Institute for Theoretical and Experimental Physics

13 – 01

ITEP-13-01

Yu.T.Kiselev

Fermilab Library
0 1160 0092403 9

MEDIUM EFFECTS IN NUCLEUS-NUCLEON COLLISIONS AT SUBTHRESHOLD ENERGIES

Moscow 2001

FEB 25 2002
LIBRARY

УДК 530.145 М-16

Medium effects in nucleus-nucleon collisions at subthreshold energies:
Preprint ITEP 13-01/

Yu.T.Kiselev – M., 2001 – 15 p.

We explore the new possibility to study the medium effects at normal nuclear density in subthreshold meson production. We show that extremely slow mesons relative to nuclear environment can be produced in nucleus-nucleon collisions. Due to attractive nuclear potential low momentum ω and K^- mesons might form the omega-mesic and kaonic nuclei. The cross sections for subthreshold meson production in the relevant momentum ranges are estimated and such experiments are found to be feasible.

Эффекты ядерной среды в ядро-нуклонных столкновениях при подпороговых энергиях.

Ю.Т.Киселев

Рассматривается новая возможность изучения влияния ядерной среды на свойства мезонов, рожденных в ядро-нуклонных столкновениях при подпороговых энергиях. Показано, что в таких процессах возможно образование мезонов с чрезвычайно малыми импульсами относительно барионного окружения. Благодаря притягивающему ядерному потенциалу медленные ω и K^- - мезоны могут образовывать ω-мезонные и каонные ядра. Проведенные оценки показывают, что сечения рождения мезонов при подпороговых энергиях достаточно велики для экспериментального изучения эффектов ядерной среды.

Fig. – 4, ref. – 17 names

© Институт теоретической и экспериментальной физики, 2001

1. Introduction

The question about the properties of hadrons and hadronic resonances in baryon environment has attracted much attention during the last years [1]. The knowleadge of these properties is important for understanding both the propagation of the hadrons through the nuclear matter and possible chiral symmetry restoration. QCD inspired effective chiral Lagrangian models [2] as well as approaches based on QCD sum rules [3] predict the decrease of vector meson masses in baryon matter. The resonance production in heavy-ion collisions in which the high density and/or temperature are accesible is apparantly best suited for such study. However, in case of nucleus-nucleus collisions due to a complex dynamics involved the interpretation of the experimental data is ambiguous up to now.

It is therefore necessary to obtain the information at normal nuclear density, where the production and propagation processes are much better under control. Only a few experimental attempts to study the problem in photoproduction [4] and in proton-nucleus collisions at above threshold [5] and subthreshold energies [6] are

known now. The subthreshold reactions have very high potential in this context since the dropping of in-medium hadron masses shifts the production threshold to lower energies which leads to an enhanced production yield. As it was mentioned in [7,8,6] the actual mass shift both for vector mesons and antikaons can well be a function of meson momentum in nuclear matter. In this work we aim at discussion of new experimental possibility to study the momentum dependence of in-medium effects for vector ω and pseudoscalar K^- mesons in specific kinematics.

2. ω meson production

The ω resonance production and its dileptonic decay in πA reaction at 1.1 -1.7 GeV/c was considered in [9]. It was shown that the invariant mass distribution for the ω decay products contains two components. The first one corresponds to resonances decaying in vacuum while the second component related to the decay inside target nucleus. The performed calculations have shown that only a small part of ω's can be produced with low momenta in the target nucleus system, such that substantial fraction of them decays inside even a heavy nuclei. The signal of the resonance mass modification is expected to be seen only in the lowest ω momentum bin $P_z = P_t \leq 0.25$ GeV/c. Besides, the ω signal in the dilepton mode is rather weak and is always accompanied by a large background from ρ^0 decay. The study of in-medium properties of the ω mesons produced in pA reaction at above threshold energy 2.4 GeV was performed in Ref.[10]. The authors suggested to use $\omega \to \pi^0\gamma$ decay channel which has a branching ratio of about three order of magnitude higher than that for dilepton mode $\omega \to e^+e^-$.

It was found that the pronounced signal of the ω with reduced mass can also be observed in the limited range of low ω momenta.

