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ANTIMATTER PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS

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The universal approach to the description of subthreshold, cumulative and twice-cumulative processes based on the self-similarity hypothesis is presented and applied to various reactions. Large experimental material including mesons, antiprotons, and antinuclei production in nucleus-nucleus and proton-nucleus interactions is analysed.

The investigation has been performed at the Laboratory of High Energies, JINR.

Образование антиматерии в релятивистских ядерных столкновениях

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Представлен универсальный автомодельный подход для описания подпороговых, кумулятивных и дважды-кумулятивных процессов. Проанализирован обширный экспериментальный материал по образованию мезонов, антипротонов и антиядер в протон-ядерных и ядро-ядерных взаимодействиях.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

In the last years there has been a great growth of interest in the problems and the methods of the description of strongly excited nuclear matter as well as in search for new effects going beyond the framework of the proton-neutron nuclear model. One of the possible ways of investigating such states is the study of antimatter production in relativistic nuclear collisions. In the present paper, the term antimatter denotes particles and nuclei mainly consisting of antiquarks. At present, there are many experimental data on antimatter production in proton- and nucleus-nucleus collisions [6—14].

However, there is as yet no adequate theoretical explanation to the most striking effects which are due to strongly enhanced A-dependences of antimatter production in subthreshold and cumulative reactions, as well as in the reactions with large transverse moment. There is a definite uncertainty from the point of view of the theoretical description in the transition energy region from units to hundreds of GeV/nucleon where the QCD methods are not valid yet, but the nucleon nuclear model is not longer applicable. It was already in the first studies on relativistic nuclear physics [1] that one stressed the importance of studying scale invariance (self-similarity) of nuclear collisions that was interpreted as a locality of hadron interactions.

The methods of self-similarity theory, which were found to be very effective in mechanics of continuous media, in the theory of diffusion, and a number of problems described by the nonlinear equations of a few variables, have successfully been applied in elementary particle physics [2,3,5].

Self-similarity is a special symmetry of solutions which consists in that the change in the scales of independent variables can be compensated by the self-similarity transformation of other dynamical variables. This results in a reduction of the number of the variables which any physical law depends upon.

This is just the way in which the self-similarity laws, caused by dimensional considerations in the region $P^2 >> M^2$, where P are the three-momenta of the particles, and M are their masses, are extensively applied [2]. In so going, self-similarity arises as a requirement for the secondary particle distribution (cross sections) to be invariant at the $P \rightarrow \lambda \cdot P$ transformation, which leads to the fact that the cross sections depend only on the momentum variable ratio.

The experimentally established self-similarity of the inclusive hadron production spectra as a function of the transverse momenta (transverse mass) [15] is widely used as a particular case of the self-similarity solution. However the condition $P^2 >> M^2$, or the consideration of the dependences on only the transverse mass strongly narrows the range of application of the self-similarity ideas. Thus the self-similarity solution suggested in Ref. [16] has made it possible to describe the subthreshold and cumulative reactions in unified manner.

The analysis of new experimental data on heavy-ion collisions [13,14] shows that the A-dependences used in Ref. [16] need to be defined more exactly. However, this approach is applicable not only to the subthreshold reactions, but also it can give some essential quantitative predictions for further experiments in the area of relativistic nuclear physics.

The general solution for the description of the inclusive hadron production is defined in a relativistic invariant form, in just the same way as in [16]

$$E\frac{d^3\sigma}{d^3p} = C_1 A_1^{\alpha(X_1)} A_2^{\alpha(X_2)} f(\Pi). \qquad (1)$$

C_1 is the constant defining the dimensionality of the invariant cross section, A_1, A_2 are atomic numbers of colliding nuclei; α and f, the functions determined from experiment. For the inclusive hadron production $A_1 + A_2 \rightarrow h + \dots$ the dimensionless parameter Π is defined as

$$\Pi = \frac{1}{2}(X_1^2 + X_2^2 + 2X_1X_2\gamma_{12})^{1/2},$$

where $\gamma_{ij} = u_i u_j = P_i P_j / M_i M_j$ is the Lorentz factor of the relative motion of colliding particles, X_1 and X_2 are the four-momentum fractions necessary for the hadron to be produced. The relationship between X_1 and X_2 is described by the laws of conservation written in the form

$$(X_1M_1u_1 + X_2M_2u_2 - M_3u_3)^2 = (M_nX_1u_1' + M_nX_2u_2' + \sum_{k=4} M_ku_k)^2. \tag{2}$$

Here M_n is the nucleon mass; and M_3, the mass of an emitted particle. Essentially, we are using an experimentally proved correlation depletion principle in the relative four-velocity space [4] which enables us to neglect the relative motion of not detected particles, namely the quantity $2\sum_{k>1}(\gamma_{kl}-1)M_kM_l$ in the right-hand part of Eq. (2).

