SUBTHRESHOLD KAONS WOULD REVEAL DENSITY ISOMERS

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ABSTRACT

If density isomers exist they can be detected by measuring the excitation function of subthreshold kaon production. When the system reaches the density, where the density isomer has influence on the equation of state (which depends on the beam energy) we observe a jump in the cross section of the kaons whereas other observables change little. Above threshold $\bar{\Lambda}$'s or $\bar{p}$'s may be used to continue the search. This is the result of microscopic BUU/VUU calculations.

One of the main motivations for the study of the heavy ion collisions at energies in between 50 MeV and several GeV is to determine the nuclear equation of state (EOS) as a function of density and temperature. Microscopic calculations have revealed the dependence of several observables on the EOS [1]-[3]. They include the transverse momentum transfer (flow), the enhanced emission of particles perpendicular to the reaction plane (squeeze) and the production of subthreshold kaons. Thus in principle it should be possible to determine it by experiments.

In these calculations two parametrizations of the potential energy of the nucleons have been employed which mark the expected boundaries of the range of values. For a hard equation we use

$$V(\rho) = -62\left(\frac{\rho}{\rho_0}\right) + 23.5\left(\frac{\rho}{\rho_0}\right)^2 [MeV] \tag{1}$$

and for a soft equation

$$V(\rho) = -178\left(\frac{\rho}{\rho_0}\right) + 140\left(\frac{\rho}{\rho_0}\right)^{7/6} [MeV]. \tag{2}$$

This form of the potential energy has the advantage of depending only on three parameters out of which two are fixed by the condition that in nuclear matter the energy per nucleon has a minimum of -16 MeV at normal nuclear matter density. It is convenient to express the third parameter in terms of the compressibility K at normal nuclear matter density. For the soft EOS we obtain K = 200 MeV, for the hard K = 380 MeV.

The first high precision experiments to determine the EOS have recently been performed at the SIS facility at GSI. They produced a puzzling result. The 4π collaboration has measured the transverse momentum transfer as a function of the transverse energy and found that a reasonable agreement between the microscopic calculation and data can only be obtained if the EOS is hard [4]. Calculations with a soft equation of state are clearly off the data. The KAOS collaboration, which measured the production of subthreshold kaons at energies around 1 GeV, has found that even a soft equation of state underpredicts the observed yield. A hard equation of state would yield an additional suppression by a factor of two [5,6].

It has been argued by several authors [7], that the nuclear equation of state may have a second minimum at densities higher than $2\rho_0$. The reason for this may be due to nonlinear scalar meson terms in the Lagrangian or collective excitations of zero frequency spin-isospin modes in nuclear matter, called pion condensation. However, many of these models had problems in describing normal nuclear matter. This problem has been solved in more elaborated relativistic mean field models using an extented Walecka Lagrangian [8] with third and fourth power terms in the scalar field [9,10]. Relativistic mean field calculations with Δ resonances [11,12] yield second minima at about $\rho = 3\rho_0$. Its exact position and depth depends on the scalar and vector coupling constants of the deltas. Anyhow it should be noted that up to now the existence of such a density isomere is still speculative. Furthermore, there is up to now no experimental evidence for its existance.

Motivated by the seemingly contradictory experimental results we have investigated how the presence of density isomers would influence the generation of flow and the production of particles. In this letter we will show that above a threshold energy a density isomers change the kaon yield by more than one order of magnitude but leave other observables like the flow more or less unchanged. Below the threshold energy the density isomer has now influence. Thus we observe a jump in the excitation function. The energy at which this jump occurs depends on the density at which the isomer is located. This is the result of microscopic Boltzmann Uehling Uhlenbeck (BUU/VUU) calculations. The details of the numerical solution can be found in ref. [1]

Fig.1 displays the three different equations of state we use in our calculations. Up to a threshold which is higher than $2\rho_0$ all these EOS are identical and follow the hard equation of state (eq.1). The EOS's with a density isomer start to deviate from the hard EOS at $2.4\rho_0$ (Hisom 1) resp. $2.6\rho_0$ (Hisom 2). The density isomer has a depth of 2 MeV at $\rho = \rho_{thres} + .3\rho_0$. Above $\rho_{thres} + .6\rho_0$ we have

$$E/N_{Hisom}(\rho/\rho_0) = E/N_{Hard}(\rho/\rho_0 - .6).$$

Before coming to the results of the calculation it is instructive to discuss qualitativly our expectations. We start with the production of kaons. Below threshold kaon production is concentrated at central collisions where the density is high. At 1 GeV Au + Au the average density at the point of the kaon production is around $2\rho_0$, the maximal value about $3\rho_0$ [13]. Therefore the kaons test the high density zone itself. Only there are a sufficient number of collisions that some baryons can gain a substantial increase of their momenta what is necessary to overcome the threshold. The Fermi motion alone is not able to provide the additional required energy. Most of the kaons are produced in a two step process

$$N_1 + N_2 \rightarrow N_1 + \Delta, N_3 + \Delta \rightarrow N_3 + \Lambda + K$$

