φ puzzle in heavy-ion collisions at 2 AGeV: how many $K^-$ from φ decays?

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Abstract. The preliminary experimental data on φ production in the reaction Ni(1.93 AGeV) + Ni point to a puzzling high φ yield which can not be reproduced with present transport codes. We survey the experimental situation and present prospects for dedicated measurements of the φ multiplicities with the $K^+$ and $K^-$ and $e^+$ and $e^-$ channels at HADES and FOPI.

1. Introduction

Within the SU(3) quark model, the φ meson has the composition $\phi = \omega_8 \cos \Theta_V - \omega_1 \sin \Theta_V$ where $\omega_1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$ and $\omega_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$ are the singlet and octet representations. For a deviation by $\Delta \Theta_V = 3.7^o$ from ideal mixing with $\Theta_V = 35.3^o$ the weight of the $s\bar{s}$ component in the φ is still 0.998, i.e. it consists exceedingly of hidden strangeness. The branching ratio for $\phi \rightarrow K^+K^-$ is 0.491; via this decay channel the φ is accessible e.g. in the FOPI and HADES detectors. The electromagnetic decay branching $\phi \rightarrow e^+e^-$ is $3.0 \times 10^{-4}$ thus allowing φ identification with HADES. The narrow vacuum width of 4.43 MeV makes the φ meson an ideal object of in-medium hadron spectroscopy in strongly interacting matter since any mass shift should become clearly visible, in contrast to the wide ρ meson.

Since the mass of the φ meson is only 32 MeV above the $K^+K^-$ threshold a substantial coupling of the φ and $K^\pm$ dynamics is to be expected. Due to this reason an understanding of the role of the φ meson in intermediate-energy heavy-ion collisions is highly desirable. It is the aim of this contribution to summarize the present experimental situation and to consider prospects for future measurements.

2. Experimental situation

The FOPI collaboration has collected about $4.7 \times 10^6$ central events (10% $\sigma_{\text{tot}}$, $\langle A_{\text{part}} \rangle = 90$) in the reaction Ni(1.93 AGeV) + Ni. The φ production is deeply sub-threshold, as the threshold in pp collisions is at 2.59 GeV. Via identified $K^\pm$ pairs within the acceptance region of the central drift chamber (CDC) original φ mesons are reconstructed [3, 4]. The corresponding acceptance is centered around target rapidity and restricted by angular and momentum limits [5]. Recently also $K^\pm$ candidates have

† Supported by BMBF 06DR920, 06DR921, PROCOPE 9910330 and GSI.
‡ There are also data for the reaction Ru(1.69 AGeV) + Ru, but not yet fully analyzed; therefore we focus here on the reaction Ni(1.93 AGeV) + Ni.
been used to reconstruct \( \phi \) mesons within the HELITRON acceptance at midrapidity [5]. The statistics is still too low to obtain any distribution. Rather, in both acceptance regions only the total numbers of \( \phi \) mesons could be given. To accomplish an extrapolation to full phase space, the assumption of an isotropic distribution seems most natural as long as other information is not at our disposal. This assumption must be supplemented by additional information on parameters of the distribution. Based on the analyses of \( \pi^- \), \( p \) and \( d \) spectra [6] an effective temperature parameter of \( T_{\text{eff}} = 125 \) MeV was used in [2] to deduce a \( \phi \) production probability of \( 4 \times 10^{-4} \) which, with additional experimental information, resulted in a \( \phi/K^- \) ratio of about 0.1. Later on, by improved analyses, both values were substantially increased [3]. In [7] the information of the \( \phi \) yields in the CDC and HELITRON acceptances were combined and yielded an even larger \( \phi \) multiplicity and a \( \phi/K^- \) ratio in the order of unity. The consistency of the CDC and HELITRON data enforced a value of \( T_{\text{eff}} \approx 70 \) MeV. In estimating the \( \phi/K^- \) ratio, \( K^- \) measurements at KaoS [8] and \( K^-/K^+ \) ratios together with \( K^+ \) multiplicities from FOPI [9] are employed and properly scaled (for details cf [7]).