Employing this approximation, the link between X_1 and X_2 can conventiently be written in the form

$$X_1X_2(\gamma_{12}-1) - X_1\left(\frac{M_3}{M_p}\gamma_{13} + \frac{M_4}{M_p}\right) - X_2\left(\frac{M_3}{M_p}\gamma_{23} + \frac{M_4}{M_p}\right) = \frac{M_4^2 - M_3^2}{2M_p}. \tag{3}$$

In the case of production of antiparticle with mass M_3, the mass M_4 is equal to M_3 as a consequence of conservation of quantum numbers. In studying the production of protons and nuclear fragments $M_4 = -M_3$ as far as minimal value of Π corresponds to the fact that any other additional particles are not produced. The X_1 and X_2 obtained from the minimum Π are used to construct a universal description of the A-dependences.

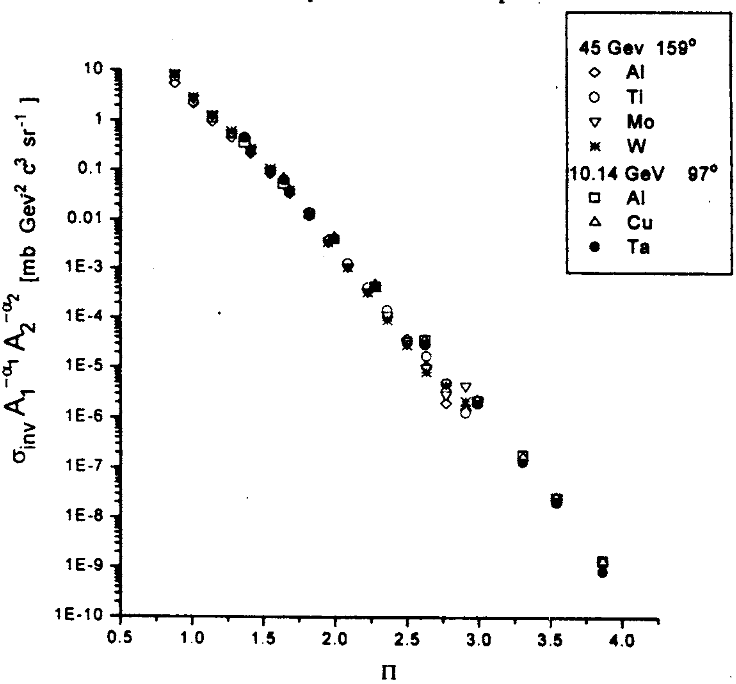

Fig.1. The cumulative pion production cross section in the reactions $p + A \to \pi^- + \ldots$ Ref. [6,11] as a function of Π (taking into account the factor describing the A-dependences

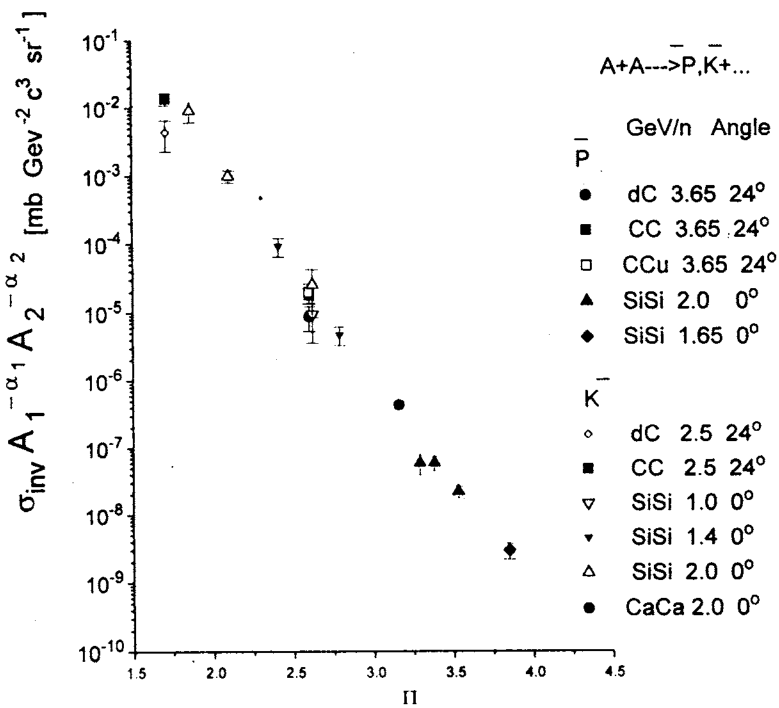

Fig.2. The experimental invariant cross section from Ref. [7,8,9,10] as a function of parameter Π (taking into account the A-dependences proposed)

