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BUDAPEST

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ABSTRACT

Proton and pion spectra from relativistic heavy ion collisions are calculated in the framework of a hadrochemical model. An explanation of the striking absence of the delta decay pion peak in the observed pion spectra is suggested.

АННОТАЦИЯ

В релятивистском столкновении тяжелых ионов рассчитаны спектры протонов и пионов с помощью модели, содержащей превращение частиц. В экспериментальном спектре отсутствует вклад пионов из распада дельта-частиц. Дается объяснение этого факта.

KIVONAT

Relativisztikus nehézion-ütközésben keletkező protonok és pionok spektrumát számoljuk egy hadrokémiai modellben. Javaslunk egy magyarázatot arra, hogy a megfigyelt pion-spektrumban miért nem lép fel a delta-rezonanciák bomlásából várható csucs.

Recently it has been a challenge to explain the pion inclusive spectra obtained in high energy heavy ion collisions /E_{beam}/ /A $\geq$ 0.5 GeV/ with parameters fixed by the proton inclusive spectra [1-3]. In most models [4,5] pions are produced through the creation and decay of delta resonances. The experimental pion spectrum, however, does not show the peak characteristic to delta decay. There are several processes which may contribute to the smearing of this peak. The aim of the present work is to investigate these processes in the framework of a detailed heavy ion reaction model [6]. We intend to show that some modification of the assumption on the creation of pions seems to be necessary.

We consider a central or near central symmetric heavy ion collision as the interpenetration of two spheres originally filled with cold nucleon gas. In the overlap volume a piece of hot and dense hadronic matter, the firecloud, is created. We shall use the hadro-chemical equations of [5] to describe the development of the firecloud until the break-up of the system. The hadro-chemical processes leading to the formation of Δ resonance, π- and ρ -mesons are taken into account.

After the complete overlap of the two spheres the reaction is modeled by a spherically symmetric expansion. In Ref. [5] this expansion was governed by the analytic solution v(x,t) of the hydrodynamical equations. In the present work, however, we use a relativistic approximation to describe the hydrodynamical flow. This is done by identifying the radial flow-velocity used in [5-7] to the radial component of the four-velocity u(x,t) as follows:

$$u(x,t) = \frac{v(x,t)}{\sqrt{1-v(x,t)^2/c^2}} = xv_o\frac{t}{\sqrt{t^2+t_o^2}} \qquad (1)$$

where $v(x,t)$ is the radial velocity, $x = r/R(t)$ with $R(t)$ being the radius of the expanding sphere as a function of time, while v_o and t_o are constants determined by the initial value of the radius and energy.

We assume uniform density, temperature and chemical composition in the expanding sphere. To include the effect of the space-dependent hydrodynamical flow we subdivide the total volume to small cells /515 in the present numerical calculation/. The flow velocity and the thermal distribution are calculated separately for each cell. In a totally homogeneous case the number of cells into which the sphere is divided, is irrelevant, the final particle spectra cannot depend on this number. Even the fluctuations do depend on the total particle number. This subdivision is a mathematical one only. The applicability of the hydrodynamics is a different question, however. There a "physical cell size", namely that determined by the average interparticle distance, is to be compared with the characteristic lengths of the hydrodynamical fields. The present analytical hydrodynamic model, however, yields smoothly varying field quantities thus ensuring its applicability to the expansion of the firecloud.

The break-up time is calculated by means of the requirement that the change of temperature during the average collision time, τ_c, cannot be larger than the temperature itself. Thus the break-up time, t_b, is determined by the condition

$$\tau_c(t_b) = \alpha\tau_T(t_b) \qquad (2)$$

where

$$\tau_T(t) = \left| \left(\frac{dT(t)}{dt}/T(t)\right) \right|^{-1} \qquad (3)$$

is the time characteristic for the cooling of the system with $T(t)$ being the temperature and the average collision time $\tau_c=\lambda/v$ with λ the mean free path, v the average thermal velocity. In calculating $\lambda=1/\sigma\rho$ we use $\sigma=60$ mb as a thermal average of the nucleon-nucleon cross section in the firecloud and for ρ the number density of the firecloud. Similar conditions are used in astrophysical calculations for neutrino decoupling and there the constant α is 0.5 [10]. If $\alpha=2.0$, the kinematics of the expansion prevents the collisions between particle pairs of distance λ after t_b. We regard λ to be an adjustable parameter to a certain extent.