3. Theoretical situation

First attempts to calculate the subthreshold \( \phi \) production in heavy-ion collisions have been performed by Ko and collaborators within a BUU transport approach [10]. They included the channels \( NN, N\Delta, \Delta\Delta, \pi N, \pi \Delta \) and \( K\bar{K} \rightarrow \phi X \). The \( K\bar{K} \) channel was found to be small, while the \( \pi N \) channel dominated. The parameterization used in [10] for the \( pp \rightarrow pp\phi \) reaction underestimates the later on measured near-threshold data [11]. Therefore, we performed a new transport calculation by employing the Nantes IQMD code [12] with newly parameterized elementary cross sections. Within

![Diagrams for the elementary \( \phi \) production processes used in [13]. Upper set: \( \pi N \rightarrow N\phi \), lower set: \( NN \rightarrow NN\phi \); \( a, b \) \( (c, d) \) denote incoming (outgoing) nucleons. Diagrams labeled by "a" are for direct processes with a \( \pi\rho\phi \) vertex, while diagrams "b" include the \( NN\phi \) coupling with poorly known strength. The relative phases between diagrams "a" and "b" are important for interferences.](image-url)
a one-boson exchange model, in [13] the $\phi$ cross sections $\pi N \rightarrow N\phi$ and $pp \rightarrow ppp\phi$ have been adjusted to recent threshold-near data [11]. The corresponding diagrams are displayed in figure 1. The parametrization of the channels described above as well as the other $\phi$ production channels from $NN$, $N\Delta$, $\Delta\Delta$, $\pi N$, $\pi\Delta$ collisions are obtained by the following formulas:

$$
\sigma(pp \rightarrow ppp\phi) = 5.78 \mu b \cdot (|\sqrt{s} - 2m_n - m_\phi|/1\text{GeV})^{1.309} \quad (1)
$$

$$
\sigma(pn \rightarrow pn\phi) = 41.3 \mu b \cdot (|\sqrt{s} - 2m_n - m_\phi|/1\text{GeV})^{1.438} \quad (2)
$$

$$
\sigma(\pi^+ n \rightarrow p\phi) = 101 \mu b \cdot (|\sqrt{s} - m_n - m_\phi|/1\text{GeV})^{0.466} \quad (3)
$$

$$
\sigma(\pi^+ n \rightarrow p\phi) = \sigma(\pi^- p \rightarrow n\phi) = 2\sigma(\pi^0 p \rightarrow p\phi) = 2\sigma(\pi^0 n \rightarrow n\phi) \quad (4)
$$

$$
\sigma(nn \rightarrow nn\phi) = \sigma(pp \rightarrow ppp\phi), \quad \sigma(p\Delta \rightarrow N\phi) = 0 \quad (5)
$$

$$
\sigma(N\Delta \rightarrow NN\phi) = 0.375(\sigma(pp \rightarrow ppp\phi) + \sigma(pn \rightarrow pn\phi)) \quad (6)
$$

$$
\sigma(\Delta\Delta \rightarrow NN\phi) = 0.25(\sigma(pp \rightarrow ppp\phi) + \sigma(pn \rightarrow pn\phi)). \quad (7)
$$

The resulting transverse momentum ($p_t$) vs rapidity ($y$) distribution for the reaction Ni(1.93 AGeV) + Ni is displayed in figure 2. Indeed, the distribution looks very isotropic, as highlighted by a comparison with the parameterization

$$
\frac{dN}{dm_\perp dy} = N m_\perp^2 \cosh(y) \exp \left\{ -\frac{m_\perp \cosh(y)}{T_{\text{eff}}} \right\} \quad (8)
$$

with $T_{\text{eff}} \simeq 70$ MeV ($m_\perp = \sqrt{p_t^2 + m_\phi^2}$ is the transverse mass). While these calculations support the isotropy assumption made in [2, 3, 5, 7] for a 4π extrapolation, the total yields remain below the preliminary experimental data. This has inspired the authors of [14] to include in transport model calculations further elementary reactions which contribute to $\phi$ production. In particular, processes with incoming $\rho$ mesons are considered. However, despite of an increase of the $\phi$ multiplicity for the full phase
space as well as for the CDC and HELITRON acceptance regions separately, still the experimental values are underestimated. This result calls for an explanation. In particular, the preliminary experimental ratio $\phi/K^- \approx 1$ indicates that half of the $K^-$ stem from $\phi$ decays. Otherwise, in many transport calculations of the $K^-$ production (cf. [15] for a recent study), the $\phi$ channel is not included at all; inclusion of the surprisingly frequent $\phi$’s would then deliver too many $K^-$. If the ratio $\phi/K^- \approx 1$ would be experimentally confirmed, then in previous experiments too few $K^-$ were seen. This appears as a puzzling situation which is caused by the restricted and partially disjunct phase space regions where the $\phi$ and $K^-$ are measured.

Notice in this context that HSD transport calculations for central Au + Au reactions [16] give a ratio $\phi/K^- \approx 1$ at beam energy of about 1.5 AGeV, while at 1.9 AGeV the ratio drops below unity.

