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Production of $\rho + \omega$ and ϕ in $p - W$ and $S - U$ collisions at 200 GeV/nucleon

NA38 Collaboration

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The transverse mass differential cross-sections for the $\rho + \omega$ and ϕ resonances is obtained, in the central rapidity region, in $p - W$ and $S - U$ interactions at 200 GeV/nucleon. The measured $\rho + \omega$ and ϕ temperatures are $\sim 15\%$ higher in $S - U$ as compared to $p - W$ collisions. The ratio of cross-sections times branching ratios into the dimuon channel $\frac{B_{\phi\sigma\phi}}{B_{\rho\sigma\rho} + B_{\omega\sigma\omega}}$ is studied as a function of the energy density reached in the collision and of the dimuon transverse momentum. The measured ratio is 2 to 3 times larger in $S - U$ than in $p - W$ collisions and an enhancement is observed in $S - U$ interactions with increasing energy density.

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1 INTRODUCTION

A. Shor suggested in 1985 that a strong enhancement of the ϕ/ω ratio in heavy ion collisions, as compared to the value measured in $p - p$, could be a clean signature of Quark-Gluon Plasma (QGP) formation [1]. In the plasma in chemical equilibrium it is expected, from chiral symmetry restoration, that strange quark pairs $s\bar{s}$ are abundantly produced with respect to light quark pairs $u\bar{u}, d\bar{d}$, for temperatures of the order of the strange quark mass. A first experimental indication has been reported by our collaboration in the high transverse dimuon momentum region [2]. Our analysis, extended afterwards to low transverse momentum, showed an enhancement of the cross-sections relative yield times branching ratio into the dimuon channel $\frac{B_{\phi\sigma\phi}}{B_{\rho\sigma\rho}+B_{\omega\sigma\omega}}$ with increasing transverse neutral energy released in the interaction [3].

It has also been anticipated that the presence of a phase transition would be revealed by the evolution of the average transverse momentum (P_T) of hadrons as a function of the energy density ϵ [4]. Moreover, it has been predicted that a collective expansion of the system produced in the collision would change the thermal spectra of the hadrons [5]. Both informations could be provided by the inverse exponential slope of the final hadron transverse mass spectra ($M_T = \sqrt{M^2 + P_T^2}$), the so-called temperature (T).

The data presented in this letter were collected with 200 GeV/nucleon proton and sulphur beams impinging on tungsten and uranium targets respectively. Two dedicated configurations of the NA38 detector were used with special emphasis on muon pair mass resolution. A detailed description of the experimental setup and data analysis can be found in [6]. Differential cross-sections for the production of $\rho + \omega$ and ϕ resonances in the dimuon channel as a function of the transverse mass M_T and of the energy density ϵ are measured. From these, the cross-section ratio $\frac{B_{\phi\sigma\phi}}{B_{\rho\sigma\rho}+B_{\omega\sigma\omega}}$ as a function of ϵ and P_T are obtained. Finally, we discuss hadron nuclear absorption effects.

2 $\rho + \omega$ AND ϕ TRANSVERSE MASS DIFFERENTIAL CROSS-SECTIONS

As pointed out by R. Hagedorn [7], a thermal radiation source in local equilibrium at fixed rapidity produces a transverse mass spectrum described by i) $\frac{1}{M_T} \cdot \frac{dN}{dM_T} = A \cdot M_T \cdot K_1(\frac{M_T}{T})$, where K_1 is the modified Bessel function and the inverse slope T is a temperature. In the limit where the mass of the resonance m_R is much greater than T , $m_R \gg T$, it follows that formula i) becomes ii) $\frac{1}{M_T^{3/2}} \cdot \frac{dN}{dM_T} = A \cdot \exp(-\frac{M_T}{T})$. The differences between the exact expression i) and the approximation ii) are substantial at low P_T , but rather small for the P_T range covered by this analysis, i.e. for $P_T \geq 0.6$ GeV/c. We also use the approximation iii) $\frac{1}{M_T} \cdot \frac{dN}{dM_T} = A \cdot \exp(-\frac{M_T}{T})$, the so-called M_T scaling. The inverse slope fitted values obtained with the three different parametrizations are summarized in Table 1. No significant differences are observed between i) and ii). On the other hand, the inverse slopes given by iii) are systematically higher by about 10 MeV than the corresponding ones obtained with i) or ii). Fig. 1 shows the resonance's differential cross-section $(1/M_T^{3/2}) d\sigma/dM_T|_{\Delta Y}$ parametrized by expression ii).

