SPECTRA OF THE FAST SUBTHRESHOLD PIONS PRODUCED IN NUCLEUS-NUCLEUS COLLISIONS

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The pion production in collisions of heavy ions is considered within the framework of the fluid dynamics approach. It is shown, that the account of pion production as a result of decay $\Delta \to N + \pi$ results in hardening high–energy “tail” of a subthreshold pion spectrum.

INTRODUCTION

A production of subthreshold pions is one of interesting phenomena of the collective nuclear dynamics shown in collision of heavy ions. It occurs at energies as small as 300 MeV/nucl., which is a threshold of a production of pions in free nucleon–nucleon collisions. The reason of the decrease of a threshold of pion production could be Fermi motion of nucleons, which is shown already in proton–nucleus collisions [1,2], as well as collective movement in nuclear matter. The last is effectively described within the framework of nuclear fluid dynamics. Such approach allows to describe adequately the time evolution of a formed hot spot [3,4] and emission of secondary particles (protons, pions, etc.). Formation of pions both at relativistic and subthreshold energies has a thermal character of nucleus–nucleus collisions. Thus spectra of pions have usually a characteristic exponential form. However the additional contribution in pion production brings the decay $\Delta \to N + \pi$. The account of this effect at relativistic energies is shown as a “bump” of a soft part of pion spectrum [5]. At subthreshold energies, as shown in the present work, there is a hardening of high–energy “tails” of pion spectra. It is confirmed by experimental data [6].

MODEL

In fact, in work [4] it has been shown, that experimental data of pion spectra produced in nucleus–nucleus collisions [7] are well enough described by model of non–coherent source of subthreshold pions, based on the fluid dynamics approach. Within the framework of this approach the description of time evolution of hot spot shows haw the system of colliding nuclei passes a stage of compression, the subsequent expansion stage and the stage of disintegration system on secondary particles which are nucleons, fragments and pions. Application of this approach on relativistic energies 1–2 GeV/nucl. appeared quite successful.

$\pi -$ meson spectra, formed in reaction $A + B \rightarrow \pi + X$, as have been shown in work [5], are described by relativistic invariant cross–section of pion production

$$E\frac{d^3\sigma}{dp^3} = \frac{2\pi}{h^3}\int l dl \int d^3\vec{r}\gamma(E - p\upsilon\cos\vartheta) f(E, p, t) \quad (1)$$

where p - meson distribution function has the form

$$f(E, \vec{p}, t) = g(\exp(\frac{\gamma(E - p\upsilon\cos\vartheta)}{T}) - 1)^{-1} \quad (2)$$

Here *E* and *p* are accordingly p - meson total energy and momentum($E=\sqrt{p^2+m_\pi^2}$),$\vec{\upsilon}(\vec{r},t)$ and $T(\vec{r},t)$ are accordingly filds of velocities and temperatures, being the solutions of relativistic fluid dynamics equations,) $\gamma(\gamma=1/\sqrt{1-\upsilon^2}$ is Lorentz factor, *l* is impact parameter, g=1 for pions.

In the fluid dynamical approach dynamics of nuclear matter movement is determined with the equation of state, which gives dependence of pressure *P* and energy density *e* from density *?* and represents the sum of kinetic terms and interaction terms ($P=P_{kin}+P_{\mathrm{int}}, e=e_{kin}+e_{\mathrm{int}}$). The contribution of interaction terms (we choose Skyrme–type interaction) for pressure and energy density is determined as follows:

$$e_{\mathrm{int}}=\rho m_N[1+a\left(\frac{\rho}{\rho_0}\right)^{2/3}-b\left(\frac{\rho}{\rho_0}\right)+c\left(\frac{\rho}{\rho_0}\right)^{\alpha+1}] \qquad (3)$$

$$P_{\mathrm{int}}=\rho\frac{\partial e_{\mathrm{int}}}{\partial\rho}-e_{\mathrm{int}} \qquad (4)$$

Parameters *a,b,c* are determined from conditions, that the cold nuclear matter had an equilibrium density $\rho=\rho_0, \alpha=1/3$, $\rho_0=0.17$ fm^{-3} with the binding energy e=16 MeV and the compression module *K*=210 MeV. The contribution of kinetic terms for pressure and energy density is determined by thermal and Fermi movements [5].

