MULTIPLE PION PRODUCTION FROM AN ORIENTED CHIRAL CONDENSATE

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Our prime objective in this work was to study a mechanism of the pion production in heavy ion collisions related to the creation of the chiral condensate and to explore how pion distributions can signal the presence of the condensate. We studied meson production by imposing a pion dispersion relation specific to the medium, i.e. with a space- and time-dependent effective mass.

In general, the problem of parametric excitation [1] of the field quanta presents an interesting question as it is encountered in many branches of physics from condensed matter to high energy physics. The problem also exhibits a vast variety of solutions ranging from adiabatic to phase transitions and condensates. We have conducted an extensive study of quantum field equations of a general form

$$\frac{\partial^2 \vec{\pi}}{\partial t^2} - \nabla^2 \vec{\pi} + m^2_{\rm eff}(\vec{x},t)\,\vec{\pi} = 0\,. \tag{1}$$

In our picture the parametric excitation of the field quanta is carried out by the externally given space- and time-dependent mass term. This term in the Lagrangian is quadratic in the field, and the states produced are often called "squeezed" [2,3]. Some analogy can be drawn here from well studied linear current type terms that produce coherent states [3,4]. However, the essential difference between coherent and squeezed states arises due to the fact that the latter correspond to the pairwise generation of quanta. In the case of pseudoscalar pions, this means that charge, isospin and parity are exactly preserved. We have emphasized the fact that the quantum solution can be built from the classical solution, and this important link was established via a canonical Bogoliubov transformation [5].

With our interest lying in the direction of chiral condensate we focused our attention on the potential of Eq. (1) to form a condensate with fast particle production and large correlations when the effective mass goes through zero. Along with a general formalism that can be used for numerical studies we have analytically solved the problem when the effective mass experiences sudden abrupt changes. Consideration of this particular temporal perturbation allowed us to clearly separate the exponentially rising collective pion condensate modes for any given spatial form of the perturbation in the effective mass. This produced conditions where the condensate and its signatures can be seen.

We have identified two basic channels of pion production. The first involves only a few discrete condensate modes with a large pion population. The second leads the production of far fewer (non-condensate) particles with a broad phase space distribution. Mathematically these channels can be identified as production of mesons from bound and continuum states of a Schrodinger equation with a potential of the form of the perturbation itself, see Fig 1. The bound states of negative energy are responsible for the characteristic features of the condensate.

Numerically, the number of non-condensed pions ranges from a few up to a dozen, and as expected is not very sensitive to the choice of the spatial and temporal form of the perturbation in the effective mass, Fig. 2. In contrast, the condensate modes have an exponential sensitivity to the input parameters. As the abrupt changes in the effective pion mass grow in strength, a critical point is reached with the appearance of the condensate mode. The population of this mode increases dramatically from zero to thousands with a further slight change in the mass parameter, Fig. 3. Due to this hyper-sensitivity of the number of

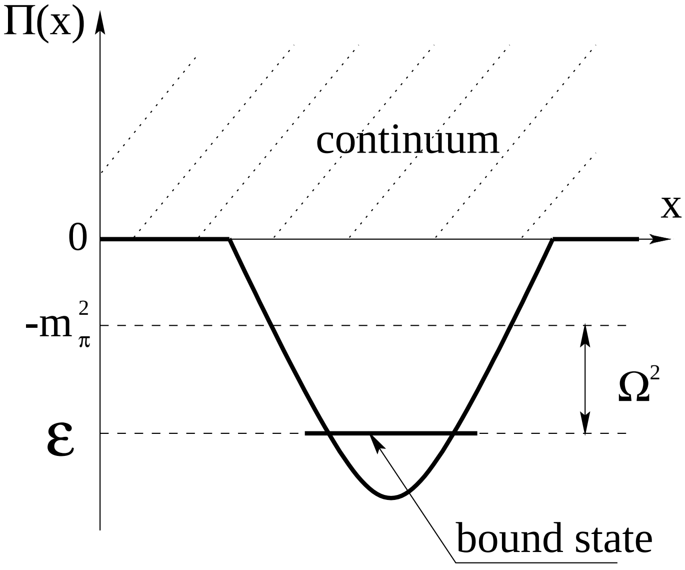

Figure 1: The schematic representation of the perturbation $\Pi(x) = m_{\rm eff}^2 - m_\pi^2$, with one condensate bound state.

condensed pions to the perturbation it is practically impossible to predict the effect quantitatively without specifying precisely the scenario of the process.

However, our results predict the number of non-condensate pions, thereby imposing a lower limit on the statistics needed to unambiguously detect the chiral condensate. Furthermore, we have shown that the condensate pions have a specific momentum distribution due to their common collective condensate mode. We have also shown that although the distribution over species starts from the famous $1/\sqrt{f}$ form [6] for one mode it quickly becomes Gaussian with the appearance of successive modes, Fig. 4. Therefore the presence of several modes greatly complicates the detection of chiral condensate. The number of modes present increases with energy. In addition, the mass parameter can be strongly perturbed in more than one region each increasing the number of modes. Tunneling and chaotic dynamics in the resulting multi-well potential lead to another class of interesting problems.

