(A Few Remarks about) Dielectron Sources

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Dileptons in hadronic/nuclear collisions

and their multiplicity dependence


1) Initial stage sources (Drell-Yan, Bremsstrahlung). The semiinclusive dilepton yield $\langle \ell^+\ell^-\rangle_{n_{had}}$ is only weakly correlated with the final hadron multiplicity $n_{had}$.

2) Intermediate stage sources (QGP, hadron gas, mixed phase, DCC). $\langle \ell^+\ell^-\rangle_{n_{had}}$ rises faster than linearly with $n_{had}$ (“quadratic dependence”). The dilepton yield is proportional to the lifetime of the intermediate state [a clock for fireball lifetimes – U. Heinz and K. S. Lee, Phys. Lett. B 259, 162 (1991)].

3) Final stage sources are the decays of freely streaming hadrons leaving the interaction region. They are considered “trivial” and parametrized as “cocktail”. $\langle \ell^+\ell^-\rangle_{n_{had}} \propto n_{had}$. 
Hadronic intermediate stage processes

1) Dilepton producing decays of hadrons ($\pi^0 \rightarrow e^+ e^- \gamma$) and hadron resonances ($\omega \rightarrow \pi^0 e^+ e^-$);
2) Reactions with two hadrons (or resonance(s)) in the initial state ($\pi^+ \pi^- \rightarrow \pi^0 e^+ e^-$, $\pi^+ \rho^- \rightarrow e^+ e^-$);
3) Reactions with three hadrons in the initial state ($\pi^+ \pi^- \pi^0 \rightarrow \pi^0 e^+ e^-$);
4) Reactions with four hadrons in the initial state ($\pi^+ \pi^- \pi^0 \pi^0 \rightarrow e^+ e^-$).

Danger of the double (triple) counting ($\pi^+ a_1^- \rightarrow e^+ e^-$, $\pi^+ \pi^0 \rho^- \rightarrow e^+ e^-$, $\pi^+ \pi^0 \pi^- \pi^0 \rightarrow e^+ e^-$).

Key: To classify the processes according to the numbers and species of stable hadrons in the initial and final states with (all) possible resonances in the intermediate states.
HADES at GSI Darmstadt, 2008

High Acceptance Di-Electron Spectrometer at Gesellschaft für Schwerionenforschung mbH, Darmstadt, Germany


Fig. 1. (a) Normalized, background-subtracted and efficiency-corrected $e^+e^-$ invariant-mass distribution compared to thermal dielectron cocktails of free $\pi^0$, $\eta$, and $\omega$ decays (cocktail A, solid line), as well as including $\rho$ and $\Delta$ resonance decays (cocktail B, long-dashed line). Only statistical errors are shown. (b) Ratio of data and cocktail A (full symbols), compared to the corresponding ratio from the 2 A GeV C + C run [14] (open symbols). Statistical and systematic errors of the measurement are shown as vertical and horizontal bars, respectively. The shaded area depicts the 15% normalization error. Averages over the 0.15–0.50 GeV/c² mass range are indicated by lines; they correspond to the $f$ factors discussed in the text. The dashed curve corresponds to the ratio cocktail B/cocktail A for 1 A GeV.
Axel Drees: Dileptons and Photons at RHIC Energies
Excess in 150-750 MeV/c² = 3.4 ± 0.2 ± 1.3 ± 0.7
\[ \rho^0 \rightarrow e^+ e^- \text{ versus } \pi^+ \pi^- \rightarrow e^+ e^- \]

Dielectron differential rates from a thermalized hadron gas

\[ \rho^0 \text{ formation: } \pi^+ \pi^- \rightarrow \rho^0 \]
\[ \rho^0 \text{ production: } \pi + N \rightarrow \rho^0 + N, \ N + N \rightarrow N + N + \rho^0, \text{ etc.} \]
Decay $\rho^0 \rightarrow \pi^+ \pi^- e^+ e^-$

Not seen


The VMD inspired form factor included by A. Faessler, C. Fuchs, and M. I. Krivoruchenko, PRC 61, 035206 (2000).

Calculation using the form factor:

$B_{e^+e^-} = 1.7 \times 10^{-4}$

$B(M_{ee} > 0.1 \text{ GeV}) = 4.5 \times 10^{-6}$

$B_{\mu^+\mu^-} = 7.1 \times 10^{-7}$
Decay $\rho^0 \rightarrow \pi^+\pi^- e^+e^-$

This decay was suggested as a possible source of dielectrons in HIC by A. Faessler, C. Fuchs, and M. I. Krivoruchenko, PRC 61, 035206 (2000).

