SUBTHRESHOLD $\phi(1020)$ MESON PRODUCTION IN CENTRAL HEAVY-ION COLLISIONS

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Abstract

We report on preliminary results of subthreshold $\phi(1020)$ meson production in central reactions of Ni+Ni and Ru+Ru/Zr at beam energies far below the production threshold in nucleon-nucleon collisions. The data are taken at SIS/GSI with the 4π detector system FOPI. Invariant-mass analyses of pairs of candidates of charged kaons are performed. Extrapolations of the ϕ yields to 4π based on an isotropic thermal model are performed. The results are compared with strange meson production probabilities found by other experiments. The importance of the channel $\phi \to K^+K^-$ for the understanding of the subthreshold production and spectral distribution of antikaons is emphasized.

1 Experiment

At the Schwerionensynchrotron SIS at GSI/Darmstadt the reactions ^{58}Ni+^{58}Ni at 1.93 A·GeV and ^{96}Ru+^{96}Ru/^{96}Zr at 1.69 A·GeV have been studied by using the detector system FOPI. About $N_{ev} = 4.7 \cdot 10^6$ $(6.8 \cdot 10^6)$ central events comprising about 9% (15%) of the total cross section have been analysed for the system Ni+Ni (Ru+Ru/Zr). Applying a simple geometrical model, from the overlap volume of sharp spheres the average number of participants has been determined as $< A_{part} >= 90 \pm 10$ (140 ± 15).

For the present analyses the FOPI subdetectors HELITRON and forward Plastic Wall have been utilized [1]. The addressed phase-space region is characterized by the intervals $\Delta\theta$ $(15^o < \theta < 27^o)$ and $\Delta\beta$ $(0.4 < \beta < 0.85$, midrapidity corresponds to $\beta_{cm} = 0.71$ (0.69) at 1.93 (1.69) A·GeV beam energy). All kinetic quantities are deduced from the velocity vectors which follow from the time-of-flight (TOF) and positions as measured with the Plastic Wall. The drift chamber HELITRON serves for particle identification only.

2 Results

The distribution of the invariant mass $M_{inv} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$ of K^+ and K^- candidates allows to extract about 480 (650) pairs for the Ni+Ni (Ru+Ru/Zr) system (cf. Fig. 1). The uncorrelated background has been determined applying the technique of event mixing. Before mixing, all events have been rotated into a unique reaction plane. This method prevents that artificial correlations arising from differently azimuthally oriented events enter into the reference distribution. The modest signal-to-background ratio is the result of an unsufficient kaon identification; i.e. protons and mirror tracks of protons contaminate the K^+ and K^- mass distributions, respectively. After background subtraction the number of reconstructed ϕ mesons via the $\phi \to K^+K^-$ channel amounts to $N_\phi = 44 \pm 18$ (57 ± 22) for the Ni+Ni (Ru+Ru/Zr) system.