There is, however, exist the alternative possibility of such study. The hadrons with low momenta relative to a nuclear matter can be produced in the inverse kinematics, i.e. in nucleus-nucleon reactions. Let us consider first the zero degree ω meson production in nucleus-proton collisions. It is easy to see that at threshold energy 1.89 GeV per projectile nucleon Ap and pA systems are equivalent. In both cases the ω meson arising with zeroth momentum in the incident nucleon - target nucleon center of mass system has the same laboratory momentum 0.79 GeV/c and moves with the same velocity (but in opposite direction) relative to a projectile or target nucleus. The production of the ω meson of higher energy is caused by internal nucleon motion. Such a process terms as subthreshold one. In case of pA reaction the increase of the ω momentum results in increasing of its velocity relative to a target nucleus. At the same time the ω velocity becomes smaller in the incident nucleus frame because of the ω is moving in the same direction as a surrounding nuclear matter. The ω of momentum about 2.2 GeV/c is near rest inside a projectile nucleus. The dependence of the ω momentum in the projectile nucleus system P_{proj} is shown in Fig.1 as a function of the ω momentum in the laboratory P_{lab}, i.e. in the target proton rest frame. By detecting of the $\omega \rightarrow \pi^0\gamma$ decay products in the laboratory system one can reconstruct the momentum of ω relative to the projectile nucleus. Thus, the momentum dependence of in-medium ω mesons modification effects can be studied explicitly by measurement of the spectrum of an ω mesons from Ap collisions at subthreshold energy regime. The experimental advantage of the

inverse kinematics is that of low momentum hadrons in a projectile nucleus frame have rather high laboratory momenta which are suitable for registration.

The cross sections for inclusive ω production in Ap collisions were calculated in frame of the folding model [11,8,6]. Note that direct ω meson production in first "hard" proton interaction with off-shell nuclear nucleon is the dominant mechanism in the subthreshold energy region. The contribution of the two-step channel ($pN \to NN\pi$, $\pi N \to N\omega$) falls rapidly with increasing of the ω momentum and become kinematically forbidden for $P_\omega > 1.45$ GeV/c. Thus, the differential cross section for direct ω production in Ap (or pA) collisions can be written as a convolution of the internal nucleon momentum distribution n($\mathbf{q}$) and the elementary cross section for ω production in $pN \to NN\omega$ reaction at the same collision energy $S^{1/2}$. In our approach the transition matrix element is assumed to be constant. Therefore the elementary cross section has been described by the tree-body phase space calculation normalized to the corresponding total cross section $\sigma_t(S)$:

$$\frac{d^2\sigma^{Ap\to\omega X}}{dpd\Omega} = N(A)\int d\mathbf{q}n(\mathbf{q})\frac{\sigma_t(S)R_2(S_{NN}, M_N^2, M_N^2)}{R_3(S, M_\omega^2, M_N^2, M_N^2)} \quad (1)$$

Here R_2 and R_3 stand for two-body and three- body phase space, S and S_{NN} are invariant collision energy squared and invariant energy squared of the NN system. The coefficients $N(A)$ account for an effective number of nucleon inside nucleus A for $pN \to NN\omega$ reaction as well as the absorption of the produced ω mesons. They were calculated in the Glauber approximation and found to be 6.0 and 13.0 for carbon and copper nuclei, correspondingly.

The energy dependence of the total cross section for the inclusive ω production in pp collisions was adopted from [12] in form:

$$\sigma_t(S) = 2.5(S/S_0)^{1.47}(S_0/S)^{1.11} \qquad , mb \qquad (2)$$

where $S_0 = (2M_N + M_\omega)^2$ stands for threshold energy squared. In Eq.1 it was assumed that the total cross sections in pp and pn interactions are the same. The function n($\mathbf{q}$) was taken in two Gaussian form with parameters suggested in [6].

The spectra of ω mesons produced at threshold energy 1.89 GeV/nucleon are presented in Fig.2. It is seen that the values of the cross sections in Ap reaction are high enough to be studied experimentally. We found equal yields of the ω with laboratory momentum P_ω=0.79 GeV/c which reflects the equivalence of the pA and Ap systems at the reaction threshold. The cross sections for the ω production in Ap collisions significantly exceed those in pA due to kinematical reason. Namely, at fixed ω momentum in the beam direction both in pA and Ap reactions the values of R_2 appear to be larger in the Ap case. Thus, by applying the appropriate cuts on the momentum of the ω in the laboratory system one can select the different ω momentum intervals in the projectile nucleus frame.

Follow the Ref.[9] we have calculated the two-component $\omega \to \pi^0\gamma$ invariant mass distribution. In-medium meson mass shift at finite nuclear density ρ was determined according [13] as:

$$M^*_\omega = M_\omega(1 - 0.18\rho/\rho_0) \qquad (3)$$

where ρ_0=0.17 GeV^{-3}. For the nuclear densities we have assumed

a three parameters Fermi form [14]:

$$\rho(r) = \rho_0 \frac{(1 + wr^2/R^2)}{1 + e^{(r-R)/a}} \tag{4}$$

with R=2.335(4.20) fm, a=0.552(0.550) fm and w=-0.149(0.0) for ^{12}C (^{63}Cu) nucleus.

