI, Darmstadt. In our experiments, π^0 and η mesons have been detected with the aid of the TAPS BaF_2 scintillator array via their strong 2-photon decay branch. Photons have been discriminated from massive particles by pulse-shape analysis, time of flight, and the use of plastic-scintillator charged-particle veto counters; neutral mesons have been identified in an invariant-mass analysis of 2-photon events. The response of the detector, as well

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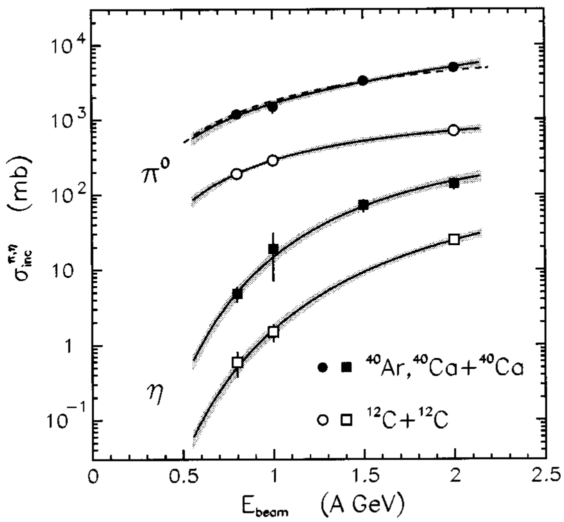

FIG. 1. Inclusive $\pi^0$and η production cross sections in the $A_{proj}+A_{targ}=12+12$ and 40+40 systems as function of the bombarding energy. Symbols are data, solid lines are log–log polynomial fits to the data, with interpolation errors indicated as shaded regions. The dashed curve corresponds to the $\sigma_{inc}^{\pi^-}$ parameterization of Nagamiya *et al.* (Ref. [20]).

as its acceptance, centered at midrapidity, have been extensively simulated with the tracking code GEANT 3.21. A detailed description of the device can be found in Ref. [16], and of our experimental methods and analyses in Refs. [17,18].

In this paper we concentrate on our results on inclusive π^0 and η production in light reaction systems, i.e., relevant for a direct comparison with the DLS data of Ref. [13]. In the first series of experiments, we had obtained data for ^{40}Ar+^{nat}Ca at 1.0 and 1.5 A GeV [14,15] and in a more recent second series of measurements we studied neutral-meson emission in ^{12}C+^{nat}Cat 0.8, 1.0, and 2.0 A GeV [17], as well as in ^{40}Ar+^{nat}Ca at 0.8 A GeV [18], and, finally, in ^{40}Ca+^{nat}Ca at 2.0 A GeV [19]. The Ar+Ca system being a close approximation of Ca+Ca we use both in our comparison.

The measured π^0 cross sections are plotted in Fig. 1 as a function of bombarding energy for the C+C and Ar(Ca)+Ca systems. The error bars shown include contributions from statistical errors on the meson peak in the 2-photon invariant-mass spectrum, from errors on the subtraction of the underlying combinatorial background, as well as from the uncertainty on the extrapolation from the TAPS acceptance to the full 4π solid angle. This extrapolation has been done with the simplifying assumption of a thermal, isotropic source located at midrapidity (see, e.g., Ref. [17] for details). Charged-pion data obtained previously for 0.8–1.8 A GeV Ar+KCl at the BEVALAC [20,21] show indeed a forward-backward peaking, which, if applied to our π^0 data, would raise the extracted inclusive production cross section by 15%–25%. Below we will demonstrate that the inclusion of such pion anisotropies has negligible impact on the present discussion. Additional confidence in our experimental and data-analysis procedures, and hence in the deduced cross sections, is gained from the comparison of our π^0 data with a parameterization given by Nagamiya *et al.* for π^- production in Ne+NaF and Ar+KCl collisions (using Eq. (17) of Ref. [20]): once the isospin factor of 1.10 expected in Ar+KCl for the ratio of π^-/π^0 yields is taken into account, we obtain indeed excellent agreement (see Fig. 1).

Our cross sections for inclusive η-meson production are also shown in Fig. 1, again for both the C+C and Ar(Ca)+Ca systems, as function of the beam energy. Because of the overall smaller yields, the statistics in the η invariant-mass peak is reduced and correspondingly the peak/background ratio becomes smaller, resulting in larger uncertainties as compared to the pion data. Systematic errors are however bound to be of similar magnitude, as in our experiments the η mesons have been measured concurrently with the neutral pions, albeit with different trigger conditions [17]. In addition the yields of both meson species have been extracted from the data with rigorously identical analysis procedures. Again, the η cross sections have been obtained by an extrapolation of the measured midrapidity yields to the full solid angle, assuming a thermal, isotropic source. As to date no experimental information on η angular distributions is available, we have used a theoretical estimate, done in the framework of the BUU model [22], to gauge the effect on our inclusive cross sections: predicted η anisotropies of the form $d\sigma/d\Omega \propto (1+0.9\cos^2\theta)$[23] would result only in an 18% increase with respect to the assumed isotropic source.