They argued that it may be a more intensive source of dielectrons than $\rho \rightarrow \pi e^+e^-$, which was considered, together with other elementary processes, in C. Gale and P.L., PRD 49, 3338 (1993).

In the following we calculate the dielectron thermal rate assuming the vacuum spectral function of the $\rho^0$ and ignoring the Bose-Einstein enhancement for the final state pions. We assume two different temperatures: $T=80$ MeV, which roughly describes the final hadron distributions in HADES experiment and $T=160$ MeV, which may be relevant for the CERN SPS and PHENIX experiments.
Decay $\rho^0 \rightarrow \pi^+ \pi^- e^+ e^-$

Dielectron differential rates from a thermalized meson gas
Decay $\rho^0 \rightarrow \pi^+\pi^-e^+e^-$

Dielectron differential rates from a thermalized meson gas

In progress: $\rho^\pm \rightarrow \pi^\pm\pi^0e^+e^-$
Dielectron decay of $a_1(1260)$?

Considered as a possible source of dielectrons in HIC by A. Faessler, C. Fuchs, and M. I. Krivoruchenko, 2000.

$a_1(1260)$ parameters (PDG 2008):
$I^G = 1^−, J^P = 1^+, m = 1230 \pm 40$ MeV,
$\Gamma = 250 − 600$ MeV

Dominant decay mode: $a_1 \rightarrow \rho + \pi \rightarrow 3\pi$

$\Gamma(a_1^+ \rightarrow \pi^+\gamma) = 640 \pm 246$ keV M. Zielinski et al., PRL 52

$a_1^+ \rightarrow \pi^+e^+e^- ...$ not seen

Massive photon production in the VMD Model:
Phenomenological $a_1 \rho \pi$ Lagrangian

J. Wess, B. Zumino, Phys. Rev. 163, 1727 (1967)

\[
\mathcal{L} = \frac{g a_1 \rho \pi}{\sqrt{2}} \left( \mathcal{L}_1 \cos \theta + \mathcal{L}_2 \sin \theta \right)
\]

\[
\mathcal{L}_1 = A^\mu \cdot (V_{\mu\nu} \times \partial^\nu \phi) \quad \mathcal{L}_2 = V_{\mu\nu} \cdot (\partial^\mu A^\nu \times \phi)
\]

\[
V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu
\]

Xiong, Shuryak, Brown, PRD 46, 3798 (1992) \hspace{1cm} 0

C. Song, PRC 47, 2861 (1993), solution I \hspace{1cm} 0.217

C. Song, PRC 47, 2861 (1993), solution II \hspace{1cm} 0.631

Faessler, Fuchs, Krivoruchenko, PRC 61, 35206 \hspace{1cm} 1

Turbide, Rapp, Gale, IJMPA 19, 5351 (2004) \hspace{1cm} 0.558
Electromagnetic Branching Ratios

\[ m_{a_1} = 1230 \text{ MeV} \]

- \[ a_1^+ \to \pi^+ + \gamma \]
- \[ a_1^+ \to \pi^0 + e^+e^- \]
- \[ a_1^+ \to \pi^0 + e^-e^- \quad M_{ee} > 150 \text{ MeV} \]
Dielectron spectra for various $\sin \theta$

$B = \frac{\Gamma(a_1^- \rightarrow \pi^- e^+ e^-)}{\Gamma(a_1^- \rightarrow \pi \rho)}$

$m_{a_1} = 1.23 \text{ GeV}/c^2$
Formation of $a_1^+$: $\pi^+\pi^0\pi^0 \rightarrow \pi^+e^+e^-$
Reaction rate in an ideal HG

\[ 1 + 2 + \cdots + N \rightarrow a + b \]

\[ R = K_i K_f \int d\Phi_N \int d\Phi_{ab} (2\pi)^4 \delta(P - p_a - p_b) \]

\[ \times \sum_{\lambda_1, \ldots, \lambda_N} \sum_{\lambda_a, \lambda_b} |M_{N \rightarrow a+b}|^2 \]

\[ d\Phi_N = \prod_{i=1}^{N} \frac{d^3 p_i}{2E_i} \frac{1}{(2\pi)^3} f_i(T, E_i, \mu_i), \]

\[ d\Phi_{ab} = \prod_{x=a,b} \frac{d^3 p_x}{2E_x} \frac{1}{(2\pi)^3} F_x(T, E_x, \mu_x). \]
$e^+ e^-$ production rates, Song II

