Anti-nuclei and nuclei production in Pb+Pb collisions at CERN SPS energies

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Abstract. We present new results on production of ^{3}He and t obtained by the NA49 experiment in 20A, 30A, 40A and 80A GeV central Pb+Pb collisions at the CERN SPS. Transverse mass spectra and rapidity distributions for clusters measured over a large phase space domain are discussed. We observe a weak dependence of the mid-rapidity t/^{3}He ratio on collision energy at SPS. The energy dependence of the total yield for ^{3}He is remarkably reproduced by a statistical hadron gas model. A gradual decrease of the coalescence parameter B_3 for ^{3}He with $\sqrt{s_{NN}}$ is observed. In addition, a measurement of the yield of anti-deuterons in Pb+Pb reactions at SPS's top energy of $\sqrt{s_{NN}}$ = 17.2 GeV is presented.

1. Introduction

The aim of the measurements, performed by the NA49 experiment during the energy scan program at the CERN SPS, was to investigate the properties of strongly interacting matter in heavy-ion collisions via a vast range of observables from light hadrons (, K) to light nuclear clusters (^{3}He, t). Data on composite particle production in reactions with heavy ions gives us valuable information about the late stage of the reball evolution and may provide a measure of the size of the particle emitting source. In addition, a comparison of experimental data on cluster yields to the statistical model expectations can also shed some light on the mechanism of formation of light nuclei in heavy ion collisions.

2. Experiment NA49 and data analysis

The main components of the NA49 apparatus [1] are four time projection chambers (TPCs) (two of them are placed within magnetic elds produced by the superconducting magnets) for tracking and particle identi cation (PID) via ionization energy loss dE/dx measurements. The time-of- ight system (two TOF scintillator arrays situated beyond the TPCs) provides timing information for PID covering the mid-rapidity region. The downstream zero degree calorimeter was used for triggering and centrality determination. This report is based on the analysis of the data collected during the 1999-2002 running period. A total of 1:2 10^6 events representing the 7% most central Pb+Pb collisions at 20A, 30A, 40A and 80A GeV were used in the study of ^{3}He and t production. Anti-deuterons are measured in the 23% most central Pb+Pb collisions at 158A GeV (2:6 10^6 events). Combined dE/dx and TOF information was used for the identi cation of single charged hadrons and (anti)clusters at mid-rapidity. Double charged ^{3}He clusters are identi ed over almost the entire phase space via the dE/dx method. The results presented below include corrections for the PID track quality cuts, background contamination, detection e ciency and geometrical acceptance. The detailed description of the analysis procedure is given in Refs. [2, 3].

3. Results and discussion

Fig.1 (left panel) shows the mid-rapidity transverse mass spectra for helium-3 and tritons observed in central Pb+Pb collisions at 20A-80A GeV. As expected, the collective transverse flow flattens m_t-spectra for clusters at low m_t, so that the distributions shown are fitted with a double exponential function (fits are shown as dashed lines in Fig.1). The mean transverse mass values as obtained from the fits at 20A and 80A GeV are plotted in Fig.1 (right panel, upper plot) together with the NA49 measurements for hadrons (π, K, p) and deuterons [2]. Here, one can see a clear indication of a large collective transverse flow effect: a considerable increase of $<m_t>-m$ with particle mass. As Polleri et al. argued [4], a linear dependence of mean $<m_t>$ on the particle mass furthermore supports the conclusion that the particle emitting source has a uniform (box-like) density distribution and a linear velocity profile. There is no significant difference in resulting values of $<m_t>$ for particle species between 20A and 80A GeV data. This may indicate little change in the strength of the transverse expansion over the SPS energy domain.

