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PRODUCTION OF ϕ MESONS IN CENTRAL Si+Au COLLISIONS AT 14.6 A·GeV/c

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ABSTRACT

The production of ϕ mesons from central Si+Au collisions has been measured by E859 at the BNL-AGS by selecting events with identified K^+K^-pairs. The values for the mass and width of the ϕ obtained from the invariant mass of the kaon pairs are consistent with those of the Particle Data Book. Preliminary results for the invariant $\frac{1}{2\pi m_T}\frac{d^2n}{dm_T dy}$ distribution and dn/dy are presented. The inverse slope parameter for an exponential m_T fit to the m_T spectrum is 171±18 MeV. An analysis of the ratio of the ϕ signal to the combinatoric background in the K^+K^- invariant mass distribution provides a rough estimate of the size of the reaction region, which is found to be consistent with the E859 interferometry measurements.

1. Introduction

The ϕ meson, as the lowest mass bound state of $s\bar{s}$ quarks, is the lightest meson with flavor-symmetric hidden strangeness. This property, coupled with the general interest in strangeness production in heavy ion reactions,[1] implies that measurement of ϕ production is an important goal in the programmatic study of heavy ion reaction dynamics. For instance, enhanced production of ϕ's in ultrarelativistic heavy-ion collisions was first proposed by Shor[2] as one of the signatures of the formation of the quark-gluon plasma (QGP). Shor's prediction on the ϕ enhancement was based on the observation that the ϕ production is suppressed in ordinary pp collisions in accordance with the Okubo-Zweig-Izuka (OZI) rule, leading to $\phi/\rho^0 \sim 1/20$ from 24 GeV/c to 1.5 TeV/c.[3,13] However, if a quark-gluon plasma were formed, ϕ's could be produced copiously via the coalescence of s and $\bar{s}$ quarks during the hadronization phase, and so could result in ϕ/ρ^0 values several times that found in ordinary collisions. More recently, an enhancement in $\phi/(\omega+\rho^0)$ in S + U collisions relative to p + U collisions has been observed by NA38[4] at CERN. While this enhanced ϕ production might be explained by the formation of a QGP, Koch, Heinz and Pisút[5] have argued that meson-meson interactions in a dense hadron gas can also lead to enhanced ϕ production. They assume that the absorption cross-sections for ϕ by mesons are large ($\sim$ 10 mb), which by detailed balance implies that the cross section for ϕ production in meson-meson collisions is also large. Rescattering also plays a role in the suggestions by Ko and Sa[6] that the decrease of hadron masses in hot and dense matter as a result of chiral symmetry restoration increases substantially the ϕ meson production cross sections from $K\bar{K} \rightarrow \phi\ \rho$ and $K\Lambda \rightarrow \phi N$ reactions. Another indicator of chiral symmetry restoration would be shifts in the width of the ϕ peak, since the small decay energy available in $\phi \rightarrow K^+K^-$ makes it very sensitive to modifications of ϕ and K meson parameters in hadronic matter.[7] In contrast, Grassi and Heiselberg[8] have argued that the enhancement observed by NA38 could be an artifact of the p_t cutoff applied to the data.

Clearly, the existing data allow for a variety of theoretical explanations. The measurement of absolute yields and p_T spectra for ϕ production will presumably help differentiate between these alternative approaches. From an experimental point of view, we should point out that in addition to the various exotic prospects, ϕ meson production in heavy ion collisions is interesting simply because it is the heaviest meson yet to be measured in BNL-AGS heavy ion experiments to date.

2. The Experiment

The experimental data were taken by using E859 experiment apparatus, which is based on the E802 magnetic spectrometer[9] as augmented by a sophisticated second-level trigger.[10] The trigger substantially enriched the interested events samples by identifying and selecting desired particles online. The data presented here were taken by using the beam (intensity $\sim 1-3\times10^6$ ions/spill) of 14.6 A·GeV/c ^{28}Si ions from BNL Tandem-AGS complex incident upon a Au target of thickness 944 mg/cm^2 (approximately 1% of an interaction length).

Potential events must first satisfy a hardware trigger that selected those interactions corresponding to the uppermost 15% of the charged multiplicity distribution as measured by the Target Multiplicity Array (TMA) which also had at least one charged particle in the spectrometer aperture. After selection by this first-level trigger, the event was then processed by the E859 particle-identifying trigger electronics.