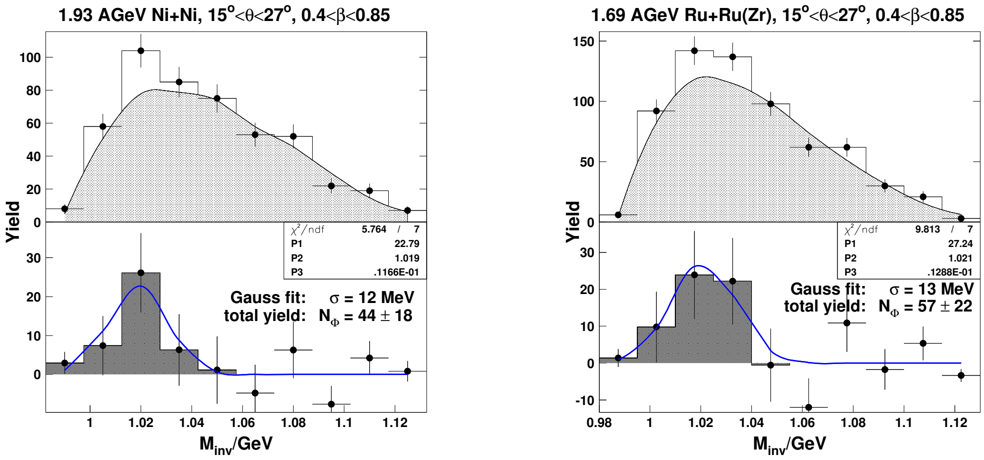

Figure 1: The invariant mass distribution of pairs of candidates of charged kaons measured in a phase-space region near mid-rapidity and at small transverse momentum (upper row). The shadowed histograms show the uncorrelated background obtained via event mixing techniques. The lower row gives the corresponding distributions after background subtraction. The statistical errors are governed by those of the true distributions, since the mixed distributions are generated with almost two orders of magnitude higher statistics. The normalization has been performed at large invariant masses $M_{inv} > 1.05$ GeV. The left (right) panels display the results for the Ni+Ni (Ru+Ru/Zr) system.

In order to enhance the portion of K^+K^- pairs in the data sample special ϕ selection cuts have been applied. They demand a high track quality in the HELITRON and a narrow matching of the extrapolated tracks with the hits on the Plastic Wall. Applying these cuts to "pseudo-kaons", i.e. protons with similar momentum range as kaons, the detection efficiency has been estimated to $\epsilon_{det,K}(\Delta\theta_K, \Delta\beta_K) = 0.44 \pm 0.02$ (0.52 ± 0.03). The efficiency-corrected ϕ multiplicity per event is determined via

$$P_\phi(\Delta\theta_K, \Delta\beta_K) = \frac{N_\phi(\Delta\beta_K, \Delta\theta_K)}{N_{ev} \cdot \epsilon^2_{det,K}(\Delta\beta_K, \Delta\theta_K) \cdot BR}. \tag{1}$$

Here, $BR = 0.491$ is the branching ratio of the decay $\phi \to K^+K^-$. Note, that $P_\phi(\Delta\theta_K, \Delta\beta_K)$ is not corrected for kaon decay. Inserting the numbers given above into Eq. (1), we find a ϕ multiplicity per central collision within the given kaon detection phase space (described by $\Delta\beta_K, \Delta\theta_K$) of $P_\phi(\Delta\theta_K, \Delta\beta_K) \cdot 10^5 = 9.8 \pm 4.0$ (6.3 ± 2.4) for the Ni+Ni (Ru+Ru/Zr) system.

These numbers can be compared directly with the output of transport approaches when implementing the given detector acceptance and geometry and taking into account the finite kaon lifetime, whereas the 4π extrapolations in Sect. 3 below depend on the assumptions on the spectral shape of the ϕ mesons, i.e. they are model dependent.

3 Extrapolation to 4π and comparison with other data

To get an estimate of the detector acceptance for the ϕ reconstruction Monte Carlo simulations have been performed.. In this simulation, the ϕ's (modelled by an initial mass distribution of Breit-Wigner shape with the mean mass $m = 1019.4$ MeV and the width $\Gamma = 4.4$ MeV taken from the free ϕ) are emitted randomly and isotropically in the c.m. system of the colliding nuclei. The expanding thermal source is characterized by two parameters, the temperature T and the radial flow velocity β_r, according to the Siemens-Rasmussen formula of an expanding spherical shell [2]. For the acceptance weight of our phase-space region $\epsilon_{acc}(\Delta\theta_K, \Delta\beta_K)$, only the exponential slope at midrapidity $T_B(y_{cm})$ of the ϕ transverse-mass distribution

$$\frac{1}{m_t^2}\frac{dN}{dm_t} \propto \exp\langle -\frac{m_t}{T_B(y_{cm})}\rangle \tag{2}$$

is relevant. In our simulations, the ϕ's decay promptly and exclusively into K^+K^- pairs. Only those pairs, where both the kaon and the antikaon survive the decay in flight ($c\tau_K = 3.71$ m) on the way ($l_{TOF} \simeq 4$ m) to the forward wall, are detected within the rather restricted phase space given by $\Delta\theta_K$ and $\Delta\beta_K$.