The analysis of the experimental data shows that the A-dependence of the inclusive production cross section can be parametrized by a universal function $\alpha = 1/3 + X/3$, where X is equal to X_1 and X_2, respectively.

Thus the dependence on the three parameters, namely the incident proton energy, the momentum and the angle of produced pions, is reduced to the dependence on a single self-similarity parameter Π (the invariant in which just consists of discovered symmetry of solution).

In Figs.2 and 3, the experimental data on antimatter ($K^-, \bar{p}$) production in deep sub-threshold reaction are presented. It should be noted that for such particles to be produced simultaneous participation of more than one nucleon from both the incident nucleus and the target-nucleus is neede, that is $X_1 > 1$ and $X_2 > 1$ (twice-subthreshold reactions). The quantity $2 \cdot \Pi$ has the physical meaning of the mass of such a system.

The analysis of the experimental data on the production of antimatter and nuclear fragments at an energy of 200—240 GeV [12] shows the possibility of a unified description of the reactions studied by the present time for the values of parameter larger than unity (Fig.4).

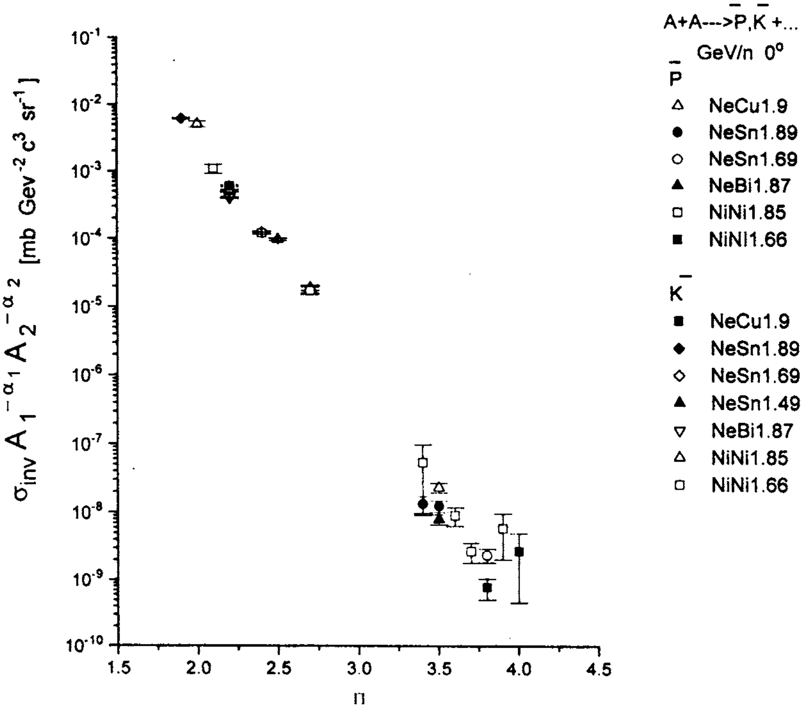

Fig.3. The experimental invariant cross section from Ref. [14] as a function of parameter Π (taking into account the *A*-dependences proposed)