To implement the task of online particle identification, two multiwire proportional trigger chambers with 6.35 mm pitch were added to the E802 spectrometer between the magnet and the Time-of-Flight (TOF) wall. Both the wire chambers and the TOF wall were read out through LeCroy ECLine CAMAC modules,[11] which were configured to provide a programmable, data-driven system capable of on-line track finding and particle identifying within 40 μs. The TOF timing signals were read out by fast-encoding TDC's. The hits on two trigger chambers and the TOF wall were used to find tracks associated with the interaction. The trigger first finds sets of three aligned hits then retrieves the momentum and path length from lookup tables. These two values combined with the time of flight are then used to determine the mass. Any desired range of particle mass and momentum can be chosen, and different one and two-particle triggers may be specified simultaneously. For example, the results reported here were obtained from a data set obtained with a Level II trigger condition requiring either two charged kaons in any sign combination or one anti-proton. Under these conditions, the second-level trigger increased the yield of kaon pairs by a factor of 12. Tests of the trigger showed that the two-particle efficiency was 99%.

A total $\sim$ 5.2 million events were taken during the AGS running period of February-91. All of this data was taken with the spectrometer spanning the range of 14° - 28° with respect to the beam line, and a value of the central field of the spectrometer magnet of 0.4T. The

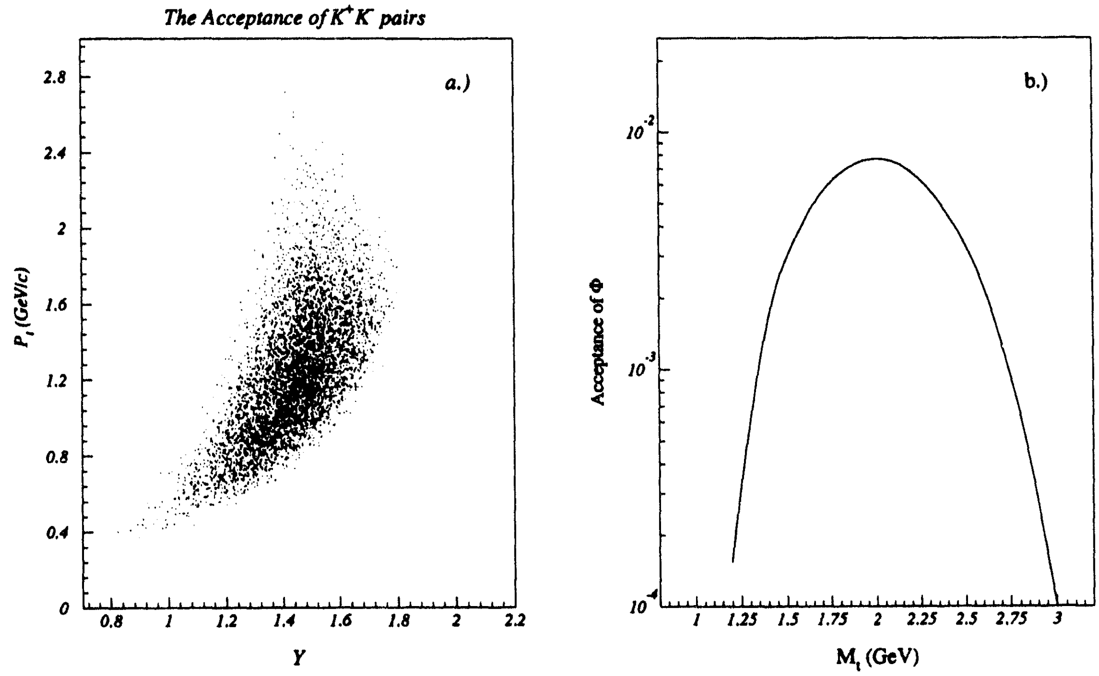

Fig. 1: a.) The experiment distribution of accepted K^+K^- pairs in p_T and y (rapidity) space. b.) The acceptance curve vs m_T for ϕ's in the region $1.2 < y < 1.7$.

acceptance region for K^+K^- pairs and and the absolute acceptance for $\phi \rightarrow K^+K^-$ are shown in Figure 1 a.) and b.), respectively. The ϕ acceptance was obtained from a GEANT Monte Carlo simulation of the full E859 spectrometer system, the results from which were passed through the same analysis chain as the data in the off-line analysis. The data were analyzed in the rapidity range of 1.2-1.7 and for kaons with momentum less than 3.5 GeV/c.