As a starting point for the 4π extrapolated ϕ production probability

$$P_\phi(4\pi) = \frac{P_\phi(\Delta\beta_K, \Delta\theta_K)}{\epsilon_{acc}(\Delta\beta_K, \Delta\theta_K, T_B(y_{cm}))} \tag{3}$$

we assume that the ϕ mesons flow similarly as the nucleons. Thus, we can use the midrapidity proton slope of $T_B(y_{cm}) = 125$ (110) MeV as measured for the Ni+Ni (Ru+Ru/Zr) system [3, 4, 5]. With $\epsilon_{acc}(\Delta\beta_K, \Delta\theta_K, T_B(y_{cm})) \cdot 10^3 = 6.0 \pm 0.1$ (6.9 ± 0.1) one gets the 4π production probability per central event $P_\phi(4\pi) \cdot 10^3 = 16.3 \pm 6.7$ (9.1 ± 3.5). It should be noted that the acceptance weight ϵ_{acc} depends strongly on the spectral shape of the $\phi(1020)$ mesons. For instance, a decrease of the midrapidity slope $T_B(y_{cm})$ by a factor of 2 would increase the acceptance (and consequently decrease the 4π extrapolated ϕ production) by a factor of about 1.7. Therefore, the extrapolated values should be treated with caution. The above assumption, namely that the ϕ's flow together with the nucleons due to frequent ϕN interactions and consequently show a similar energy distribution as protons, is a hypothesis. Especially, the ϕN cross section is poorly known [6, 7]. Let us now compare our findings with the results of recent investigations [8, 9] of the ϕ meson production for the same systems but utilizing the FOPI subdetectors Central Drift Chamber and Plastic Barrel [1] which allow to select low-momentum kaons in the phase-space region near target rapidity ($p_t > 0.1$ GeV/c, $p_{lab} < 0.5$ GeV/c, $39^o < \theta < 140^o$). An extrapolation to 4π with the same spectral distribution as described above would yield a production probability for the system Ni+Ni (Ru+Ru/Zr) which is a factor 8.6 (3.3) smaller than estimated for the phase-space region around midrapidity. This finding can be interpreted as a hint to a much steeper spectral distribution of the ϕ mesons. Indeed, when changing the slope parameter to $T_B(y_{cm}) = 59$ (72) MeV the 4π production probabilities (per central collision) of ϕ mesons deduced from these very different phase-space regions would coincide hence yielding

$$P_\phi(4\pi) \cdot 10^3 = 8.7 \pm 3.6 \ (6.4 \pm 2.5). \tag{4}$$

A preliminary estimate of the 4π extrapolated ϕ-to-K$^-$ ratio leads to the result that about 30% of the antikaons found in subthreshold heavy-ion reactions at (negative) excess energies with respect to the nucleon-nucleon threshold of $\sqrt{s} - \sqrt{s_{thr}^{NN}} \simeq -200$ MeV to -300 MeV arise from the decay of intermediate $\phi(1020)$ mesons [10]. Note, however, that this result carries typical uncertainties of about 50% both in statistics (arising from the low measured yields and the poor signal-to-background ratio of the ϕ mass distribution) and systematics (due to the rather uncertain spectral distribution of both the ϕ's and the low-energy antikaons). Moreover, as a result of the decay kinematics, the daughter-antikaons of the ϕ's preferentially populate the low-energy (c.m.) part of the K$^-$ spectrum which in heavy-ion reactions is a superposition of quite a lot of baryon-baryon and meson-baryon channels [11, 12]. Until now, only a few experimental hints for such a low-energy enhancement of the antikaon yield have been found experimentally [13, 14].

4 Summary

In summary we report here on first attempts to identify ϕ mesons in central subthreshold heavy-ion collisions via the hadronic decay channel $\phi \to K^+K^-$ with $K^\pm$ detection in the HELITRON subdetector of the FOPI detector system. In the present stage of the analysis, our very preliminary results on the ϕ production probability are shown to be consistent with results obtained in a different phase-space region [8, 9] when using a ϕ spectral distribution being different from that of protons.

If the present unexpected high ϕ production will be proved true then for K^- meson production the channel $\phi \to K^+K^-$ would play a comparably important role in sub-threshold heavy-ion reactions as in near-threshold proton-proton collisions where about 50% of the antikaons arise from intermediate ϕ's [15].

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