In general, if the system is thermalized, the temperatures given by the different parametrizations are of the order of 200 MeV. The temperatures $T_{\rho+\omega}$ and T_{ϕ} are 23 to 26 MeV higher in $S - U$ than in $p - W$ collisions, which could be interpreted as a possible evidence for higher energy densities in $S - U$ collisions or as an indication of a collective

transverse expansion of the system [5]. As a function of the energy density ϵ ¹⁾ the vector meson temperatures, as shown in Fig. 2, exhibit a pattern (rise and plateau) which is qualitatively in agreement with what is expected from a first order phase transition [4]. Finally, we observe that T_ϕ temperatures are slightly smaller than $T_{\rho+\omega}$.

3 CROSS-SECTION RATIO

The relative yield $R = \frac{B_{\phi\sigma\phi}}{B_{\rho\sigma\rho} + B_{\omega\sigma\omega}}$ is studied for low ($0.6 \leq P_{T\mu\mu} \leq 1.15$ GeV/c) and high ($1.15 \leq P_{T\mu\mu} \leq 3.0$ GeV/c) dimuon transverse momentum regions. In addition, an extrapolation from $P_{T\mu\mu} \geq 0.6$ GeV/c to zero is done in order to obtain an integrated result, using the parametrization ii) mentioned above. The integrated value of this ratio does not depend on the parametrization, within a 1% uncertainty. The systematic error assigned to the ratio R is estimated to be in the range 10 – 15 %. The different sources of uncertainty are discussed in detail in [6].

As shown in Fig. 3, the measured ratio is 2 to 3 times larger in $S - U$ than in $p - W$ collisions, independently of P_T . A clear rise of the ratio with the energy density is seen for high P_T . Fig. 4 shows the dependence of the ratio R with ϵ for the whole P_T domain, after the extrapolation to zero as described above. A smooth increase with ϵ is observed in $S - U$ reactions and an enhancement of a factor of 2.5 is seen (Fig. 4) for the most central $S - U$ collisions with respect to $p - W$ interactions. The Helios/3 experiment finds similar results [10].

4 NUCLEAR ABSORPTION EFFECTS

The P_T and E_T^0 integrated results are particularly interesting when compared to other experiments. Moreover, they allow a common discussion of nuclear absorption effects in $p - N$ and $N - N$ collisions. The value of $\frac{B_{\phi\sigma\phi}}{B_{\rho\sigma\rho} + B_{\omega\sigma\omega}}$ measured in $p - W$ is consistent with other $p - p$ and $p - N$ measurements [11]. Within experimental uncertainties, these combined results favour a similar $(A_{beam} \cdot A_{target})^\alpha$ dependence, i.e. alike nuclear effects, for the ϕ and $\rho + \omega$ resonances [12], since they lead to $\Delta\alpha_{\phi,\rho+\omega} = \alpha_\phi - \alpha_{\rho+\omega} = 0.05 \pm 0.05$. On the other hand, comparing the ratio R measured in $S - U$ collisions, with the value obtained in $p - W$, we are led to $\Delta\alpha_{\phi,\rho+\omega} = 0.23 \pm 0.06 \pm 0.05$, a result which can hardly be explained by hadronic rescattering processes in nuclear matter as described in ref. [13], given the p-induced experimental results.

From our $\rho + \omega$ and ϕ cross-section measurements for $P_{T\mu\mu} \geq 0.6$ GeV/c [6], we obtain directly $\alpha_{\rho+\omega} = 1.00 \pm 0.02 \pm 0.11$, $\alpha_\phi = 1.23 \pm 0.03 \pm 0.05$, leading to $\Delta\alpha_{\phi,\rho+\omega} = 0.23 \pm 0.04 \pm 0.07$, which is consistent with the P_T integrated value quoted above²⁾.