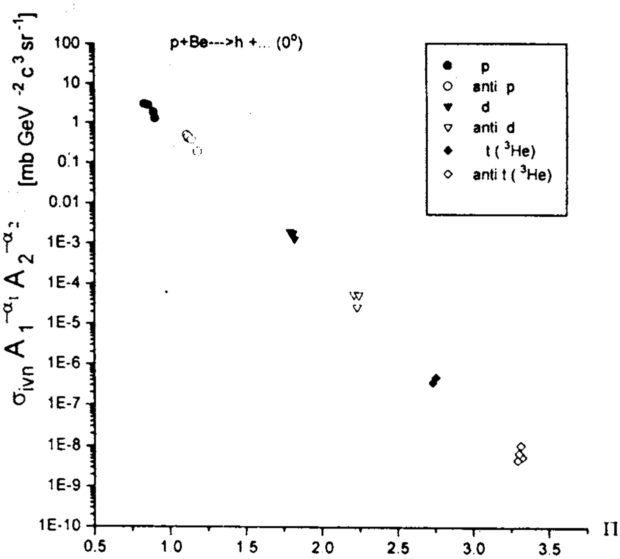

Fig.4

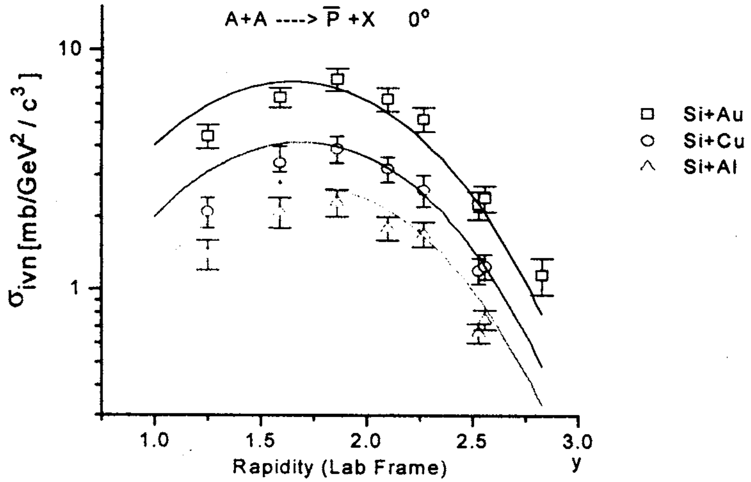

Fig.5

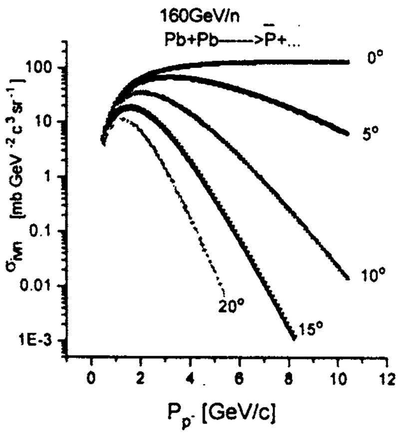

Fig.6

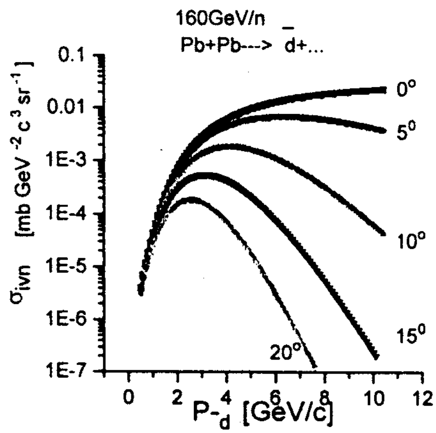

Fig.7

Making use of the exponential dependence of the invariant cross section on the parameter Π in the form

$$E\frac{d^3\sigma}{d^3p} = C_1 A_1^{\;1/3+X_{1/3}} A_2^{\;1/3+X_{2/3}} \exp(-\Pi/C_2), \tag{4}$$

the constant C2 is found to be equal to $C2 = 0.125 \pm 0.002$ for all experimentally studied reactions. For nuclei with $A > 20$ the constant $C1 = 19000$ [mb GeV^{-2} c^3 sr^{-1}].

Figure 5 shows the experimental data on antiproton production at an incident silicon nuclei energy of 13.7 GeV/n and the result of calculation by Eq. (4).

Figures 6 and 7 give the predicted cross section for the $\bar{p}$ and $\bar{d}$ production in Pb Pb collisions at 160 AGeV, the angular and momentum dependences of these cross sections. It is possible to test this prediction in CERN experiments, in particular in the WA-98 experiment.

Conclusion

The self-similarity solution in the form of Eq. (4) gives the quantitative description of the cross section for production of antimatter (and also nuclear fragments) with the use of only two universal constants C_1 and C_2 equal to $C_2 = 0.125 \pm 0.002$, $C_1 = 19000$ for nuclei with $A > 20$ and $C_1 = 2700$ for proton and light nuclei with $A < 10$. The constant C1 for light nuclei with $A = 5$—20 needs to be improved.

The approach has been tested in a wide range of collision energies from 1 to 240 GeV/n for $\Pi > 1$ and the transverse momentum of detected particles less than 2.5 GeV.

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