For the description of experimental data, for example, on π^- - meson spectra in $^{28}Si+^{28}Si$ reaction at *Si* ion energy 2 GeV/nucl. except for thermal pions it is necessary to take into account pions from decay $\Delta \rightarrow N+\pi$ and to replace the formula (2) with the formula from work [8]:

$$Ef(E,\vec{p},t)=\frac{m_\Delta g_\Delta T}{2pq_0h^3}[(E_-^\pi+T)\exp(\frac{\mu-E_-^\pi}{T})-(E_+^\pi+T)\exp(\frac{\mu-E_+^\pi}{T})] \quad , (5)$$

where

$$E_\pm^\pi=\frac{m_\Delta}{m_\pi^2}[E_\pi(q_0)E\pm q_0p],\ p=\sqrt{E^2-m_\pi^2},E_\pi(q_0)=\sqrt{q_0^2+m_\pi^2}=\frac{m_\Delta^2+m_\pi^2-m_N^2}{2m_\Delta}$$

$$q_0=\{[m_\Delta^2-(m_\pi+m_N)^2][m_\Delta^2-(m_N-m_\pi)^2]\}^{1/2}/2m_\Delta$$

$m_\Delta=1232$ MeV is ?- particle mass , $g_?$=4 , μ is chemical potential

RESULTS OF CALCULATION

In fig. 1 the spectrum of thermal pions (curve (1)), a spectrum of pions from decay $\Delta \rightarrow N + \pi$ (curve (2)) and a resulting pion spectrum under a corner 90^0 for the (2 GeV/nucl.) $^{28}Si+^{28}Si$ reaction are shown. Experimental points are from work [9]. As can see from figure, the spectrum maximum corresponds to pion energy ~ 140 MeV.

We carry out calculation on above mentioned model for heavy ion collisions at subthreshold energies of produced π^0 - mesons.

In fig. 2 the energy spectrum $\frac{d\sigma}{dE}$ for the $^{12}C + ^{238}U$ reaction integrated on corners of π^0 - mesons is shown at 84 MeV/nucl. energy. The spectra for the $^{12}C+^{12}C$ reaction are shown at 74 MeV/nucl. and 60 MeV/nucl. energies(two bottom curves are solid lines). Points is experimental data from work [6].

Solid curves correspond to the contribution of thermal pions (dashed curves) and pions produced at decay . The last results in characteristic hardening of π^0 - meson spectrum at energies 100 – 140 MeV.

That is at subthreshold energies the contribution of produced pions from decay $\Delta \rightarrow N + \pi$ - particles falls at energy near to tail of a spectrum . That is in satisfactory agreement with the available experimental data.