To obtain the spectra first the thermal distributions of the different particles are to be calculated for each individual cell in its rest frame. We use relativistic Boltzmann distributions for the nucleons and deltas and a relativistic Bose distribution for the pions /the zero-energy pion contribution is added explicitly [8]/. Since the delta particles decay well before reaching the detector, we assume that all the surviving deltas decay at the break-up time contributing to the spectra of pions and nucleons. Thus the spectra are known in the cell frames. Choosing any individual cell moving with velocity v_i one can take a momentum p in the firecloud center of mass system, transform it back to the cell frame by a Lorentz transformation resulting in $q_i = q_i(p,v_i)$. In the cell the number of particles of momentum q_i can be calculated from the known distribution functions. Especially for the delta-decay pions this procedure yields the Lorentz-invariant cross section:

$$E\,\frac{d^3N_{\pi\Delta}(p)}{dp^3} = \frac{V}{N_{cell}} \cdot \frac{16}{h^3} \cdot \sum_i \frac{(m_\Delta c^2)^3\, e^{\mu_{\Delta i}/kT_i}}{2(q_i c)(p_\pi^* c)} \left(\frac{kT_i}{m_\Delta c^2}\right)^2 \Big[(z+1)e^{-z}\Big]_{z_{i+}}^{z_{i-}} \tag{4}$$

where

$$z_{i\pm} = \frac{m_\Delta}{kT_i m_\pi^2 c^2}\,(E_{\pi i}E_\pi^* \pm q_{\pi i}p_\pi^* c^2) \tag{5}$$

and

$$E^*_\pi = \frac{1}{2m_\Delta}(m_\Delta^2 - m_N^2 + m_\pi^2)c^2$$

$$p^*_\pi = \frac{1}{c}\sqrt{E^{*2} - m_\pi^2 c^4} \tag{6}$$

are the energy and momentum of the pion in the Δ rest frame, while $\mu_{\Delta i}$ is the chemical potential in cell i. Expression (4) is similar to that given in Ref. 9. The numerical calculations have been carried out for the reaction U + U at the bombarding energy $E_{beam}/A=800$ MeV.

The short lifetime of the Δ particles and the low temperature of the firecloud close to the break-up, however, raise some doubt about the treatment of the Δ particles as an independent component. Due to the short lifetime of the deltas, their number is a function of the number of nucleons and pions and the temperature only. We have a hot interacting gas of two components with the only hadrochemical reaction

$$N + N \rightleftharpoons N + N + \pi \tag{7}$$

In this picture the simplest way to include the interaction is to approximate its effect by a collision scheme. On identifying the $N\pi$ cross section with the cross section of delta production and the duration of the collision by $\hbar/\Gamma_\Delta$ we arrive at a simple reinterpretation of the earlier hadrochemical calculations namely that the new densities ν_N' and ν_π' should be calculated according to the prescription:

$$\nu_\pi' = \nu_\pi + \nu_\Delta$$

$$\nu_N' = \nu_N + \nu_\Delta \tag{8}$$

where ν_N, ν_π and ν_Δ are the old densities. The quantity ν_Δ is now interpreted as the density of pairs just being in the process of collision. The energy of these pairs is the sum of the energies of their constituents. At low temperatures close to the breakup the spectrum of pions emerging from these pairs remains approximately thermal. /By low temperature we mean that the average thermal kinetic energy of the $N\pi$ collision is essentially smaller than the energy of the resonance in the $N\pi$ cross section./ With this modification the numerical results of the previous model yield a good approximation to the chemistry of the firecloud in spite of the doubts raised above. We shall see, however, that the two different interpretations of the $N\pi$ interactions lead to different inclusive pion spectra. In the first case the spectrum has a delta peak or shoulder at $E_\pi \approx 130$ MeV, while in the other case one cannot expect serious deviations from the thermal distribution. In the following we present the results of the numerical calculations showing the effects of the different processes discussed above.