3. Data Analysis

In the off-line analysis, both time-of-flight and Čherenkov information is used, in conjunction with the momentum determined in the tracking system, to unambiguously identify kaons. Below a momentum of 2.2 GeV/c, time-of-flight alone separates kaons from pions at the 3σ level, and also separates kaons from protons to roughly 4 GeV/c (this latter number safely extends beyond the range of our online trigger momentum cut of $\sim$ 3.6 GeV/c). Above momenta of 2.2 GeV/c, the information from a segmented gas Čherenkov detector is used to separate kaons from pions.

Following particle identification, the invariant mass of K^+K^- pairs is constructed, as shown in Fig. 2. The solid line in the figure is a fit to a function combining a relativistic Breit-Wigner[15] and the background:

$$N_{K^+K^-}(m) = a \cdot BW(m) + b \cdot BG(m) \tag{1}$$

where BW is the relativistic Breit-Wigner convoluted with a gaussian experimental resolution

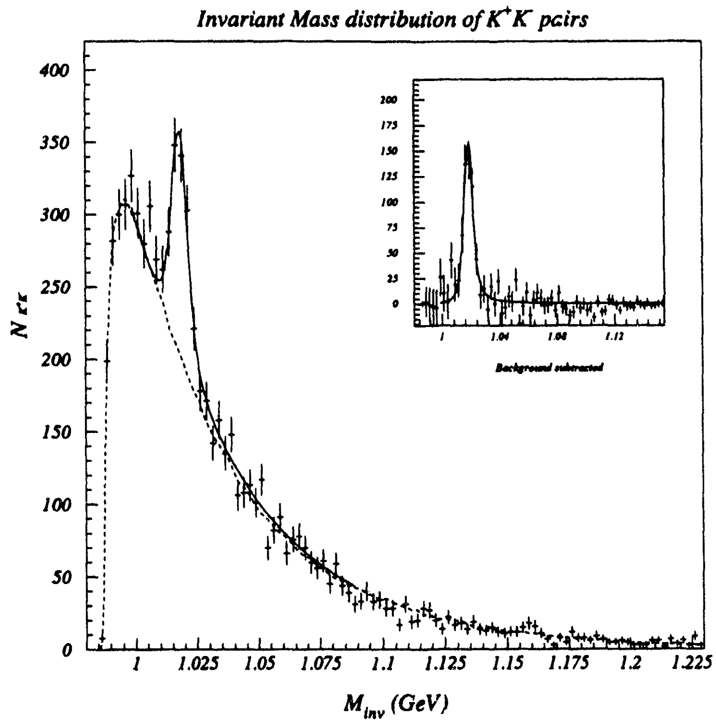

Fig. 2: The invariant mass distribution of K^+K^- pairs. The solid line is the fit to a function combining a relativistic Breit-Wigner and the background. The dashed line is the background distribution from mixing events. The insert shows the the background subtracted M_{inv} distribution.

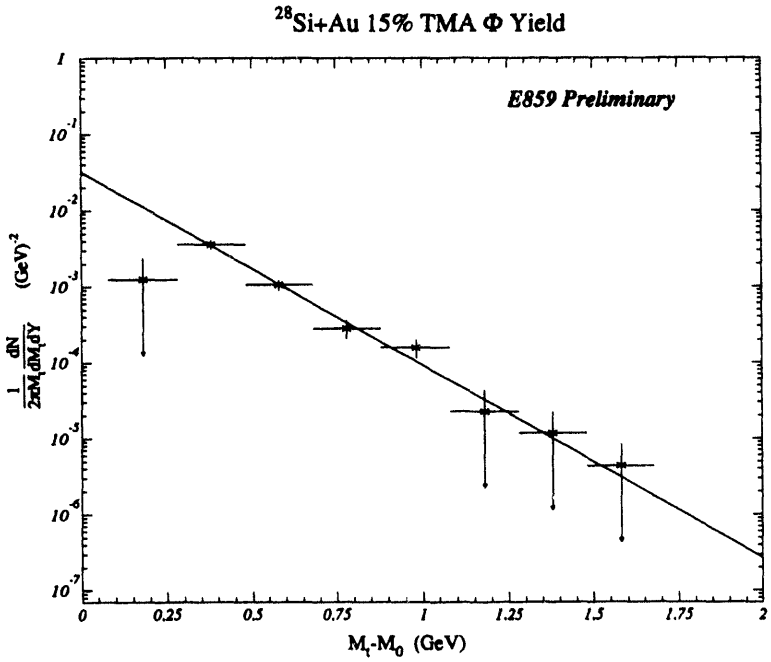

Fig. 3: The invariant yield for ϕ's versus m_T. Multiply the y-axis by 0.578 barns to convert into invariant cross section. The rapidity range of the data is 1.2 to 1.7. The line is a fit to an exponential m_T distribution.