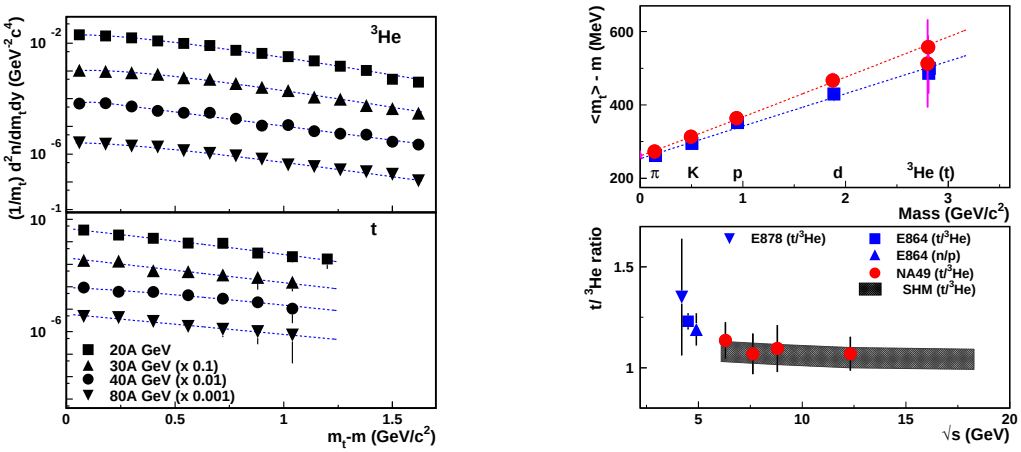

Figure 1. Left: the mid-rapidity m_t-spectra for ^{3}He (upper panel) and t (lower panel) for the 7% most central Pb+Pb collisions (dashed lines show the double-exponential fits used for extrapolation to the unmeasured range). Right: (upper panel) $<m_t>-m$ versus particle mass as obtained from the fits to the spectra at 20A (■) and 80A GeV (▲); (lower panel) mid-rapidity t to ^{3}He ratio as measured (points) and predicted by the SHM model [5] (band).

For the complete picture of nuclear cluster production, information about the phase space distribution of neutrons in the final state (at freezeout) is of importance. However the yield of n (usually) remains unmeasured. As it has been established in the RQMD model, the initial ratio of neutrons participating in the collision to protons (n:p = 1.54:1 for ^{208}Pb) changes considerably toward the equilibrium value of n/p = 1 during the fireball evolution as a result of strong resonance production. Assuming a simple additive scheme which relates the yield of the cluster to the product of the yields of nucleons, the freezeout n/p ratio may be deduced from the t/^{3}He ratio. The right bottom panel of Fig.1 shows the ratio t/^{3}He as a function of $\sqrt{s_{NN}}$. We observe a weak energy dependence of this ratio in central Pb+Pb collisions at $\sqrt{s_{NN}} > 6$ GeV. The average value $<t/^3He>$ is about 1.1 at SPS, which indicates a large degree of equilibrium in the final state of the reaction in this energy domain. This trend is well reproduced by the Statistical Hadronization Model (SHM) [5] (SHM predictions are shown by the dark band in Fig.1). The yields of ^{3}He in Pb+Pb collisions at 20A-80A GeV extracted in rapidity slices of $\Delta y = 0.4$ are shown in Fig.2 (left) as a function of rapidity. The rapidity distributions for ^{3}He are concave at all energies while those for protons are essentially flat at around mid-rapidity [6]. The

observed increase of ^{3}He formation rate at very forward rapidities in central Pb+Pb collisions has not been explained yet. The total yields for ^{3}He were obtained by fitting the measured rapidity distributions with a parabola (fits are shown as dashed lines). The 4π yields of ^{3}He are plotted in Fig.2 (center) as a function of $\sqrt{s_{NN}}$. Also shown are the total multiplicities of ^{3}He predicted by the SHM model. The agreement with the NA49 measurements is remarkable.

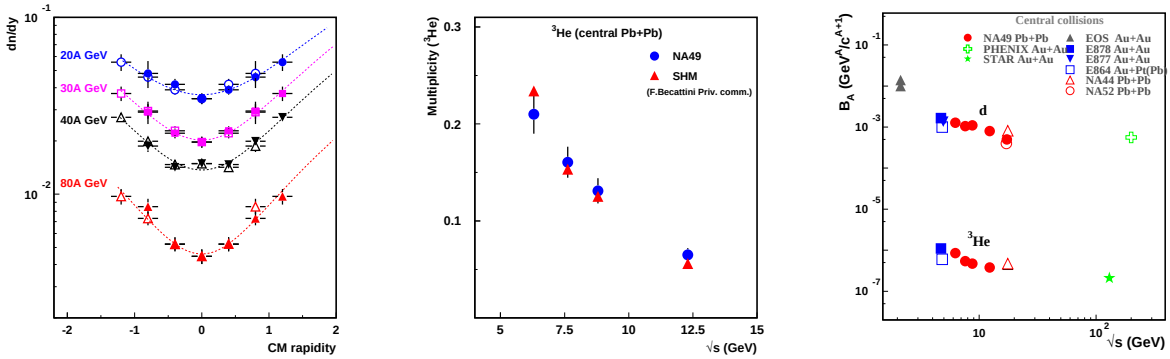

Figure 2. Left: the rapidity distributions and the parabolic fits (dashed lines) for ^{3}He in Pb+Pb at 20A-80A GeV (open symbols are obtained by reflection at mid-rapidity). Center: total yields of ^{3}He as measured by NA49 (circles) and predicted by the SHM model (triangles). Right: energy dependence for B_2 and B_3 in central A-A collisions.