On *Fig. 1* the effect of the hydrodynamical flow is shown. We display proton and pion spectra obtained i) as described above and ii) artificially putting the flow velocity $v_i=0$ for each cell. Coulomb effects are not included. Proton and pion spectra in the comoving cell-frames are considered to be thermal. It is clear from *Fig. 1* that the flow has a much smaller effect on the pions than on the protons. This has also been pointed out in [3] and can be understood taking into account the mass difference between protons and pions. In *Fig. 2* we show pion spectra obtained according to the different philosophies described above. The dashed curve represents the pure thermal /Bose/ spectrum. The dotted and the continuous curves include the contribution of the delta decay pions calculated with sharp and finite width delta mass, respectively. The value of the break-up parameter of eq. /2/ is fixed to $\alpha=0.35$. The finite width delta mass was simulated by using six different mass delta particles within the $\Gamma_\Delta = 120$ MeV width and weighting them corresponding to the Breit-Wigner shape of the delta resonance.

It can be seen from *Fig. 2* that the inclusion of the delta decay pions manifests itself in a pronounced difference from the thermal distribution even in the case of the finite width delta mass. To show the dependence of the spectra on the break-up time, on *Fig. 3* pion spectra obtained with different break-up conditions are presented. The delta particles are treated as real particles according to the first interpretation. It is seen that different break-up times result in qualitatively different spectral shapes. /They are implemented by choosing the parameter α in eq. (2) $\alpha = 0.5$, 1,2 respectively./ This is a consequence of the fact that the nonmonotonic component of the pion spectrum arising from delta decay /see *Fig. 2*/ is rapidly decreasing with increasing break-up time. It is seen that none of these break-up conditions produces a spectral shape resembling the experimental pion spectra. On *Fig. 4* the spectra obtained on the basis of the second interpretation /i.e. that the delta particles do not form an independent thermodynamical component/ are compared to the experimental data [1]. The agreement is quite reasonable.

We conclude that the hydrodynamical flow is very important to explain simultaneously the experimental proton and pion spectra. Neither the hydrodynamical flow nor a finite width mass distribution of the delta particles is enough, however, to produce agreement with experimental spectra if the deltas are treated as real particles in the expanding firecloud. Therefore in the expansion stage of the heavy ion reaction the $N\pi$ interaction should be approximated by some other method. In the present work described such a possibility in the form of a collision sheme.