Together, these results show clearly that the ϕ meson production is enhanced in ion collisions as compared to proton interactions.

5 CONCLUSIONS AND DISCUSSION

The higher $\rho + \omega$ and ϕ temperatures measured in $S - U$ collisions with respect to those measured in $p - W$ could be interpreted as an evidence of a collective transverse expansion of the system produced in heavy ion reactions. The study of the vector-meson

¹⁾ The energy density is estimated in the framework of the Bjorken model [8] and can be written as $\epsilon = 3 \langle E_t^0 \rangle / A_T \Delta y \tau_0$, where A_T is the transverse area of the participant's region determined within a geometrical model [9], $\langle E_t^0 \rangle$ the average transverse neutral energy corresponding to the rapidity interval $\Delta y = 2.4$ and $\tau_0 = 1$ fm/c the formation time.

²⁾ All the alpha values quoted in this paper are calculated in the rapidity region $3 < y_{lab} < 4$. They may differ if determined for the whole rapidity domain as pointed out in the previous paper.

temperatures as a function of the energy density in $S-U$ interactions shows a behaviour which qualitatively agrees to what is expected from a first order phase transition.

The observed strangeness enhancement of a factor of 2 to 3, in low and high P_T regions, in $S-U$ as compared to $p-W$ collisions is found to be compatible with a Quark Gluon Plasma scenario [14]. Interpretations based on secondary scattering processes in the framework of Hadron Gas formation, including or not high P_T effects, [15, 13] are ruled out since experimentally ϕ and $\rho + \omega$ resonances show similar absorptions rates and the observed ϕ enhancement exhibits no P_T dependence. Recent calculations considering string fusion models show the same trends as our results [16, 17]. In any case, the observed increase requires the presence of a dense and strongly interacting system evolving towards chemical equilibrium.

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Parametrization of $\frac{1}{M_T} \cdot \frac{dN}{dM_T}$	Temperature (MeV)			
	$p - W$		$S - U$	
	$\rho + \omega$	ϕ	$\rho + \omega$	ϕ
i) $M_T K_1 (M_T/T)$	180.3 ± 2.0	173.6 ± 2.5	203.4 ± 3.0	197.4 ± 9.4
ii) $\sqrt{M_T} \exp(-M_T/T)$	178.7 ± 2.0	171.9 ± 3.3	202.6 ± 2.3	195.4 ± 3.7
iii) $\exp(-M_T/T)$	190.4 ± 2.0	182.1 ± 3.5	216.1 ± 3.0	207.7 ± 2.5

Table 1: $\rho + \omega$ and ϕ temperatures measured in $p - W$ and $S - U$ collisions.

Figure 1: $(1/M_T^{3/2}) d\sigma/dM_T|_{\Delta Y}$ ($\mu\text{b}/(\text{GeV}/c)^{5/2}$) for $\rho + \omega$ and ϕ measured in $p - W$ and $S - U$ collisions at 200 GeV/nucleon.

Figure 2: Temperature T (MeV) of $\rho + \omega$ and ϕ resonances as a function of the energy density ϵ obtained in $S - U$ collisions. The shaded areas represent the temperature measured in $p - W$. The values presented were obtained by fitting the data with parametrization ii).

Figure 3: The ratio $B_{\phi\sigma_\phi}/(B_{\rho\sigma_\rho} + B_{\omega\sigma_\omega})$ in the dimuon channel, as a function of the energy density ϵ in $S-U$ collisions: a) $0.6 \leq P_T < 1.15$ GeV/c and b) $1.15 \leq P_T < 3.0$ GeV/c. The shaded areas represent the value measured in $p-W$.

Figure 4: The ratio $B_\phi\sigma_\phi/(B_\rho\sigma_\rho + B_\omega\sigma_\omega)$ in the dimuon channel, integrated in P_T with extrapolation to zero (as explained in the text), as a function of ϵ in $S-U$ collisions. The shaded area represents the value measured in $p-W$.