Between measured data points, the cross sections have been extrapolated with log–log polynomial fitting functions shown as curves in Fig. 1. Under the reasonable assumption that meson production follows a smooth trend with bombarding energy, one can see that the uncertainty of the interpolation will be small in the energy range of interest. Making use of the available data set, we have now been able to obtain the inclusive $\pi^0$and η production cross sections at the nominal beam energy employed in the DLS experiment, namely 1.04 A GeV, with overall uncertainties estimated to be $\leqslant$15–25% (see Table I). Furthermore, a fit to the cross sections of the form $\sigma_{inc} \propto (A_{proj}\cdot A_{targ})^{\alpha}$ yields at this bombarding energy $\alpha=0.72\pm0.05$ for π^0 and $\alpha=0.91\pm0.10$ for η production.

TABLE I. Interpolated meson production cross sections and temperatures used in the calculation of the di-electron Dalitz components. Errors listed are those propagated in the interpolation procedure and, for the asymmetric systems, estimated systematic errors of the scaling method. Anisotropy effects result in an additional systematic error of +30% on $\sigma_{inc}^{\pi^0}$ and +20% on σ_{inc}^{η} (see text for a detailed discussion).

Collision system	$\sigma_{inc}^{\pi^0}$ (mb)	T_{π^0} (MeV)	σ_{inc}^{η} (mb)	T_η (MeV)
1.04 A GeV Ca+Ca	1757±173	65±2	17.5±3.0	65±2
1.04 A GeV C+C	306±22	55±3	1.93±0.36	46±5
1.04 A GeV α+Ca	361±26 (±20%)	55±5	2.3±0.4 (±30%)	46±5
1.06 A GeV d+Ca	221±18 (±30%)	55±5	1.5±0.3 (±50%)	46±5

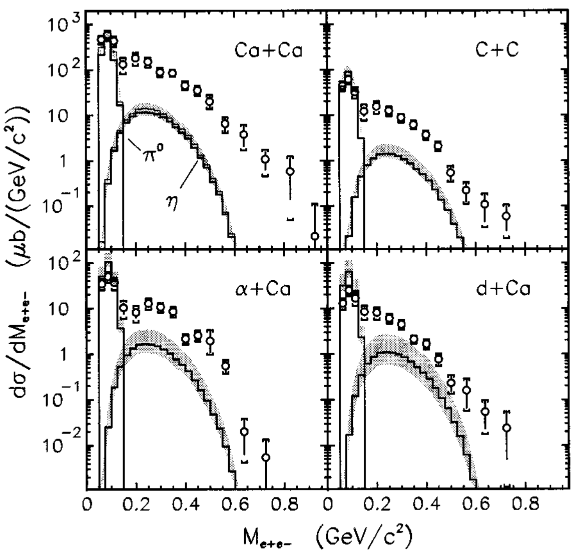

FIG. 2. Evaluated $\pi^0$and η Dalitz contributions to the di-electron invariant-mass distributions (histograms), compared with the DLS data (Ref. [13]) (symbols). The Dalitz decays have been computed assuming isotropic midrapidity meson sources and have been filtered with the DLS response; the shaded bands encompass statistical and systematic errors. Results for Ca+Ca and C+C have been obtained from directly measured meson production cross sections, estimates for α+Ca and d+Ca are from scaled cross sections. For Ca+Ca, the calculation made with an angular distribution $d\sigma/d\Omega \propto (1+0.9\cos^2\theta)$is also shown (dashed lines).

These values are in perfect agreement with fits obtained if our corrected [24] data from the heavy systems Kr+Zr and Au+Au [14,15] are included, and are also consistent with charged-pion data of the FOPI [24] and KaoS [25] collaborations.

In order to obtain the $\pi^0$and η Dalitz contributions to the di-electron mass spectrum, we have done a Monte-Carlo calculation with the following steps:

(1) Neutral pions and η mesons have been emitted from a thermal source moving along the beam axis with half the beam rapidity, i.e., $y_{1/2}=0.691$. The temperature of the source has been taken from fits to our measured transverse-mass distributions at 1 A GeV [14,17] (see also Table I).

(2) The mesons were assumed to decay in vacuum, i.e., well outside of the nuclear environment, into γe^+e^- with branching ratios [26] of 1.198% for the π^0 and 0.49% for the η, respectively. The phase-space population of the three-body decay products was governed by a transition form factor inspired by the vector-dominance model [27].

(3) The momentum vectors of both decay leptons were transformed into the laboratory frame and di-electron invariant-mass distributions $d\sigma/dM_{e^+e^-}$ weighted with the adequate meson production cross sections were generated.