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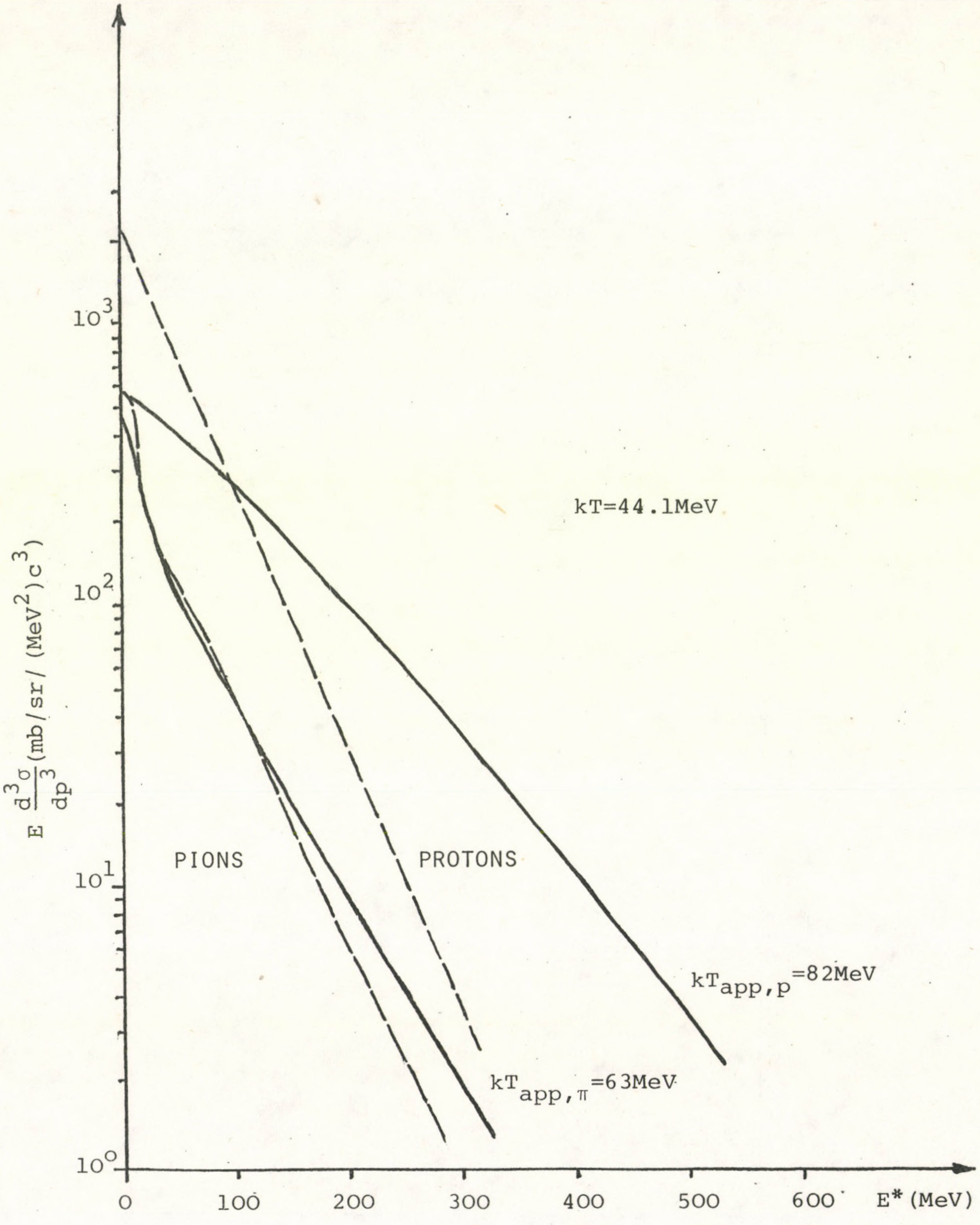
FIGURE CAPTIONS

Fig. 1 *The effect of a hydrodynamical flow on the particle spectra. Continuous curves are obtained by taking into account both thermal and hydrodynamical velocities. Dashed curves show spectra calculated by artificially putting the hydrodynamical velocities equal to zero in computing the momentum distributions. Proton and pion spectra in the comoving cell-frames are considered to be thermal. /The calculations are made for central U + U collisions at the bombarding energy* E_{lab}*=800 MeV/A. Invariant cross sections* $E\,\frac{d^3\sigma}{dp^3}$ *are plotted with arbitrary normalization against center of mass kinetic energy E*/. On the figure the temperature of the firecloud kT as well as the apparent temperatures for protons and pions defined by the slope factors /*$kT_{app,p}$ *and* $kT_{app,\pi}$ *respectively/ are given.*