Due to kinematical reasons this channel is much more effective than the channel

$$\pi + N \rightarrow \Lambda + K$$

which counts for not more than 20% of the produced kaons[14]. A decreasing mean free path of the Δ therefore enhances the kaon production because it reduces the probability that the Δ decays before it collides with another nucleon. A softening of the equation of state at high density allows the system to reach a higher density and hence a shorter mean free path and therefore favours the production of kaons.

If a density isomer exists there is a region at which there is no additional energy energy necessary to compress the system further. If the system enters this region in the course of a heavy ion reaction we expect a rather sudden increase of the density and consequently a increase of the kaons as well. Thus all depends whether the system reaches the required density. Below that density the system does not "notice" the fact that an isomer exists.Since the density is a monotonous function of the energy, we expect a jump appearing in the excitation function. Due to the increasing number of inelastic collisions we expect also a moderate dependence of the pion yield.

The transverse momentum transfer, in the other hand, is caused by the potential gradient, which is build up during the collision between the high density central region and the surrounding [15,16]. This density gradient is the source of a potential gradient. Particles which suffer a large transverse momentum transfer never enter the high density region but the density gradient which causes a force reflects them sideswards. The average density which these particles "see" is around the normal nuclear matter density. Thus the flow tests the potential around ρ_0. Thus the flow analysis yields information about the surface of the high density zone rather than about the compression zone itself. We expect therefore little change if we modify the eqution of state at densities beyond $2\rho_0$.

Thus kaons and the transverse momentum transfer test the potential energy and therefore the EOS at different densities.

We come now to the numercial results. We performed calculations of the reaction Au + Au, b = 3 fm for the three different equations of state employing the BUU/VUU model. The details of this model can be found in ref. [1]. Fig.2 displays, from top to bottom, the number of collisions the kaon and the pion yield. Up to 600 MeV the number of collisions is the same for all three EOS's. At 700 MeV Hisoms 1 starts to deviate from H and Hisom 2.At this energy the system reaches densities more than $\rho/\rho_0 = 2.4$ but not yet a density of 2.6 ρ/ρ_0. If the density of $\rho/\rho_0 = 2.4$ is reached for Hisom 1 we have a negative pressure and the systems collapses. Hence the mean free path decreases and as a consequence the number of collision increases. At 900 MeV we observe also a difference between Hisom 2 and H. At that energy the system exceeds the density of 2.6 ρ/ρ_0 and hence the density isomer of Hisom 2 becomes effective. At still higher densities the exact position of the isomer becomes unimportant and the number of collisions coincides for Hisom 1 and Hisom 2. The density reached for the EOS's with density isomer is about $0.6\rho_0$ larger than for the hard EOS. Thus the compressional energy stays about constant.

At 600 MeV/N the kaon yield of all three EOS is identical. At that energy the density of the system does not exceed $\rho/\rho_0 = 2.4$. At E_{beam} equal 700 MeV/N the kaon yield for Hisom 1 is more than 1 order of magnitude higher than that of the other two. . The latter density is reached around E_{beam} = 1000 MeV/N and consequently we observe now the jump in the kaon yield for Hisom 2. At still higher energies the difference between Hisom 1 and Hisom 2 becomes smaller because the density is now beyond $3.2\rho/\rho_0$ where both EOS become identical. Also the difference between the EOS's with isomer and the hard EOS becames smaller. More and more kaons are produced now in peripheral reactions because the Fermi motion can provide the additional energy to overcame the threshold of 1.58 GeV. At still higher energies we expect that the majority of the kaons come from these peripheral reactions. Therefore the three curves merge and kaons are not suited anymore as a signal of a density isomer. However, if the isomer appears at a density which is not reached with beam energies below the kaon threshold, other processes which have a higher threshold may be used, like the production of $\bar{p}$'s or $\bar{\Lambda}$'s.