For the meson decay inside nucleus its form was described by Breit-Wigner formula:

$$\Gamma(M) = \frac{1}{2\pi} \frac{\Gamma^*_\omega}{(M - M^*_\omega)^2 + \Gamma^2_\omega/4} \tag{5}$$

where

$$M^*_\omega = M_\omega + \delta M \quad , \quad \Gamma^*_\omega = \Gamma_\omega + \delta\Gamma \tag{6}$$

According to [9] the effect of collisional broadening $\delta\Gamma$ and the shift of the meson mass δM can be expressed as:

$$\delta M = -\gamma v \sigma_{\omega N} \rho \alpha \tag{7}$$

$$\delta\Gamma = \gamma v \sigma_{\omega N} \rho \tag{8}$$

In Eqs.(7,8) v is the resonance velocity relative to the projectile nucleus in our case, γ is the associated Lorentz factor, $\sigma_{\omega N}$ stands for the resonance-nucleon total cross section [15] and α=Re(f(0))/Im(f(0)). Our analysis disregards the shift of the ω mass according Eq.7 since the ratio α is small in the case of considered reactions.

The fraction of the ω mesons decaying inside a projectile nucleus (Fig.3) was determined as:

$$F = 1 - e^{-R/v\tau} \quad , \tag{9}$$

where τ stands for the ω mean life.

Fig.4 shows the $\pi^0\gamma$ invariant mass distributions in the $C+p$ and $Cu+p$ reactions when the in-medium mass shift as well as the collisional broadening (dashed curves) effects are taken into account.

The fraction of π^0 mesons rescattered in a projectile nucleus was estimated as:

$$f = 1 - e^{-\rho\sigma_{\pi N}R} \quad , \tag{10}$$

where $\sigma_{\pi N}$ is the total cross section for $\pi^0 N$ interactions at appropriate collisions energy. Due to pion rescattering the values of $M(\pi^0\gamma)$ are spread over a wide range of the invariant masses (dotted curves in the figure). The relative contribution of this effect significantly depends on the size of a projectile nucleus.

As it is seen from Fig.4. the disappearance of vacuum ω peak and the enhancement in the spectra at lower $M(\pi^0\gamma)$ becomes more pronounced with increasing of the resonance laboratory momentum due to domination of the resonance decay inside the projectile nucleus.

The most important source of three photon background is associated with the reactions $pp \to p\Delta^+(p\gamma)\pi^0(2\gamma)$ and $pn \to p\Delta^0(n\gamma)\pi^0(2\gamma)$. Thus, the additional criterion for the selection of real events is desirable. At subthreshold energy regime an ω mesons are predominantly produced with small transverse momentum. This provides the possibility to use kinematical correlations for the background suppression. The registration of

$\pi^0(2\gamma)$ and γ events with large azimuthal separation close to 180° makes possible to distinguish the real ω decays from incorrelated three photon background events [10].

3. Antikaon production

Let us consider now the zero degree K^- meson production in Ap reaction. The recent studies of subthresholdd antikaon production in proton-nucleus collisions, carried out within a coupled channel transport approach [7] and a folding model based on the internal nucleon momentum distribution [6] as well as nucleon spectral function [8] indicate that the K^- potential has a strong impact on K^- yields at low antikaon momenta. At the reaction threshold 2.5 GeV/nucleon the K^- of laboratory momentum 1.74 GeV/c have the same velocity as an incident nucleus. Thus the measurement of the antikaon yield in appropriate laboratory momentum range provides the possibility to explore the behavior of very slow kaons in nuclear medium. As it was suggested by Kishimoto [16] due to attractive potential the deeply bound kaonic nuclei should exist. The performed calculations similar to those outlined above for the ω mesons shows that the values of the cross sections for high momentum K^- subthreshold production are acceptable for experimental observation. It should be noticed that the registration of very slow K^- mesons from pA collisions is extremely hard experimental problem due to the strong kaon rescattering and decays.

4. Summary

We have explored the possibility to investigate the momentum dependence of in-medium vector ω mesons and pseudoscalar K^- mesons properties at normal nuclear density. It was argued that the process of subthreshold meson production in the Ap collisions is well suited for such study since the mesons can be produced with extremely small momenta in the projectile nucleus system. Due to attractive nuclear potential low momentum ω and K^- might form the omega-mesic and kaonic nuclei.

We have found that the cross sections for subthresholdd high momentum K^- and ω production are high enough to be measured experimentally. The contribution of the background processes is expected to be small in subthreshold reactions due to low collision energies.

