φ-Meson Mass Modification in Heavy-Ion Collisions

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Abstract

We recently presented a method of analyzing invariant-mass spectra of kaon pairs resulting from decay of φ mesons produced in high-energy heavy-ion collisions. It can be used to extract the shifts in the mass and the width (\(\Delta M\) and \(\Delta \Gamma\)) of the φ mesons when they are inside the dense matter formed in these collisions. We have now performed a Monte-Carlo simulation of this process. We illustrate our method with the help of available preliminary data. Extracted value of \(\Delta M\) is significantly larger than that obtained with an earlier method. Our results are consistent with the experimentally observed \(p_T\) dependence of the mass shift.

1. Introduction

Relativistic heavy-ion collisions and the consequent formation of a dense and possibly thermalized blob of matter provides a means to test the theoretical prediction of (partial) restoration of chiral symmetry, which would manifest itself in a downward shift in the mass of a hadron so long as it is inside the blob. Here we outline our work\textsuperscript{1} regarding the φ-meson mass and describe results of a Monte-Carlo simulation that we have performed more recently.

Recently E-802 collaboration at AGS (BNL) has reported preliminary results on the shift in the mass of the φ mesons produced in central Si + Au collisions at 14.6 A GeV/c.\textsuperscript{2,3} It
was found that in the events with the highest multiplicity (top 2% target-multiplicity-array cut) the mass drops by $2.3 \pm 0.9 \pm 0.1$ MeV compared to the free-space value. For the $\phi$ mesons with $p_T < 1.25$ GeV/c, the shift was even more ($3.3 \pm 1.0 \pm 0.1$ MeV), whereas for $p_T > 1.25$ GeV/c, there was no apparent shift. No numbers were reported for the shift in the decay width of the $\phi$ mesons. However, from the confidence contours for 1, 2 and 3 standard deviations in the observed mass versus width plot given in Ref. 3, it appears that the central value of the width is higher than the free-space value by about 0.78 MeV.

2. Method

We present a different method of analyzing the invariant-mass spectra of kaon pairs. We then use the data in Refs. [2-3] only to illustrate our method. We find that our method yields a shift in the $\phi$-meson mass which is significantly larger than the values quoted above. We caution the reader that since these data are preliminary, our numerical results are obviously subject to change. However, our main point is the method presented here which is independent of whether the published data$^{2,3}$ are eventually confirmed or not. We think the present method has relevance to the analysis of future data on $\phi$ production. This acquires added importance in view of a similar experiment having been performed at SPS (CERN).

Let $M_0$ and $M_1$ be the rest masses and let $\Gamma_0$ and $\Gamma_1$ be the widths of the $\phi$ meson in the free space and in the dense medium, respectively. We define the shifts as $\Delta M = M_0 - M_1$ and $\Delta \Gamma = \Gamma_1 - \Gamma_0$, so that both are positive when the mass drops and the width increases with respect to their free-space values.

In Ref. 3, the invariant-mass spectrum of the $K^+K^-$ pairs was fitted by a function consisting of a background term and a relativistic Breit-Wigner (BW) resonant term convoluted with a Gaussian experimental mass resolution function; see Fig. 1. This procedure yielded the values of $\Delta M$ and $\Delta \Gamma$ given above. However, are these values obtained by fitting a single BW term to the (background-subtracted) data correct? We think they are not.

Since the mean lifetime of $\phi$ in its rest frame is about 45 fm/c, a majority of $\phi$’s are
expected to decay long after the dense medium in which they were produced has ceased to exist. That is, they will decay essentially in free space ($\Delta M = 0 = \Delta \Gamma$). The rest of the $\phi$'s will decay while still inside the dense medium. Hence a better procedure would be to fit the background-subtracted data with two instead of one BW terms, one unshifted and the other shifted, added with appropriate weights. This we now proceed to do.

We work in the centre-of-mass frame of the dense medium. Let $f$ be the fraction of $\phi$'s decaying inside the medium; then $(1 - f)$ is the fraction decaying in free space. The unshifted BW has mass $M_0$, width $\Gamma_0$ and weight $(1 - f)$, and the shifted BW has mass $M_1$, width $\Gamma_1$ and weight $f$. We reanalyze the background-subtracted data by using:

$$\frac{dN_{K^+K^-}}{dM} = (1 - f) \, BW_c(M, M_0, \Gamma_0) + f \, BW_c(M, M_1, \Gamma_1).$$

Here $BW_c$ denotes the relativistic BW term convoluted with a Gaussian experimental mass resolution function; see Ref. [1] for details. If the effect of the time dilation on the lifetime of a $\phi$ is taken into account, the fraction $f$ can be shown$^1$ to be given by

$$f(\Delta M, \Delta \Gamma) = 1 - \exp\left(-\frac{M_1 \Gamma_1 d}{\sqrt{M_T^2 \cosh^2 y_{cm} - M_T^2}}\right),$$

where $M_T$ and $y_{cm}$ denote, respectively, transverse mass and centre-of-mass rapidity of the $\phi$ traversing the medium and $d$ is the distance traversed. We have used a Monte-Carlo simulation procedure to calculate $f$ by averaging over these three variables. We generated $\phi$'s according to the experimental distributions in $M_T$ and $y_{cm}$. The distance $d$ was also sampled by assuming a cylindrical geometry for the medium. More details of this will be published elsewhere.

3. Results

Results of a least-squares fit to the same experimental data as in Fig. 1, with two instead of one BW terms, are shown in Fig. 2. The two fitted parameters are $\Delta M = 6.1 \pm 1.8$ MeV and $\Delta \Gamma = 4.2 \pm 3.9$ MeV. The resultant value of $f$ is 0.35. Note that the above value of the mass shift is significantly larger than that obtained with a one-BW fit.
It is evident from Eq. (2) that as $p_T$ increases the fraction $f$ decreases. This means a larger fraction of $\phi$’s decay in free space and hence the mass shift decreases. This is exactly what has been observed experimentally.\(^3\)

References

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Fig. 1: The background-subtracted invariant-mass spectrum for the $K^+K^-$ pairs. The histogram represents data from Ref. 3. The two curves represent two convoluted BW terms. The dashed curve corresponds to $\Delta M = 0 = \Delta \Gamma$, and the solid curve to $\Delta M = 2.3$ MeV and $\Delta \Gamma = 0.78$ MeV.

Fig. 2: The two dashed curves represent two convoluted BW terms, one unshifted and the other shifted. The solid curve corresponds to their weighted sum as in Eq. (1).
Fig. 1
Fig. 2

$M_{\text{inv}}$ (MeV)