The pions show a intermediate behaviour. Since from the enhanced kaon production we can conclude an enhanced Δ production in the high density region. However, only very few of the observed pions come directly from the high density zone. Most of them are reabsorbed on their way to the surface and the majority of the observed pions is produced close to the surface of the system. However, their number still chances by 40% if a density isomer is present.

Fig. 3 presents the result for three dynamical observables, the flow measured by $p_x^{dir} = \sum_{i=1}^{N} sign(y_i) p_x(i)$, the transverse energy $E_T/N = \sqrt{m^2 + p_T^2} - m$ and $\sigma(p_z) = \sqrt{< p_z^2 > - < p_z >^2}$. When the strong increase of the particle production takes place we observe practically no difference of the flow between H, and Hisom. Only at much higher energies we see, as already anticipated [17] - [20] a reduction of the flow. There the zone of negative pressure has increased to that extend that it starts to have influence on the potential gradient in the low density zone - where the flow is produced.

The transverse energy increases for Hisom 1 and Hisom 2 as a consequence of the higher stopping and the subsequent thermalization caused by the increase of the number of collisions. The same is seen in the direction of the beam where also $\sigma(p_z)$ has increased. A detailed investigation shows that this increase is not due less stopping but due to more thermalization.

If a density isomer is present, it will have strong influence on several observables, especially the particle production yields, whereas other observables change little. Hence the puzzling experimental observation may point to the fact that the three parameter parametrization (with all parameters adjusted to nuclear matter properties at ρ_0) does not give sufficient freedom to find a potential which reproduces the experiment at low and at high densities.

Is there any evidence for existence of a isomer yet? Not really, but we would like to point out one remarkable fact. Harris et al. [21] have measured the excitation function of the π^- production and for the systems La + La and Ar + KCl. If we take the ratio of the observed pion yield R = $N_\pi(1800MeV)/N_\pi(600MeV) = 7$ and compare it with our calculation we found the values of 4.29 and 6 for H and

Hisom.

Theoretical calculations conjecture the density isomers at densities larger than 2.5 ρ_0. At 1 GeV/N, the highest energy available at SIS, we are just at the boundary of this domain. Thus it would be interesting to be able to measure this excitation function up the AGS energies, where an enhancement of the kaon production has been observed as well.