The same kinematics can be used for φ meson production with low momentum relative to a projectile nucleus. As it was argued in [17] the bound $\varphi - N$ states can be created inside a nucleus by the van der Waals attractive force if the relative motion between φ and nucleon is slow.

An experimental advantage of the Ap kinematics are related to the fact that slow hadrons in the projectile nucleus frame have a laboratory momenta favorable for measurements. Thus, we can conclude that the experimental study of the momentum-dependent in- medium properties of mesons in nucleus-nucleon collisions at subthreshold energies looks to be quite promising.

It is obvious that slow particles in the projectile frame can also be produced in nucleus-nucleus collisions at subthreshold energies which will provides an information on in-medium properties of a hadrons and hadronic resonances at higher baryon density. Such an experiment might be carried out at GSI-SIS using an available ion beams in the GeV region. However, the understanding of low momentum mesons properties inside a normal nuclei are extremely important nowadays for observation and unambiguous interpretation of specific nucleus-nucleus phenomena.

Acknowledgements

The author greatfully acknowledges many helpful discussion with V. Sheinkman. This work was partially supported by the Russian Fund for Basic Research, grant N 99-02-16372.

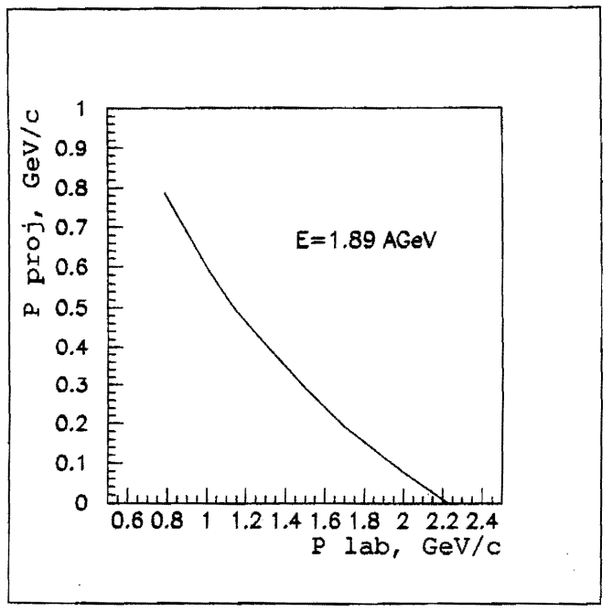

Fig.1. Momentum of the ω- meson in the projectile nucleus frame versus its laboratory momentum.

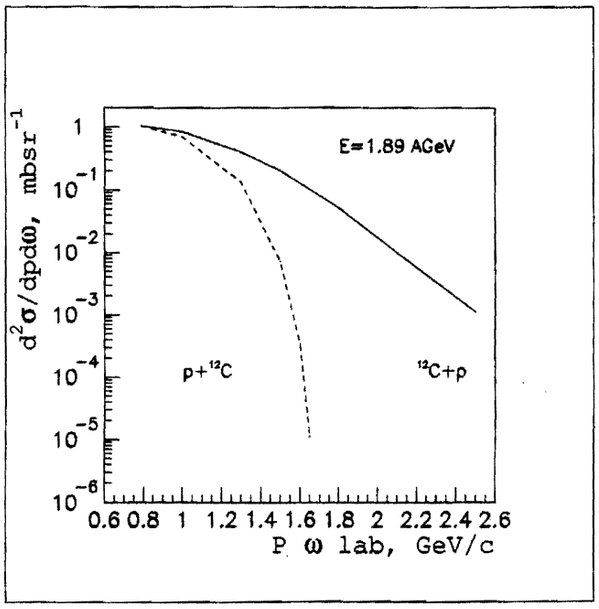

Fig.2. Spectra of the ω - mesons from Ap (solid) and pA (dashed) collisions at 1.89 AGeV.

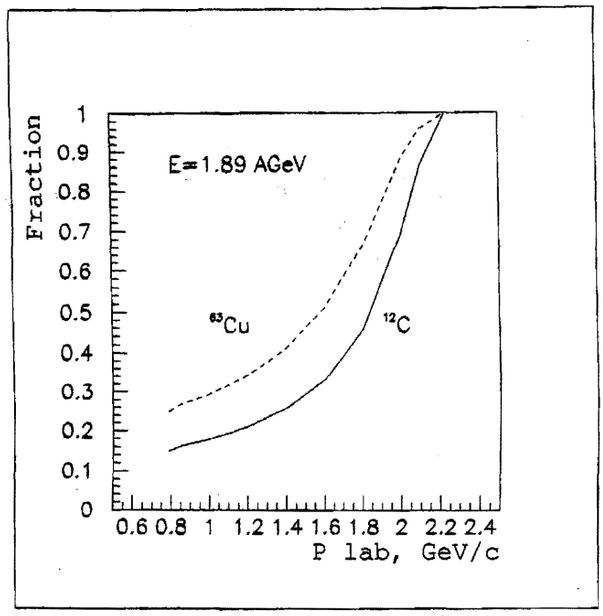

Fig.3. Fraction of the ω-mesons decaying inside the projectile nucleus.