function in the following form

$$BW(m) = \int_{m_1}^{m_2} \frac{m' m_0 \Gamma(m')}{(m'^2 - m_0^2)^2 + (m_0\Gamma)^2} \cdot \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}(\frac{m-m'}{\sigma})^2} dm' \tag{2}$$

where

$$\Gamma(m) = \Gamma_0 (\frac{q}{q_0})^{2\ell+1} \frac{2q_0^2}{q^2 + q_0^2} \tag{3}$$

where ℓ is the relative angular momentum of the decay products (= 1 for $\phi \to K^+K^-$), q and q_0 are the momenta of the decay products (kaons) in the rest frame of the resonance for the invariant masses m and m_0 respectively, i.e., ($q = \sqrt{m^2/4 - m_K^2}$). and Γ_0 is the width of the resonance. This function is convoluted against a mass resolution function of width σ, the mass resolution of the spectrometer, which is mainly determined by the momentum and angular resolutions of the track. In one approach to the fitting procedure, σ was fixed to a value of 2.2 MeV, as determined by a GEANT simulation of the detector system. As a check, we have fitted the data for two different cases. In one case, we fit the data by fixing the ϕ width to the standard value in the Particle Data Book, which is $\Gamma_0 = 4.43$ MeV, and we found $\sigma = 2.4 \pm 0.5$ MeV. In the second case, we treat σ as a free parameter, and performed a fit to the three quantities (σ, m_0, Γ_0). We found for this case $\sigma = 2.3 \pm 0.4$ MeV. In order to perform the fit for the second case, we have to restrict Γ_0 to not less than 3.5 MeV during the fit because of the strong correlation between Γ_0 and σ. In short, those numbers are in excellent agreement with the value predicted by Monte Carlo simulation.

The background term BG(m) in Eq. 1 was determined by studying artificial pairs obtained by mixing K^+ and K^- from different events in the sample. The resulting distribution in invariant mass was fit to the empirical form

$$BG(m) \sim e^{a_1 m + a_2 e^{-m}} \quad . \tag{4}$$

This distribution is shown in Fig. 2 as a dashed line.

The mass and the width of the ϕ obtained by fitting to Eq. 1 with σ fixed to (the GEANT-predicted) value of 2.2 MeV are $m_0 = (1.0179{+}0.0025){\pm}0.0004$ GeV and $\Gamma_0 = 4.6{\pm}1.1$ MeV, where the small additional term in m_0 corrects for the asymmetric fit to the ϕ peak.[12] The quoted errors are statistical only. The values of mass and width are consistent with the values in the Particle Data Book. Treating σ as a free parameter provides similar values: $m_0 = (1.0178 + 0.0025) \pm 0.0004$ GeV, $\Gamma_0 = 4.7 \pm 0.8$ MeV, and $\sigma = 2.3 \pm 0.4$ MeV.

To find the transverse mass spectrum for ϕ's, the invariant mass distribution is calculated as a function of m_T of the ϕ. The number of ϕ's in a given m_T bin is found by a background

Inverse Slope	ϕ	π^+	π^-	K^+	K^-
T (MeV)	171 ± 18	163 ± 2	154 ± 3	191 ± 7	174 ± 11

Table 1: Inverse slope parameters for ϕ, pions and kaons at y = 1.45 in Si+Au central collisions (15% centrality cut).

System	ϕ/π	ϕ/K^+	ϕ/K^-
$\mathrm{Si} + \mathrm{Au} \rightarrow \phi + X$	0.45%	2.8%	14%
$pp \rightarrow \phi + X$	$(0.2 \pm 0.1)\%$	$3.4 \pm 1.7\%$	$13 \pm 6.5\%$
Si+Au/pp	2.3 ± 1	0.82	1.1

Table 2: The ratios of ϕ to other particles in two different systems. For Si+Au collisions, ratios were obtained from dN/dy at $y = 1.45 \pm 0.25$. For pp collisions, ratios are from inclusive cross sections. See text for a discussion of errors.

subtraction, then converted to a normalized spectrum by making an m_T-dependent acceptance correction. The results of this procedure are shown in Fig. 3 as the absolute invariant yield.