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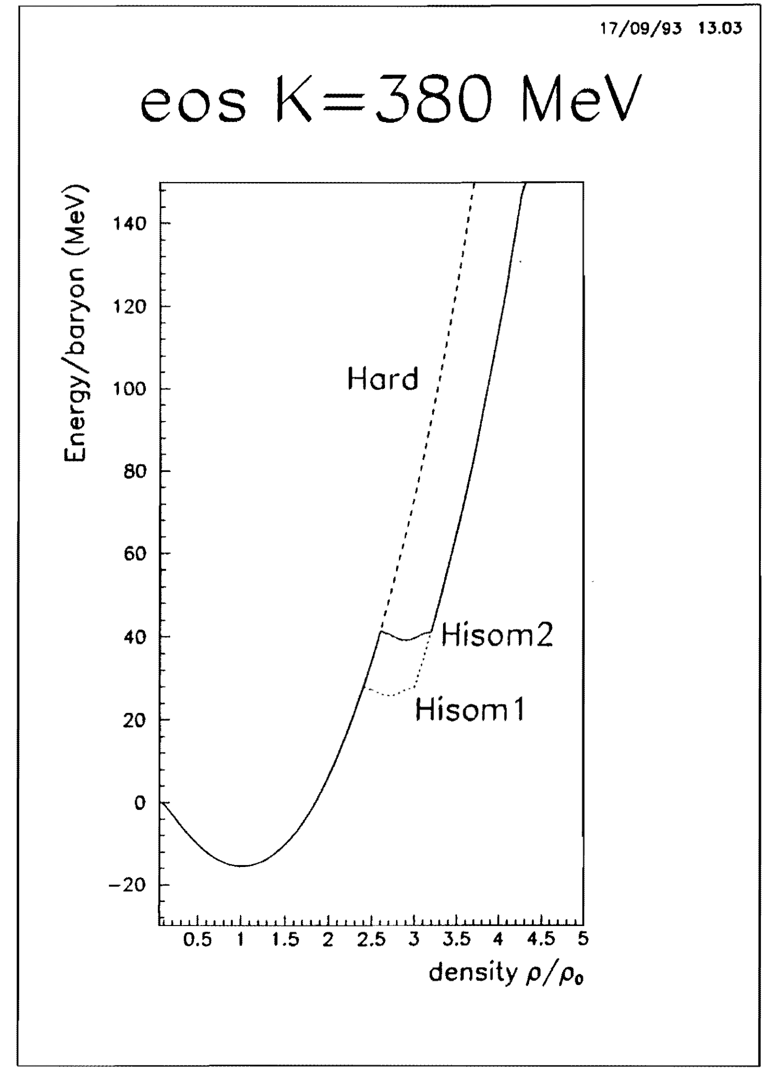
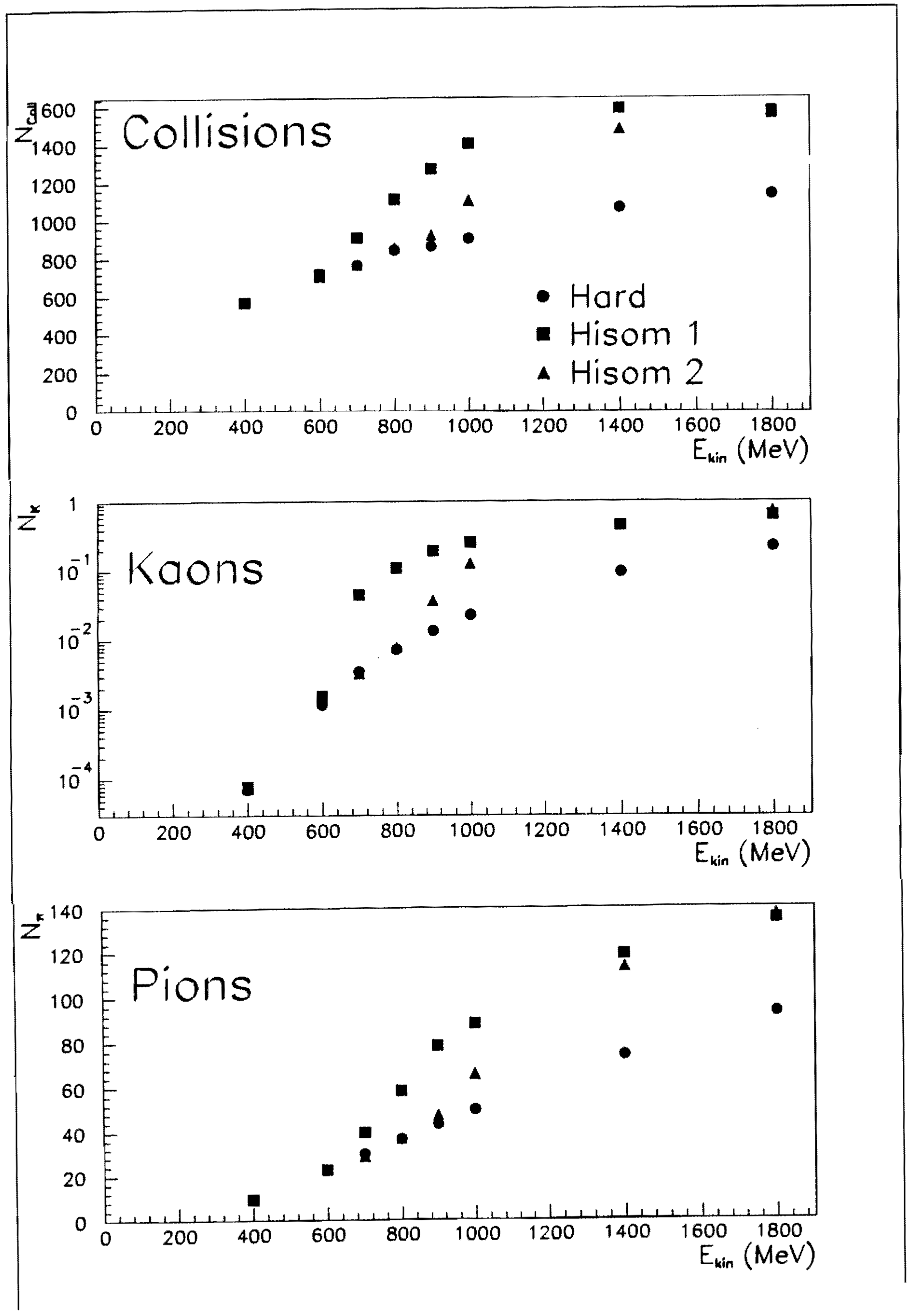
Figure Captions:

