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Protons with large momentum from ^{12}C fragmentation at 300 MeV/nucleon

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Proton momentum spectrum from reaction ^{9}Be(^{12}C, p)X at 0.3 GeV/nucleon and at 3.5^{o} has been measured with high sensitivity in a cumulative region where proton velocity is larger than that of the projectile. Obtained data cover seven orders of the differential cross section magnitude and give an indication for a cut-off of the spectrum near a kinematic boundary for protons from ^{12}C fragmentation on a free nucleon.

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1. Introduction

One of the most interesting puzzles of relativistic nuclear physics is an origin of cumulative particles. Study of the cumulative particles was pioneered by A.M.Baldin [1] and G.A.Leksin [2] in seventies. Though a lot of efforts has been spent over decades for measurement and an analysis of such processes in hadron-nucleus interactions the origin of these particles is still an open question. Kinematic parameters of cumulative particles lie in a region forbidden for interactions of free nucleons. Heavy ion collisions give a possibility to open new region for the cumulative particle study namely a region forbidden for nucleon-nucleus interactions. It can shed new light on above mentioned problem. In our present study we made a step in this direction by high sensitivity measurement of high momentum protons at small angles from ^{12}C fragmentation. Projectile energy was chosen to be 300 MeV per nucleon in hope for larger yield at this relatively small energy.

2. Experiment

The experiment was carried out at the heavy-ion complex TWA (Tera Watt Accumulator) at ITEP which includes an ion laser source, a linac, a booster and an accelerator-accumulator ring. Ions of 200-1000 MeV/n could be accumulated in this ring for successive use in experiments on high-energy-density physics or accelerated to maximal energy of 4 GeV/n. During our measurements each four seconds the carbon ions C^{+4} were accelerated in the booster up to 301.6 MeV/nucleon, that corresponds to carbon ion momentum of 0.8079 GeV/c/nucleon. Then while injection in the accelerator-accumulator ring they were totally stripped and captured in the ring. Due to gradual growth of the internal ion beam emittance it was dropped to the internal target of 50 μm Be foil strip providing the spill, continuous in time. The products of the carbon nucleus fragmentation outgoing at 3.5^o were captured by the double-focus beam line of 42 meters long. Sets of few scintillation counters were placed at intermediate and final focuses for multiple measurements of dE/dx and time of flight (TOF). Fragments with different charge and mass were unambiguously selected in two-dimensional plots dE/dx vs TOF. The set up has been described in more details in [3] and [4]. The proton momentum spectrum was obtained by beam line energy scan in steps of 50-100 MeV/c and protons were selected by above mentioned procedure. Much larger flux of carbon ions was used in comparison with previous measurements [3].

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3. Data analysis

In Fig.1 invariant cross section $(E/P^2)d^3\sigma/(dXd\Omega)$ for proton yield at 3.5^o is presented as function of the cumulative variable X = P/P$_0$ where P (E) - proton momentum (total energy) and P$_0$ - projectile momentum per nucleon. By its definition X is a ratio of proton momentum to maximal momentum accessible in an interaction of free nucleons. X=1 is a mean value of a so-called evaporation peak which width is defined by Fermi motion of nucleons in carbon nucleus. This peak is well described by all models of nucleus-nucleus collisions. In Fig.1 calculations in the QMD-model are shown by dash-dot line. (We used QMD version [5] from the CERN/GEANT4 package [6]). At higher momentum (X>1.1) the deviation between calculations and the data gets very large. This difference demonstrates well known but yet unsolved problem of cumulative particles. In a region above evaporation peak the proton momentum spectrum is well described by an exponent $exp(-\alpha X)$. The result of the fit in a range 1.1<X<2.1 is shown by straight line. Obtained slope parameter α is equal to 9.77±0.08. At larger X a cut-off of the spectrum was observed near X=2.4 (proton laboratory momentum is equal to 1.95 GeV/c) where only upper limit was obtained. The cross section in this region is seven orders of magnitude less than in the evaporation peak. This cut-off can be connected with the kinematic boundary for the reaction p(^{12}C, p)X on free nucleon that is at P = 1.865 GeV/c or X=2.31. In Fig.1 this boundary is marked by an arrow. In Fig.2 proton momentum spectrum of Fig.1 is presented as function of V.S.Stavinsky variable X$_s$ [7]. In units of nucleon mass this variable is equal to the minimal mass of the projectile that can produce proton with given momentum on free nucleon target. In case of proton emission X$_s$ (as function of emitted proton momentum at fixed projectile energy per nucleon) can be calculated from energy momentum conservation for the elastic scattering