A typical coalescence prescription [7,8,9] relates the invariant yield of light nuclei of atomic mass number A to that of protons raised to the Ath power (n and p distributions are assumed to be the same) through a dimensioned variable - coalescence parameter B_A as:

$$E_A \frac{d^3N_A}{d^3P} = B_A \left(E_p \frac{d^3N_p}{d^3p} \right)^A ; \qquad P = A \, p$$

B_A can be converted, under specific assumption, into the volume of the fireball at freeze-out (B_A is inversely related to that volume). Fig.2 (right panel) shows energy dependence for coalescence parameters B_2 and B_3 in central heavy ion collisions. Our measurements (circles) are plotted together with AGS [10,11] and RHIC [12,13] data. One can see, that both B_3 and B_2 decrease as $\sqrt{s_{NN}}$ increases, suggesting increasing freeze-out volumes. To examine this general trend futher, the (coalescence) radii of the emitting source have been extracted, using the prescription of Scheibl and Heinz [14] for a thermalized fireball with transverse flow. A comparison of the obtained radii for d and ^{3}He with those measured at other energies is shown in the left panel of Fig.3. It is seen, that the source sizes for different cluster species agree with each other within the error bars and are found to be rising with center-of-mass energy.

Now we turn to anti-deuterons. In Fig.3 (center) the centrality dependence of the invariant yield of anti-deuterons and anti-protons [3] normalized to the number of wounded nucleons is shown. Anti-deuterons are measured in two centrality bins, corresponding to the 0-10% and 10-23% most central Pb+Pb collisions. The yield of anti-deuterons per wounded nucleon exhibits very weak variation with centrality in the measured range in a manner similar to that observed for anti-protons. B_2 for both deuterons and anti-deuterons, measured in these event samples, is plotted in Fig.3 (right panel). The B_2 values for deuterons agree with those for anti-deuterons within the errors. The observed centrality dependence suggests increase of the source size in more central collisions.

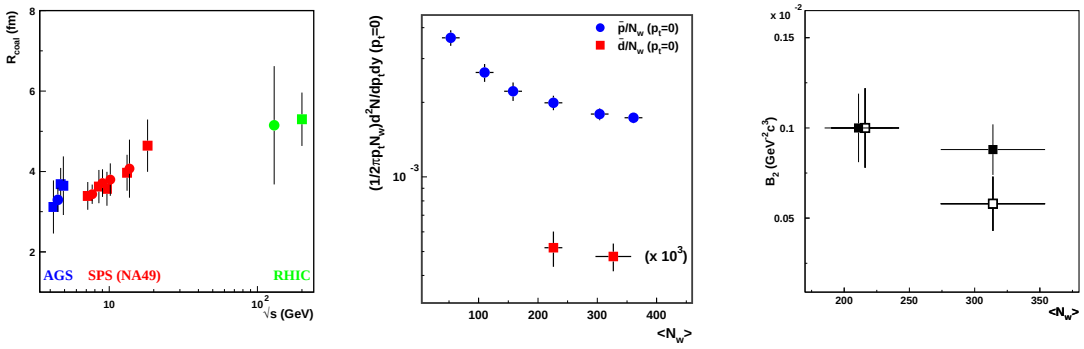

Figure 3. Left: R_{coal} for d(■) and ^{3}He( ) in central A-A collisions at AGS (blue), SPS (red) and RHIC (green). Center: invariant cross section per wounded nucleon at $p_t = 0$ as a function of $< N_w >$ for anti-protons ( ) and anti-deuterons (■). Right: B_2 for deuterons (tu) and anti-deuterons (■) as a function of $< N_w >$.

4. Summary

The NA49 experiment has measured ^{3}He and t production in central Pb+Pb collisions at 20A–80A GeV. The invariant yields for clusters are described by a sum of two exponential functions in m_t and the $< m_t >$ values appear to follow a linear increase with particle mass. The mid-rapidity t/^{3}He ratio in central Pb+Pb collisions at SPS energies is measured to be t/^{3}He 1.1, which is considerably smaller than the initial participant's n/p ratio of 1.54. We observe that the rapidity distributions for ^{3}He are concave at all studied energies. It appears that a statistical hadron gas model is able to reproduce data on ^{3}He yields. B_3 and B_2 coalescence parameters follow a decreasing trend with collision energy. The source radii deduced from the measured B_2 and B_3 parameters are found to be consistent.

Acknowledgments

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