Fig. 2 *Invariant pion cross sections /arbitrary normalization/ in the U + U reaction at* E_{lab} *= 800 MeV /nucleon. The dashed line refers to pure thermal distribution /Bose statistics with hydrodynamical flow/, the other two curves both contain the contribution from delta decay, the dotted line corresponding to the sharp delta mass* $m_\Delta c^2$ *= 1236 MeV while the continuous one corresponding to a delta mass distribution around* $m_\Delta c^2$ *= 1236 MeV with a width of* Γ_Δ *= 120 MeV.*

Fig. 3 *Invariant pion cross section/arbitrary normalization/ in the U + U reaction at* E_{lab} *= 800 MeV/ nucleon. All three curves contain both the thermal and delta decay contribution /with sharp delta mass/. The curves differ only in break-up times and are labelled accordingly /see text/.*

Fig. 4 *Invariant proton and pion cross sections /arbitrary normalization/ in the U + U reaction at* E_{lab} *= 800 MeV/ nucleon. The curve for protons is obtained using Boltzmann statistics/including the effect of hydrodynamical flow/. For pions Bose statistics with the contribution of the condensate [8] is used and hydrodynamical effects are included. Dots refer to the 800 MeV/A Ar+KCl,* $\Theta_{CM}=90^o$*, high multiplicity experimental data of Ref. 1.*


$E\frac{d^3\sigma}{dp^3}$(mb/sr/(MeV^2)c^3)
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10^2
10^1
10^0
kT=44.1MeV
PIONS
PROTONS
$kT_{app,p}$=82MeV
$kT_{app,\pi}$=63MeV
0
100
200
300
400
500
600
E*(MeV)