$$A+p \rightarrow p+A,$$

where A is a "nucleus" with mass equal to X$_s$ nucleon masses and p is a free nucleon. For ^{12}C ions maximal value of X$_s$ is obviously equal to 12. (Binding energy and proton-neutron mass difference are too small to be taken into account here.) X$_s$ = 12 marked by arrow in Fig.2 corresponds to the same boundary as in Fig.1. In this experiment we measured cross section up to X$_s$=15 and obtained an upper limit for X$_s$=20. It means that the mass of the target participants relevant to high energy proton emission is larger than nucleon mass and that this region is unreachable for nucleon-nucleus interactions. The spectrum in Fig.2 is well described by power law (X$_s$)$^{-\kappa}$ in 2< X$_s$<15 with $\kappa = 6.70 \pm 0.09$ as shown in Fig.2 by full line. In contrast to Fig.1 the X$_s$ dependence does not show significant change near X$_s$=12 but this variable losses its physical meaning at X$_s$>12. It is worth to mention here that at fixed X and at high energy X$_s$ is equal to X. So the difference between distributions of Fig.1 and Fig.2 is due to relatively small energy of this experiment.

4. Conclusion

An evidence for a cut-off of the cumulative proton spectra near kinematic boundary for proton emission from ^{12}C fragmentation on free nucleon has been obtained. This boundary is not the only one in the cut-off region. Almost at the same momentum there are kinematic boundaries for high momentum proton emission from interaction of two nuclei with mass numbers 2 and 8 as

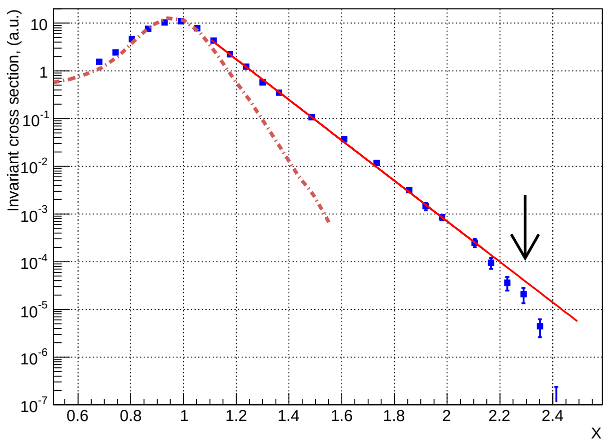

Figure 1: Invariant cross section (in arbitrary units) for proton yield from ^{12}C fragmentation at 0.3 GeV/nucleon at 3.5^{o} as a function of cumulative variable X. The dash-dot curve is the QMD-model prediction and full straight line is an exponential ($\sim \exp(-\alpha X)$ fit in cumulative region with α= 9.77$\pm$0.08. Arrow shows a kinematic boundary for proton production in ^{12}C fragmentation on free nucleon.

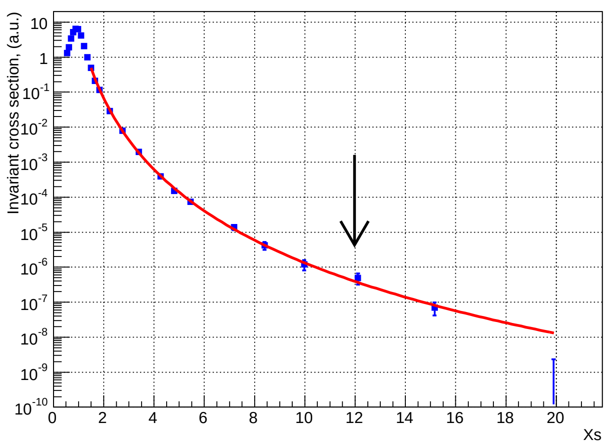

Figure 2: The same as in Fig.1 but as function of variable X$_s$. The solid curve is a power law ($\sim X_s^{-\kappa}$) fit with $\kappa = 6.70 \pm 0.09$. Arrow shows a kinematic boundary for proton emission in ^{12}C fragmentation on free nucleon.

well as with 3 and 5. In any case in our experiment for the first time the cumulative protons have been measured in a region forbidden for nucleon-nucleus interactions. Our measurements at 600 MeV/n and at higher energies [4] show that the cross section is too small to obtain results near this kinematic boundary. Lower energies seem to be preferable for this study. If such effect will be observed at other projectile energies it will give a possibility to discriminate between possible different kinematic boundaries and shed new light on underlying mechanisms of high momentum proton emission. For general nucleus-nucleus interactions it is not expected to observe any threshold effect apart from total energy momentum conservation. The observed cut-off can be result of a dominant role of a single nucleon component of target nucleus in high momentum proton emission. In this case the cut-off is just a step or change of the slope of proton spectrum. This hypothesis can be checked by even more sensitive measurements.

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