$T = 150$ MeV

Song II

$\pi^\pm \pi^0 \pi^0 \rightarrow \pi^\pm e^+ e^-$

$\pi^\pm \pi^0 \pi^0 \rightarrow \pi^\pm e^+ e^-$ direct

$\frac{1}{2} a_{1}^\pm \rightarrow \pi^\pm e^+ e^-$

$M (\text{GeV})$

$0.1 \ 0.2 \ 0.3 \ 0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.8 \ 0.9 \ 1$
Formation of $a_1^+$: $\pi^+\pi^+\pi^- \rightarrow \pi^+e^+e^-$
$e^+ e^-$ production rates, Song II
$\pi^\pm \pi^\mp \pi^- \text{ versus } \pi^\pm \pi^0 \pi^0$

$T = 150\text{ MeV}$

Song II

$M (\text{GeV})$

$\frac{dR}{dM} (\text{fm}^4 \cdot \text{GeV}^{-1})$

$\pi^+ + \pi^+ + \pi^- \rightarrow \pi^+ + e^+ e^-$

$\pi^\pm + \pi^0 + \pi^0 \rightarrow \pi^\pm + e^+ e^-$
Total rate from the three-$\pi$ reactions

\begin{center}
\begin{tikzpicture}
  \begin{axis}[
    width=\textwidth,
    xlabel=M (GeV),
    ylabel=dR/dM (fm$^{-4}$ GeV$^{-1}$),
    xmin=0.1, xmax=1,
    ymin=10^{-9}, ymax=10^{-6},
    xtick={0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1},
    ytick={10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}},
    legend pos=south east,
  ]
    \addplot[red, mark=x] coordinates {
      (0.1, 1.0) (0.2, 0.5) (0.3, 0.2) (0.4, 0.1) (0.5, 0.05)
    } node[above right] {Song I}
    \addplot[green, mark=square] coordinates {
      (0.1, 0.1) (0.2, 0.05) (0.3, 0.02) (0.4, 0.01) (0.5, 0.005)
    } node[above right] {XSB}
    \addplot[magenta, mark=diamond] coordinates {
      (0.1, 0.01) (0.2, 0.005) (0.3, 0.002) (0.4, 0.001) (0.5, 0.0005)
    } node[above right] {Song II}
    \addplot[blue, mark=triangle] coordinates {
      (0.1, 1.0) (0.2, 0.5) (0.3, 0.2) (0.4, 0.1) (0.5, 0.05)
    } node[above right] {$\pi^+\pi^-\rightarrow e^+e^-$}
    \addplot[black, mark=star] coordinates {
      (0.1, 0.1) (0.2, 0.05) (0.3, 0.02) (0.4, 0.01) (0.5, 0.005)
    } node[above right] {$\pi^+\pi^-\rightarrow e^+e^-$}
  \end{axis}
\end{tikzpicture}
\end{center}
Lagr. mixing angle from $e^+e^- \rightarrow 4\pi$

Fitting the excitation function from all available data.

\[ e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- \]
Result: \( \sin \theta = 0.460 \pm 0.003 \)

\[ e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^- \quad \& \quad e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0 \]
Result: \( \sin \theta = 0.466 \pm 0.005 \)
Lagr. mixing angle from $\tau^- \rightarrow 3\pi + \nu_\tau$


Simultaneous fit to five data sets (total of 330 data points).

$\sin \theta = 0.463 \pm 0.005$
$\chi^2/\text{NDF}=219.5/318$
Confidence Level=100%

(4 pi reminder: $0.460 \pm 0.003$, $0.466 \pm 0.005$)
Total $\chi^2/N$ versus $\sin \theta$
Total rate from the 3 pi annihilation
What next?

\[ \nu_\tau \rightarrow W^- a_1^\tau \rightarrow \rho, \sigma \rightarrow \pi \]

\[ \pi^- \rightarrow \sigma \rightarrow \rho^o \rightarrow \gamma^* \]

\[ \pi^+ \rightarrow a_1^+ \rightarrow \pi^+ \]

\[ \pi^+ \rightarrow \sigma \rightarrow \rho^o \rightarrow \gamma^* \]

\[ \pi^- \rightarrow a_1^\tau \rightarrow \pi^- \]

\[ \pi^+ \rightarrow a_1^+ \rightarrow \pi^+ \]
The $a_1(1260)$ and $a_1(1640)$ interfering