Fig. 1

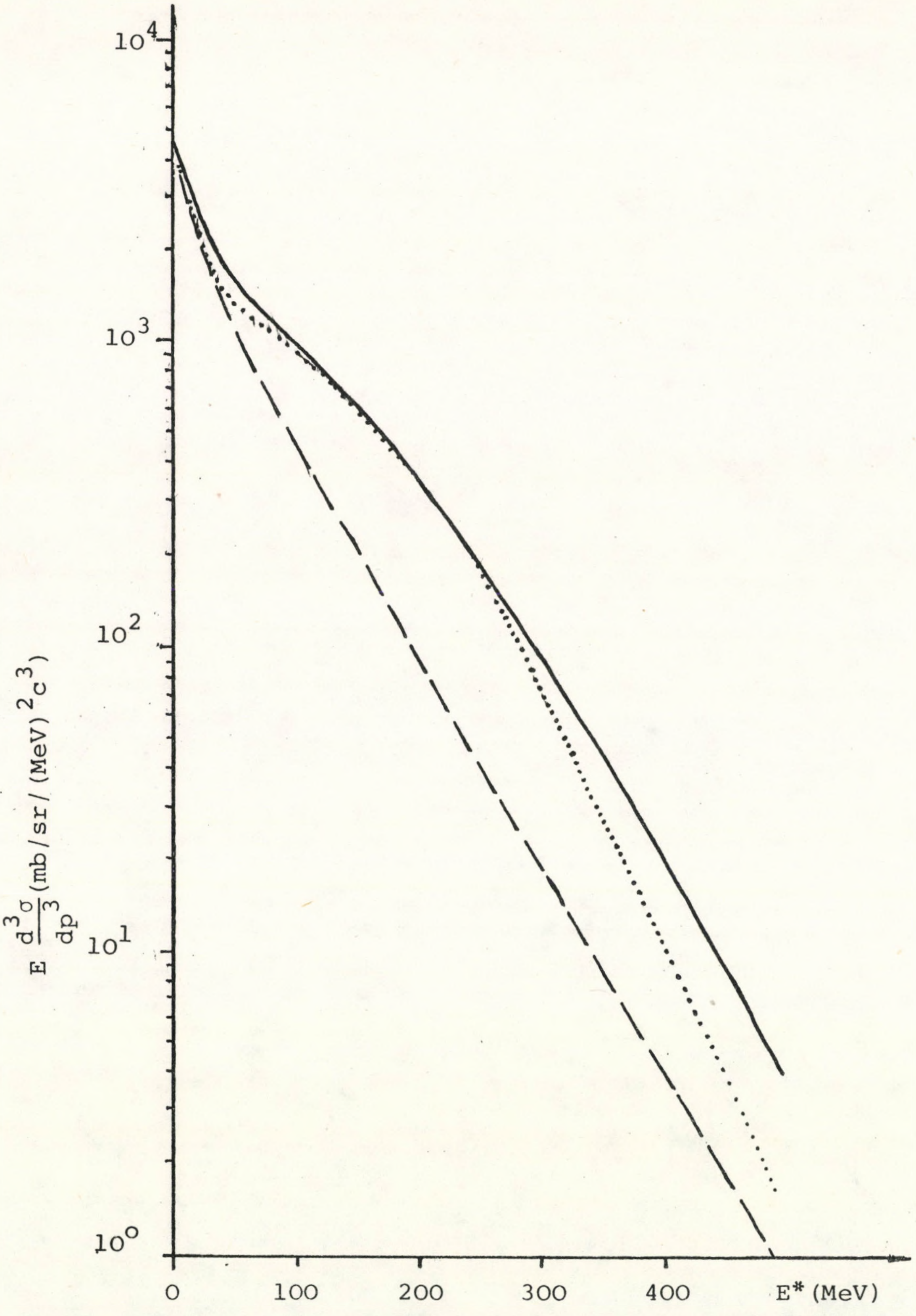

10^4
10^3
10^2
10^1
10^0
$E\,\frac{d^3\sigma}{dp^3}$ (mb/sr/(MeV)^{2}c^3)
0
100
200
300
400
E* (MeV)