4. Prospects of improved measurements

To elucidate the maximum count rates of $\phi$ mesons in future experiments we present here estimates for the symmetric reaction C(2.0 AGeV) + C which are based on (i) the isotropic distribution in equation (8) with $T_{\text{eff}} = 70$ MeV, (ii) target thickness corresponding to 1% interaction probability, (iii) maximum beam intensities compatible with the data acquisition times and taping rates for the detector systems HADES and FOPI, and (iv) acceptance regions, efficiencies, and geometry of the detectors. The corresponding details are described in [17]. The normalization factor $N$ in equation (8) corresponds to a $\phi$ production probability of $P_{\phi} = (\sigma_{\phi}/\sigma_{K^-}) \times (\sigma_{K^-}/\sigma_{\text{tot}})$, where the first term is 0.2 from [18] and the second one equals $2 \times 10^{-4}$ from [19]. Taking into account the corresponding branching ratios, the maximum count rates of $\phi$ mesons per day are: (i) 30 (HADES, $e^+e^-$ channel, $18^\circ \leq \Theta_e \leq 88^\circ$), (ii) 5 (HADES, $K^+K^-$ channel, $44^\circ \leq \Theta_K \leq 88^\circ$, and $p_K < 1$ GeV/c), (iii) 160 (HADES, $K^+K^-$ channel, $18^\circ \leq \Theta_K \leq 88^\circ$ and $p_K < 1$ GeV/c), (iv) 50 (FOPI, $K^+K^-$ channel, detector combination of CDC and upgraded Barrel: $37^\circ \leq \Theta_K \leq 140^\circ$ and $0.1$ GeV/c < $p_K < 1$ GeV/c, combination of HELITRON and Plastic Wall: $10^\circ \leq \Theta_K \leq 27^\circ$ and $0.2$ GeV/c < $p_K < 0.8$ GeV/c, as well as mixed combination of CDC and HELITRON). These numbers do not include any background estimates. While (iii) looks very promising, it needs an upgrade since at present both the granularity and the time-of-flight resolution within the TOFino angular region $18^\circ \leq \Theta_K \leq 44^\circ$ are not sufficient for $K^\pm$ identification.

At HADES the $e^+e^-$ channel gives the most complete phase space distribution ($\sim 40\%$ geometrical acceptance), as seen in the upper left panel of figure 3. Though the $K^\pm$ channel is accessible with an order of magnitude lower acceptance it will still allow for reliable reconstruction of the $\phi$ distribution and the corresponding total production probability (see upper right panel of figure 3). No momentum restriction is invoked in case of the leptonic decay while for the hadronic branch the $K^\pm$ momenta are restricted to $p_K < 1$ GeV/c for ensuring the particle identification. The corresponding cut squeezes the covered phase space distributions only marginally.

At FOPI the $\phi$ identification via the $K^\pm$ channel within the CDC/Barrel acceptance gives access only to the target rapidity region (see lower left panel of figure 3). The phase space coverage is enlarged hence allowing access to the region of highest phase-space density, i.e. at midrapidity and at small transverse momentum,
Figure 3. Phase-space distribution $d^2 N/dp_t dy$ of $\phi$ mesons within the acceptance regions of HADES (figures on top, left panel: $e^+e^-$ channel, right panel: $K^+K^-$ channel) and FOPI (figures on bottom, $K^+K^-$ channel, left panel: $K^\pm$ in the acceptance of CDC with upgraded Plastic Barrel, right panel: $K^\pm$ within HELITRON). Here, $p_t^0 = (p_t/A)/(p_{proj}/A_{proj})_{cm} = (\beta_t/\gamma)/(\beta/\gamma)_{cm}$ and $y^0 = (y/y_{cm})_{cm} = (y/y_{cm} - 1)$ are the normalized transverse momentum and rapidity, respectively, and $A = m/m_p$ is the particle mass number. Both observables are related to the corresponding projectile quantities in the center-of-mass (c.m.) frame of the colliding nuclei (with $y_{cm} = 0.904$ and $(\beta/\gamma)_{cm} = 1.032$ for 2.0 A-GeV beam energy). A logarithmic intensity scale is used.

when exploiting the HELITRON/Plastic Wall subdetector combination (see lower right panel of figure 3). When combining the kaons of the HELITRON with the antikaons of the CDC even the intermediate region can be populated (not displayed). Further details of these simulations can be found in [17].
5. Summary

In summary we refer to transport model calculations which underestimate the preliminary φ yields in individual phase space regions. This together with a large ratio $φ/K^- = O(1)$ points to the need of an improved understanding of the φ dynamics in intermediate-energy heavy-ion collisions. We present a series of simulations to elucidate the prospects for dedicated φ measurements in the $K^+K^-$ and $e^+e^-$ channels at already existing facilities at SIS/GSI Darmstadt.

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