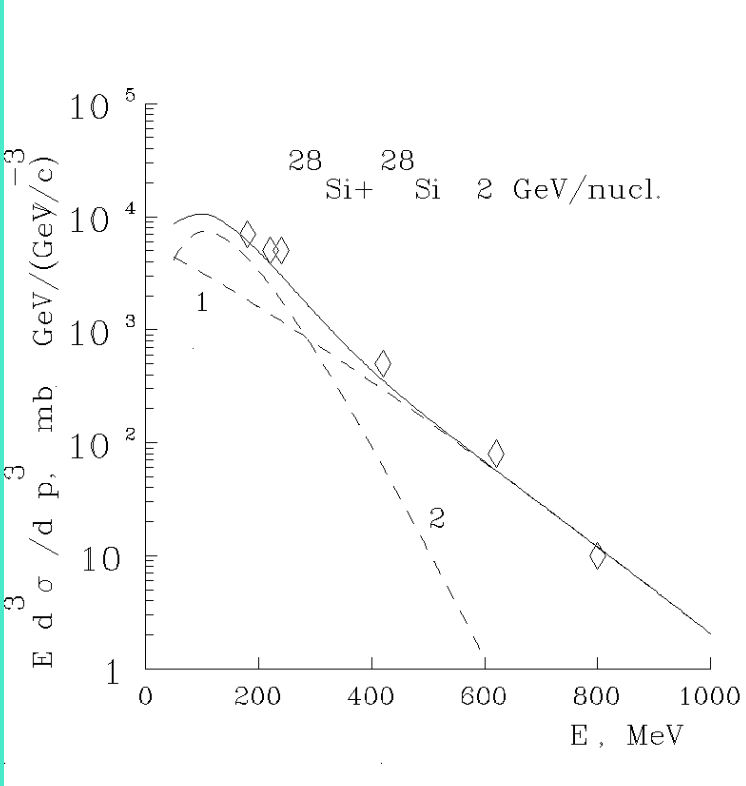

Fig.1. Experimental (points) [9] and calculated (solid line) π^- - meson spectra, produced in $^{28}Si+^{28}Si$ reaction for ^{28}Si ion at 2 GeV/nucl. energy. A dashed curve (1) is the contribution of thermal pions. A dashed curve (2) is the contribution of the pions produced in decay $\Delta \to N+\pi$

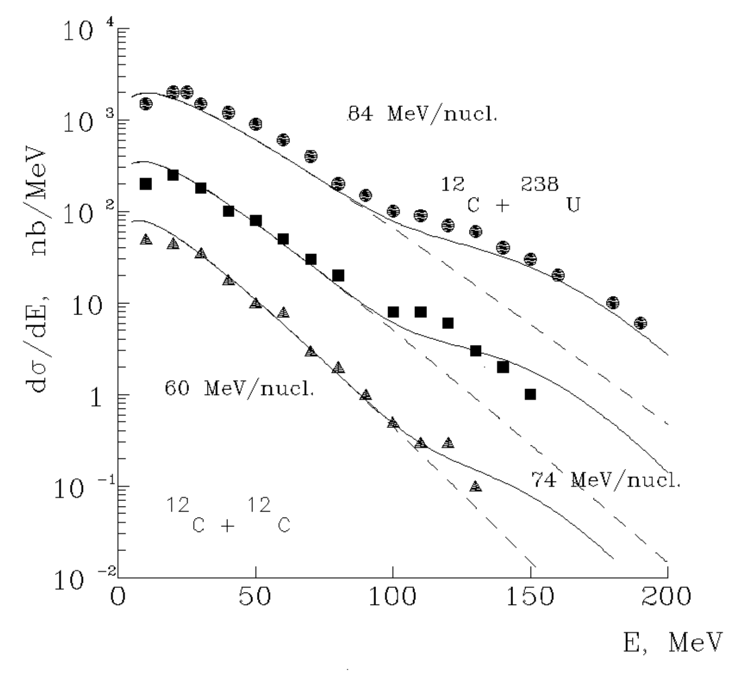

Fig.2. Experimental (points) [6] and calculated, integrated on corners π^0 - meson spectra, produced $^{12}\tilde{N}+^{238}U$ in reaction for ^{12}C ion at 84 MeV/nucl. energy and in $^{12}C+^{12}C$ reaction for ^{12}C ion at 74 MeV/nucl. and 60 MeV/nucl. energies. Dashed curves are the contribution of thermal pions. Solid curves are pion spectra taking to account of the pions produced in decay $\Delta \to N+\pi$.

REFERENCES

1. *D’yachenko A.T., Baryshnikov V.N.* // Izv. RAN. ser. fiz. 2007. V. 71. no. 6. P. 905.
2. *D’yachenko A.T., Baryshnikov V.N.* // Izv. RAN. ser. fiz. 2008. V. 72. no. 3. P. 371.
3. *D’yachenko A.T.* // Yad. Fiz. 1994. V. 57. P. 2006.
4. *D’yachenko A.T.* // Izv. RAN, ser. fiz. 1995. V. 59. no. 11. P. 177.
5. *D’yachenko A.T.* // J. Phys. G. 2000. V. 26. P. 861.
6. *Noll H. et al.* // Phys. Rev. Lett. 1984. V. 52. P. 1284.
7. *Badala A. et al.* // Phys. Rev. C. 1991. V. 43. P. 190.
8. *Mishustin I.N., Russkikh V.N., Satarov L.M.* // Yad. Fiz. 1991. V. 54. P. 429.
9. *Shor A. et al.* // Phys. Rev. Lett. 1989. V. 63. P. 2192.