Fig. 2

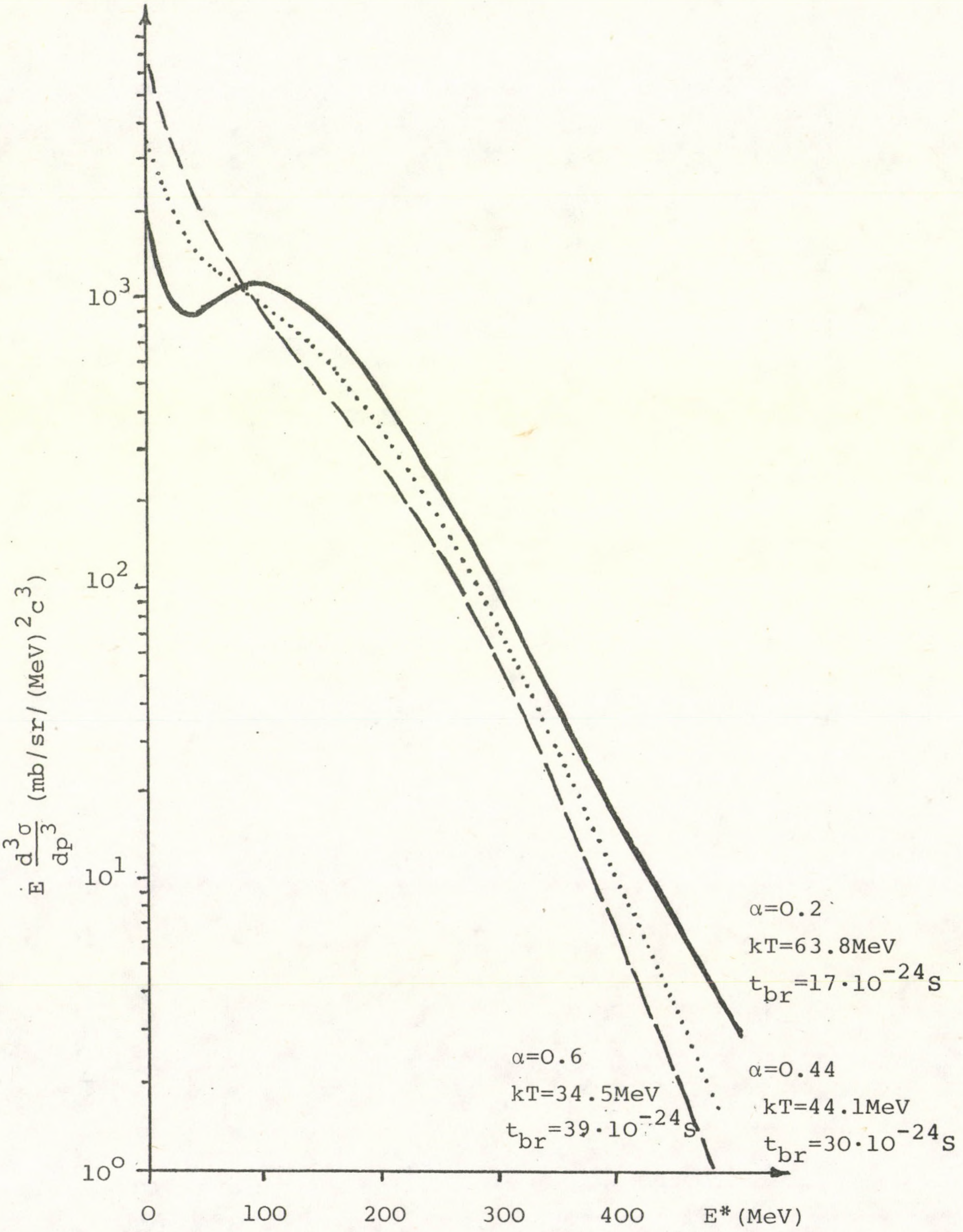

$E\frac{d^3\sigma}{dp^3}$ (mb/sr/(MeV)^{2}c^3)
10^3
10^2
10^1
10^0
0
100
200
300
400
E* (MeV)
α=0.2
kT=63.8MeV
$t_{br}=17\cdot10^{-24}$s
α=0.44
kT=44.1MeV
$t_{br}=30\cdot10^{-24}$s
α=0.6
kT=34.5MeV
$t_{br}=39\cdot10^{-24}$s