This work can be extended in several directions. With the formalism presented here, large numerical studies of the effective pionic field in a hot medium can be conducted involving realistic and even self-consistent forms of perturbation given by the σ field. Constraints on the perturbation of the mass parameter should be related more rigorously to observables. Further analysis of our results applied to phase transitions, zero mass particle production, energy transfer and many other field theory problems would definitely be fruitful. We feel that this work may provide a step forward in the study and classification of field theories with parametric excitations and possibly clarify the nature of the produced squeezed states.

Acknowledgments

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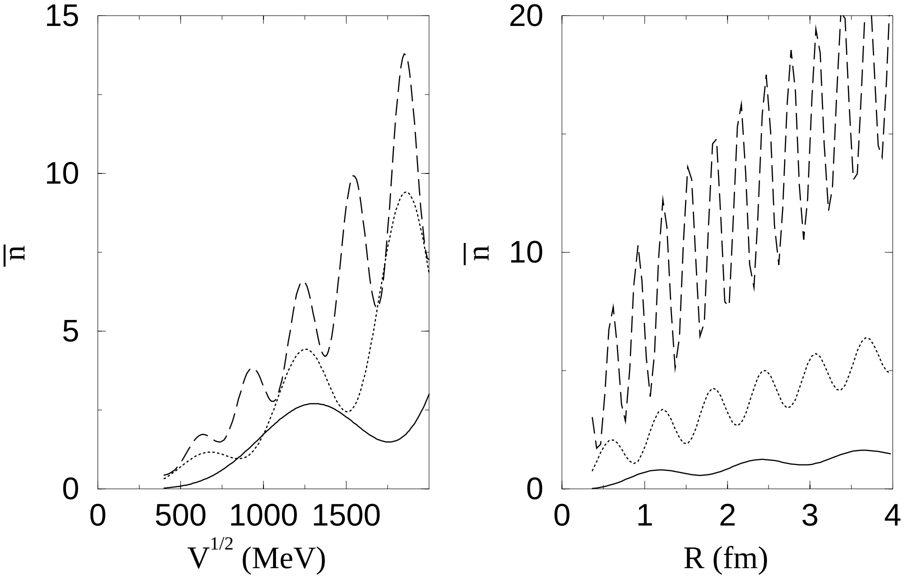

Figure 2: The left side shows the average number of pions of a particular type as a function of V, the depth of the perturbation. Curves displayed as solid, dotted and dashed lines correspond to the values of the radius R of 0.5, 1, and 2 fm, respectively. Plotted on the right hand side is the number of pions versus the radius R for values of $\sqrt{V}$ of 0.5, 1 and 2 GeV as solid, dotted and dashed lines, respectively.

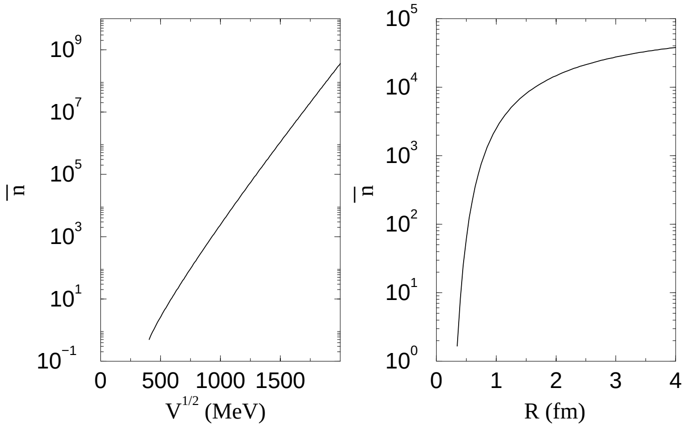

Figure 3: The average number of particles produced as a function of the depth of the potential field $\sqrt{V}$ is shown in the left panel, the size R was fixed at 1 fm. The right panel shows the number of particles produced as a function of size R given a fixed depth $V = 1$ GeV^2. The time length of the perturbation is set at T =1 fm/c.

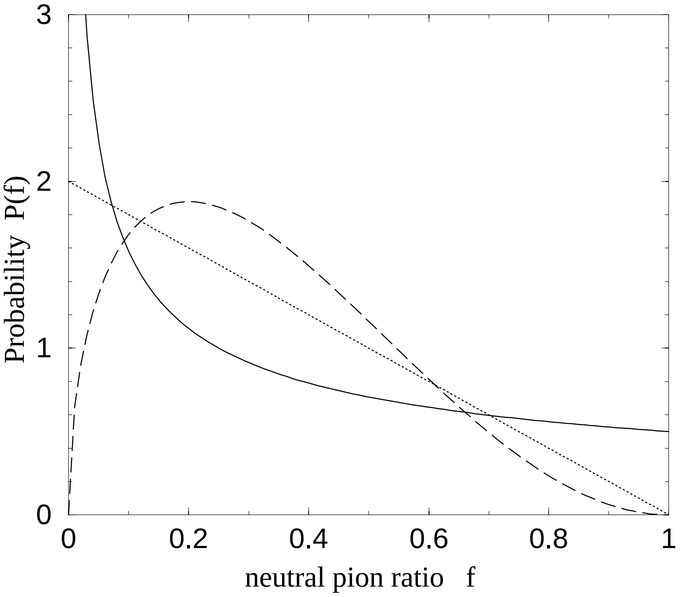

Figure 4: The probability $\mathcal{P}(f)$ that a given neutral pion fraction f is observed. The three curves display cases of one condensate mode (solid line), two energy-degenerate modes (dotted line), and three modes (dashed line).

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