(4) Finally, the mass distributions were filtered with the three-dimensional DLS detector acceptance $A(M,y,p_t)$[28], where M, y, and p_t are the pair mass, rapidity, and transverse momentum, respectively; in addition a mass cut of $M \geqslant 0.05$ GeV/c^2 was applied.

The resulting distributions are compared in the upper part of Fig. 2 with the latest DLS data [13] for 1.04 A GeV Ca+Ca and C+C collisions. Our calculations differ to some extent from those of Ref. [13] where different meson-production cross sections have been used, as well as a QED form factor for the Dalitz decay of the η [29]. The coverage of the DLS apparatus is peaked at forward angles, corresponding to projectile rapidity, whereas the TAPS detector covers the midrapidity region. Consequently, in our calculation the effects of neglecting possible meson anisotropies are amplified, but we estimate that, within the realistic limits discussed above, they can lead to an increase of at most 30% for the π^0 Dalitz component accepted in DLS, and 20% for the η component. This fact has been taken into account in the evaluation of the systematic errors which are included in Fig. 2 as shaded bands.

We have also done calculations for the asymmetric collision systems α+Ca and d+Ca, using values for the corresponding neutral-pion and η-meson production cross sections $\sigma_{\rm inc}^{\pi^0,\eta}$ estimated from the C+C data with a simple scaling law:

$$\sigma_{\rm inc}^{\pi^0,\eta}=\sigma_{\rm reac}\langle A_{\rm part}\rangle P_{\rm part}^{\pi^0,\eta}, \tag{1}$$

where $\sigma_{\rm reac}$ is the total reaction cross section, $\langle A_{\rm part}\rangle$ is the average number of participating nucleons, and $P_{\rm part}^{\pi^0,\eta}$ are the average meson production probabilities per participant (see Ref. [17] for details). From the C+C fit curves of Fig. 1, we find $P_{\rm part}^{\pi^0}$ (1.04 A GeV)$=6.0\times10^{-2}$ and $P_{\rm part}^{\eta}$ (1.04 A GeV) $=3.4\times10^{-4}$, which produce the cross-section estimates listed in Table I for α+Ca and d+Ca. A scaling of type $\sigma_{\rm inc}\propto(A_{\rm proj}\cdot A_{\rm targ})^{\alpha}$ leads to very similar results. Furthermore, for the d+Ca system an independent check of our scaling procedure is provided by an interpolation of the $p+A\rightarrow\eta$ data of Chiavassa *et al.* [30,31], which gives $\sigma(p+{\rm Ca}\rightarrow\eta@1.06\,A$ GeV$)=0.30$ mb, and further the rough estimate of $\sigma(d+{\rm Ca}\rightarrow\eta@1.06\,A$ GeV$)\approx0.7$–1.4mb [32], in fair agreement with the scaled value of 1.5±0.3 mb obtained with Eq. (1). The Dalitz decay components of the α+Ca and d+Ca systems are shown in the two lower frames of Fig. 2. Here, the added uncertainty in the meson production cross sections has been taken into account by allowing for appropriately larger systematic errors, as shown in this figure.

From the comparison of Fig. 2 of our results with the DLS data, it appears clearly that the experimental di-electron mass spectra are indeed dominated for $M_{e^+e^-}\leqslant0.15$ GeV/c^2 by the π^0 Dalitz decay. Whereas we obtain good agreement with DLS in the Ca+Ca and C+C systems, our calculation overshoots somewhat in the two lighter systems, which could be impounded on the scaling procedure. However, in the mass range spanned by the η Dalitz decay, i.e., $M_{e^+e^-}\simeq0.15$–0.5 GeV/c^2, the DLS data exceed the calculated η component by large factors, ranging, e.g., at 0.25 GeV/c^2, from 10 in Ca+Ca and C+C, to 6 in α+Ca and still 4 in d+Ca. Consequently, in this mass range, additional physical processes, like pn bremsstrahlung, Δ decays or yet other processes, are needed to account for the dilepton yields measured by the DLS. This conclusion holds even if the full range of the systematic errors discussed here is allowed for.

In summary, we have evaluated the Dalitz contribution of π^0 and η decays to the inclusive di-electron mass spectra in

1 *A* GeV heavy-ion collisions from measured meson production cross sections. After filtering those components with the DLS detector acceptance, a direct comparison with recently published dilepton mass spectra has been presented. It clearly supports the conclusion of the DLS collaboration that the measured di-electron yields for masses 0.15–0.55 GeV/c^2 cannot be explained by Dalitz decays of η mesons alone and that, for all systems studied by DLS, additional physical processes are therefore needed to explain the observed set of data. Furthermore, it will have to be investigated whether there is any link to the dilepton enhancement observed recently in ultrarelativistic heavy-ion collisions [4–6].

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