The solid line in Fig. 3 shows the results from fitting the m_T spectrum to

$$\frac{1}{2\pi m_T} \frac{dN}{dy dm_T} = Ae^{-m_T/T} \quad ,$$

from which it was determined that T = 171±18 MeV. As a comparison, the inverse slope parameters for pion's, kaon's and our result for the ϕ are tabulated in Table 1. In short, the inverse slope of ϕ is comparable to that of other particles. We have also integrated the m_T distribution to find $dN/dy = 0.051 \pm 0.021$ for $1.2 < y < 1.7$. These values have been corrected by the square of our single-track reconstruction efficiency, estimated on the basis of hand-scans to be $90 \pm 5\%$. The error on dN/dy includes a 30% systematic error due to the uncertainty of extrapolating the data to the lower m_T region for the integration.

4. Discussion

Ideally, one would like to investigate the ϕ yield as a function of centrality, and to compare these results to those obtained from p-A and p-p collisions at the same $\sqrt{s}$. Unfortunately, the difficulties in obtaining a large sample of ϕ's do not allow this, either within our data set or via comparison to world data. In this section we present what is available, and also discuss the possible significance of the peak-to-background ratio in the K^+K^-spectrum.

4.1. Comparison to other data

The ϕ yield has been compared with the yields of pions, $K^+$and K^-. For pions, we have taken the average yield of π^+'s and π^-'s, as measured in the E859 apparatus. Identical centrality and rapidity cuts were imposed on the pions and the kaons as for the ϕ's. These ratios are shown in Table 2.

It is unfortunate that there are no data on ϕ inclusive production in pp collisions below a beam momentum of 24 GeV/c, thereby necessitating a non-trivial extrapolation to AGS energies. This is illustrated in Fig. 4, which shows the ϕ yield in pp collisions as a function of s, along with possible upper and lower limits for the region below the lowest data point. The open circles are from Ref. 13 and the references therin. The triangular point at small s is

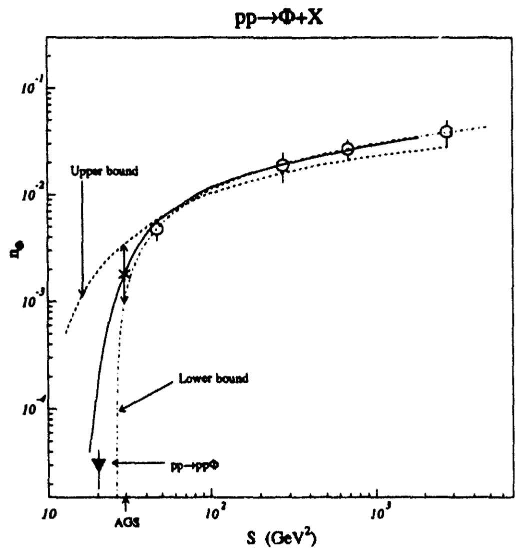

Fig. 4: The ϕ multiplicity in pp collisions as the function of S.

exclusive data from the reaction $pp \to pp\phi$,[14] used here as a lower limit in the extrapolation. The functional form $n_\phi = A + B{\cdot}\ln s$ describes the s dependence of the available data very well, but fails badly on the (lower energy) exclusive data. Clearly, this curve may be used only as a lower bound. The solid and dotted lines on Fig. 4 represent two plausible extrapolations of the higher energy data, and show that the uncertainty in the extrapolation to the AGS regime can be as large as factor of 2, leading to an estimate of $n_\phi = (2 \pm 1) \times 10^{-3}$, and the values presented in Table 2. One should also keep in mind that the pp data are from inclusive reactions, but our data are in differential yield (dN/dy). A direct comparison between A-A central collisions and p-A or A-A peripheral collisions would be much more informative. **4.2.**

The ratio of N_ϕ to $N_{K^+K^-}$

Recent, Pratt[16] has observed that (assuming that the population of states is purely statistical), the ratio of the ϕ peak to the combinatoric background is sensitive to the size of the interaction region. Begin by defining $C_{S/B}$, the signal to background ratio as

$$\begin{aligned} C_{S/B} &\equiv \frac{N_\phi(k) + N_{K^+K^-}(k)}{N_{K^+K^-}(k)} \\ &= 1 + \frac{dN_\phi/dk}{dN_{K^+K^-}/dk} \end{aligned} \tag{5}$$

where k is the momentum of one of the kaons in the rest frame of the pair with invariant mass $M = 2\sqrt{m_K^2 + k^2}$. The number density of ϕ's in momentum interval $k \to k + dk$ is given by