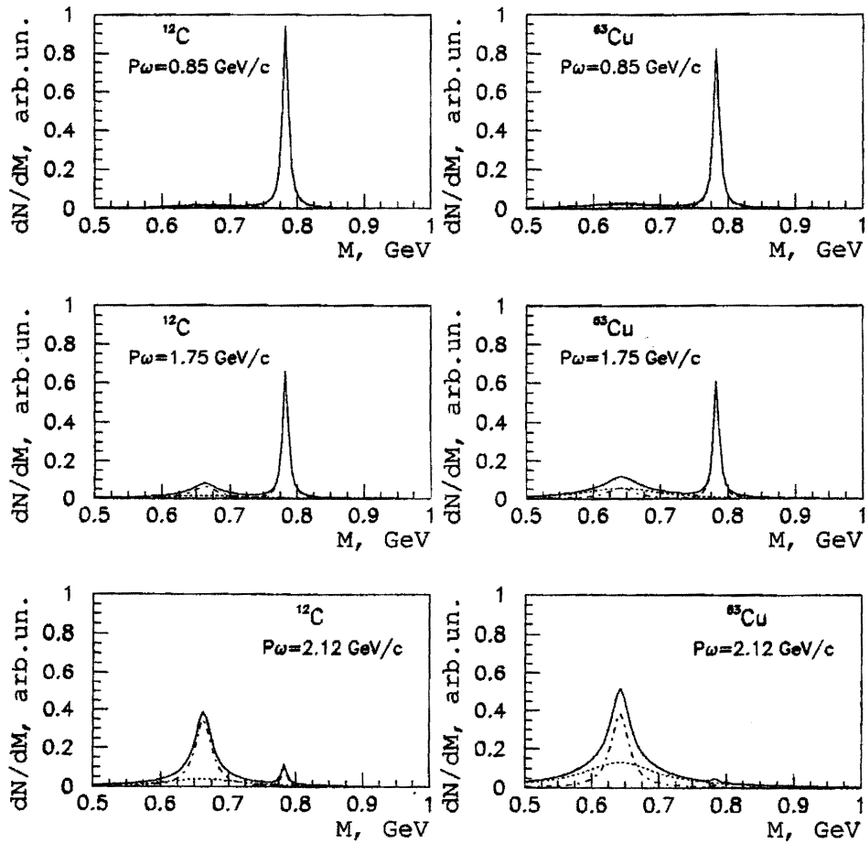

Fig.4. $\pi^0\gamma$ invariant mass distribution for different ω momenta in the laboratory. The meaning of the curves is explained in the main text.

References

1. W.Cassing and E.L.Bratkovskaya, Phys.Rep.308(1999)65
2. F.Klingl and W.Weise, Nucl.Phys. A606 (1996) 329
3. M.Asakawa and C.M.Ko Phys.Rev.C48 (1993) R526
4. G.L.Lolos et al., Phys.Rev.Lett. 80 (1998) 241;
G.M.Huber et al., Phys.Rev.Lett. 80 (1998) 5285
5. S.Yokkaichi et al.,Abst.vol.Quark Matter'97 Conf.I-E-45(Japan)
6. Yu.T.Kiselev for the FHS Collaboration J.Phys.G.25 (1999) 381
7. A.Sibirtsev and W.Cassing, Nucl.Phys.A641 (1998) 476
8. E.Ya.Paryev, Eur.Phys.Jour.A9 (2000) 521
9. Ye.S.Golubeva et al., Nucl.Phys.A625 (1997) 832
10. Ye.S.Golubeva et al., KFA Annual Report, Juelich, 2000
11. W.Cassing et al., Phys.Rep.188 (1990) 363
12. A.Sibirtsev et al., Z.Phys.A358 (1997) 357
13. T.Hadsuda and S.Lee, Phys.Rev.C46 (1992) R34
14. C.Gobbi et al., Phys.Rev.C50 (1994) 1594
15. G.I.Lykasov et al., Eur.Phys.Jour.A6 (1999) 71
16. T.Kishimoto, nucl-th/9910014
17. H.Gao et al., Phys.Rev.C63, 022201(R)