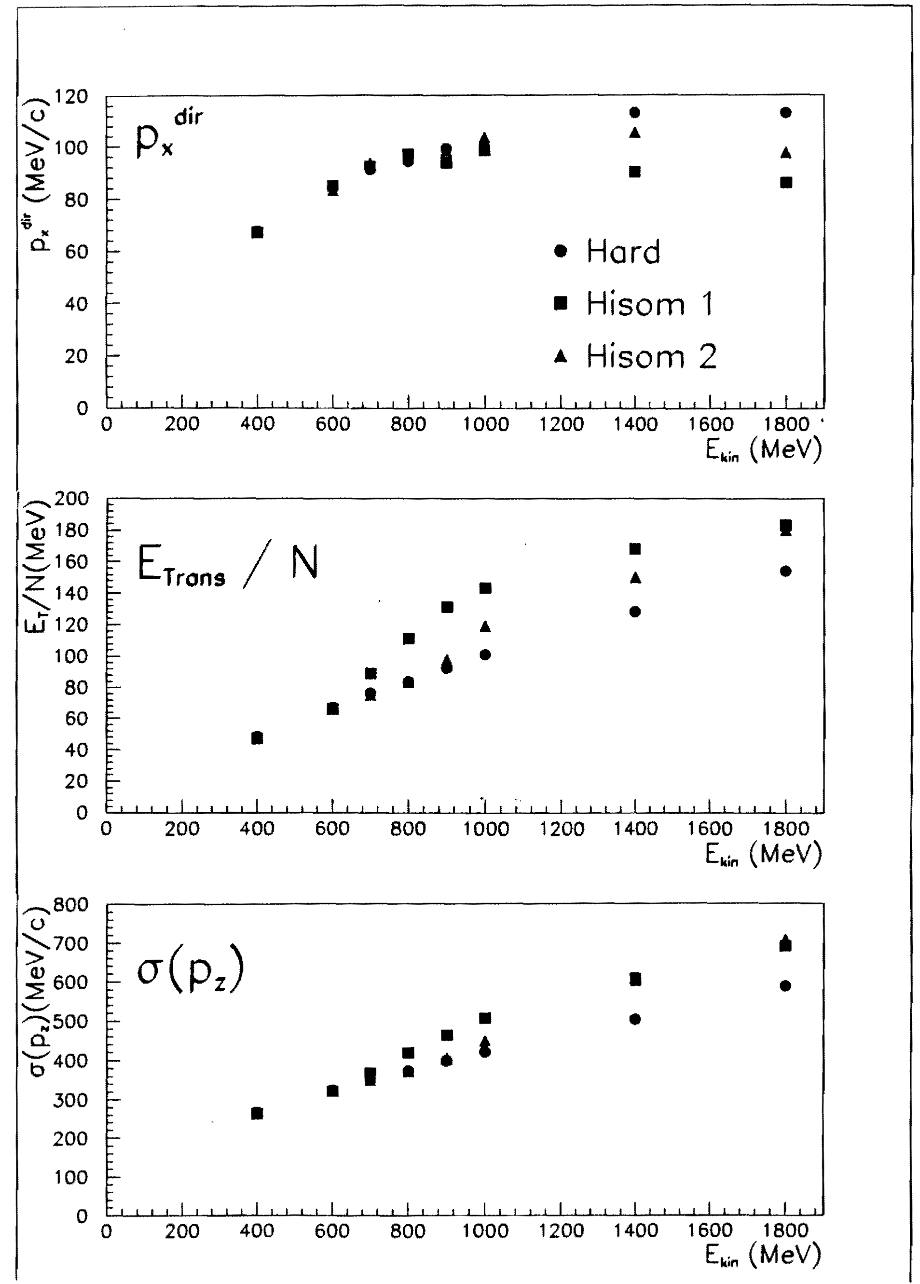
Fig.1 : The three equations of state employed in our calculation

Fig.2 : The number of collisions produced kaons and pions as a function of the beam energy for Au + Au, b = 3 fm for the three equations of state.

Fig.3 : The flow, the transverse energy and $\sigma(p_z)$ as a function of the beam energy for Au + Au, b = 3 fm for the three equations of state.




Collisions
N_{Coll}
Hard
Hisom 1
Hisom 2
E_{kin} (MeV)
Kaons
N_K
E_{kin} (MeV)
Pions
N_π
E_{kin} (MeV)


p_x^{dir}
p_x^{dir} (MeV/c)
Hard
Hisom 1
Hisom 2
E_{kin} (MeV)
E_{Trans} / N
E_T/N(MeV)
E_{kin} (MeV)
$\sigma(p_z)$
$\sigma(p_z)$(MeV/c)
E_{kin} (MeV)