$$\frac{dN_\phi}{dk} = \frac{dN_\phi}{dM} \cdot \frac{dM}{dk}$$

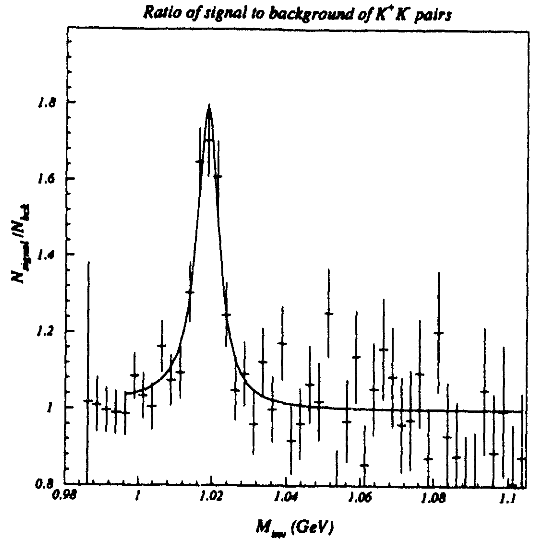

Fig. 5: The actual data (signal) to background ratio as the function of M_{inv}. The solid line is a fit to Eq.(8), and the fit gives $R_{rms} = 3.5 \pm 0.1\ fm$.

$$\begin{aligned} \frac{dN_\phi}{dk} &= \frac{dN_\phi}{dM}\cdot 2\frac{k}{M} \\ &= 3\cdot\frac{\Gamma/2\pi}{(M-M_\phi)^2+(\Gamma/2)^2}\cdot\frac{2k}{M}\cdot B_{K^+K^-} \end{aligned} \tag{6}$$

where Γ and M_ϕ are the width and the mass of ϕ, respectively, and the factor of three is the spin degeneracy of the ϕ. Since we only measure the decay channel $\phi \rightarrow K^+K^-$, the ϕ yield is multiplied by the branching ratio $B_{K^+K^-} = 0.497$. For the unbound K^+K^- pairs, the number density is given by

$$\frac{dN_{K^+K^-}}{dk} = \frac{V}{(2\pi\hbar)^3}\cdot 4\pi k^2 \tag{7}$$

where V is the volume of the interaction region. Combining (6) and (7), one finds

$$C_{S/B} = 1 + \frac{6\pi\hbar^3}{V}\frac{1}{Mk}\frac{\Gamma}{(M-M_\phi)^2+(\Gamma/2)^2}B_{K^+K^-} \tag{8}$$

If we assume the source or the reaction region to be a "hard sphere" with radius R_H, then $V = \frac{4\pi}{3}R_H^3$ and $R_H = \sqrt{\frac{5}{3}}R_{rms}$, where R_{rms} is the rms radius typically quoted by HBT particle correlation measurements. We have made a fit to Eq.(8), treating Γ and R as free parameters, and obtained $R_{rms} = 3.5 \pm 0.1 fm$ and $\Gamma = 7.2 \pm 0.8$ MeV, as shown in Fig. 5 with the solid line. This value of Γ is larger than the standard ϕ width since it contains the experimental mass resolution.[17] The result for Γ obtained in this fashion, is in good agreement with the result of fitting the data to a bare non-relativistic Breit-Wigner (without the experimental resolution function), in this case, $\Gamma = 8.6 \pm 1.1$ MeV. These results are in good agreement with those found via HBT with $2K^+$'s for this same sample of central Si+Au events: $R(2K^+) = 3.2 \pm 0.4$ fm.[18,19] However, ons should note that this analysis is quite preliminary, and needs modification to include a correct relativistic treatment, and also requires further investigation into both its theoretical validity and the experimental treatment of systematic errors.

5. Conclusions

The ϕ meson has been measured in experiment E859 at BNL-AGS in Si+Au central collisions at 14.6 A·GeV/c. The measured mass and width of the ϕ are consistent with world averages. The inverse slope of the m_T spectrum of the ϕ is comparable to that of pions and kaons. The ϕ yield at one point of rapidity was obtained and compared to the yields of pions and kaons at the same rapidity. Attempts to compare to the ϕ yield in p-p collisions are hampered due to the lack of data at the appropriate energy. An analysis based on the population of ϕ and K^+K^- pairs in phase space gives an estimate for the source size which is in good agreement with the values given by $2K^+$interferometry.

This data analysis is still in progress. In the near future, one can expect improved data for the m_T spectrum and dN/dy distribution in both central and minimum bias Si+Au collisions.

6. Acknowledgements

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