Fig. 3

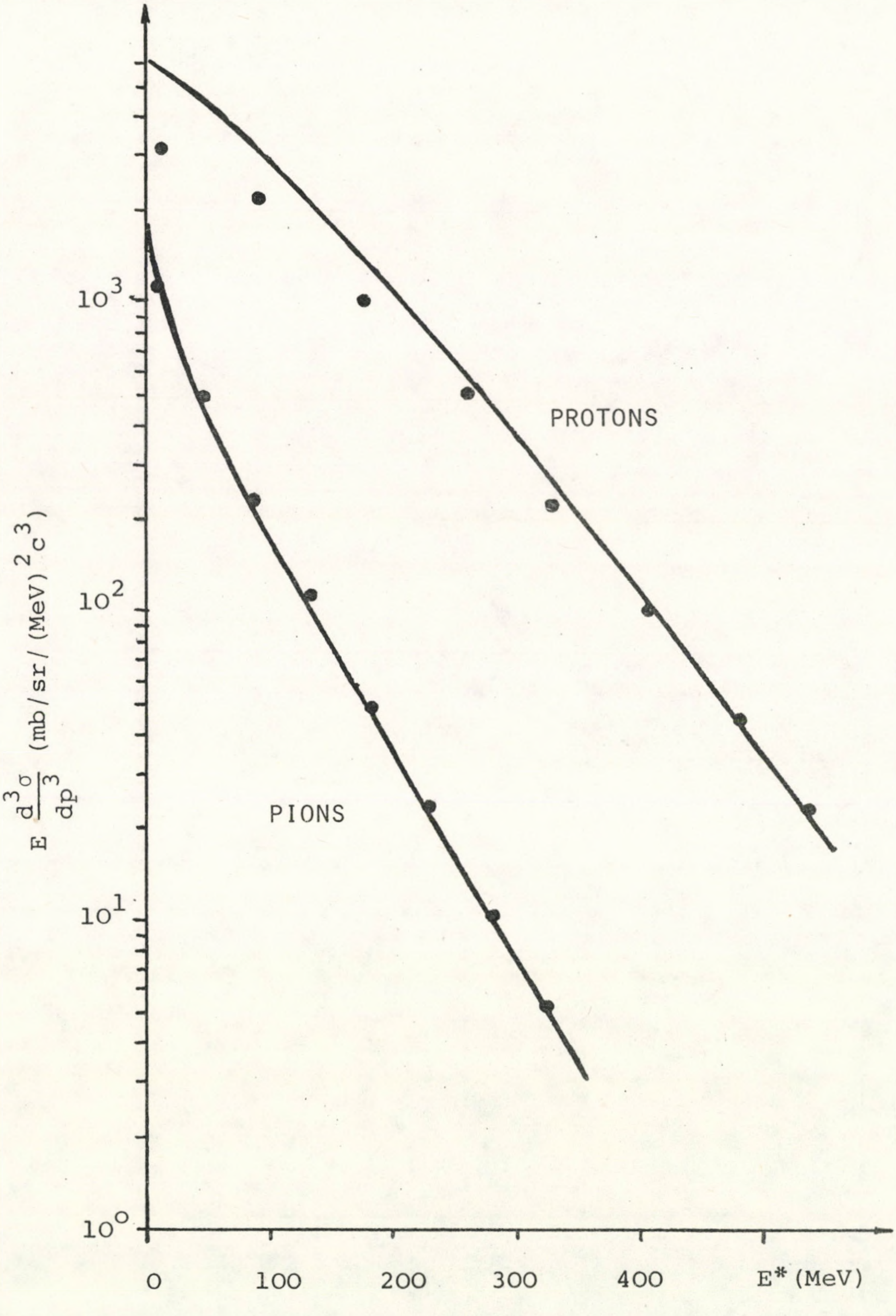
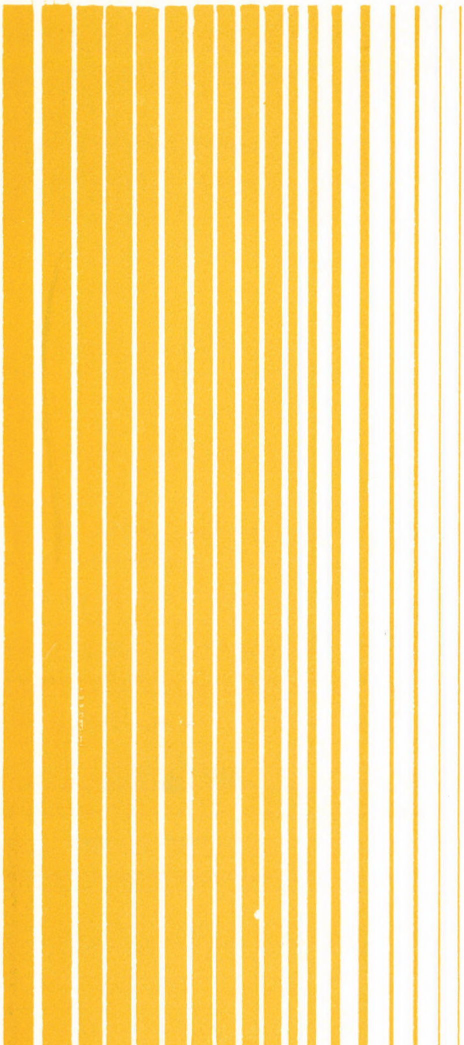

$E\frac{d^3\sigma}{dp^3}$ (mb/sr/(MeV)^{2}c^3)
10^3
10^2
10^1
10^0
PROTONS
PIONS
0
100
200
300
400
E* (MeV)

Fig. 4



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