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Subthreshold Antiproton Production In Heavy Ion Collisions

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Abstract

We present a RQMD calculation of antiproton yields and their momentum distribution in $Ne + NaF$ collisions at 2 GeV/u. The antiprotons can be produced below threshold due to multi-step excitations for which meson-baryon interactions play a considerable role. In this system the annihilation probability for an initially produced antiproton is predicted to be about 65%.

Subthreshold particle production provides a useful tool to extract information about the hot high density phase of a heavy ion collision. This process is energetically forbidden in free NN-collisions. So it can give clues about cooperative contributions of many participant nucleons. Subthreshold production of $\bar{p}$ has first been observed experimentally for $Si + Si$ at BEVALAC [1]. The yields were found to be inconsistent with calculations which take into account the Fermi-momentum of the nucleons (three orders of magnitude larger than expected)[2]. Experimental studies of subthreshold antiproton production have been done recently with a 2.0 GeV/u and 1.8 GeV/u Ne beam from the heavy ion synchrotron (SIS) at GSI and will be continued[3]. Various mechanisms of antibaryon enrichment in general have been proposed, e.g. hadronic multi-step processes[4][5][6], strong mean field effects[7] and meson-meson interaction like $\rho\rho \rightarrow p\bar{p}$[8] as well as string-string interaction[9] and the quark-gluon plasma [10][11]. Consequently, there is a need for learning about the weight of all those contributions. Here we want to demonstrate the effect of hadronic multi-step excitation to $\bar{p}$ production and the annihilation rate. For our investigations we used a microscopic phase space approach – the relativistic quantum molecular dynamics (RQMD 1.07)[12] – which includes the excitation of Δ and N^* resonances, the formation and decay of colour strings and the mesonic degrees of freedom. The number of produced baryons in our model – based on the LUND scheme[13] – depends strongly on the excited mass of the resonance (baryonic resonances are treated as a string if $m > 2\ GeV$, mesonic resonances if $m > 1\ GeV$). So the excitation mechanism in elementary hadronic collisions is a crucial feature for the production. The new mass of an excited nonstrange baryon is chosen according to a Breit-Wigner distribution and projected on 20 different isospin $\frac{1}{2}$ and $\frac{3}{2}$ resonance states with corresponding lifetime. The average $\bar{p}$-formation time τ is about 1.5 fm/c (see [6]). For the $N\bar{N}$ annihilation cross section we implemented a parametrisation according to available experimental data of the elementary reaction. In our calculations the effective potentials in the RQMD are switched off (pure cascade mode). We performed the Monte-Carlo calculation in two steps, to cope with the extremely low production probabilities in subthreshold collisions: First we triggered on highly excited baryon masses above 2.8 GeV, then we rerun those events forcing a decay into an antibaryon but weighting them with the elementary production probability according to the string-fragmentation scheme.

As we have shown already for AGS-energies[6], heavy particles are not dominantly created in the first collisions of a nucleus-nucleus reaction but in secondary interactions. This looks the same at SIS-energies. RQMD calculations exhibit a scenario of cumulative scattering of participants and secondaries, a multi-step process of successive binary collisions like πN, ρN, ηN^* etc. as well as $\Delta\Delta$ etc.. Baryons and mesons get more and more excited and decay or rescatter subsequently. Eventually the invariant mass of a single resonance-resonance interaction exceeds the threshold for antiproton production. Note that the mechanism responsible for the *enhancement* of the antiproton yields at AGS is mandatory to get *any* antiproton production at all for SIS-energies.

We investigated $Ne + NaF$ and $d + Cu$ reactions at 2.0 GeV/u. RQMD calculations show that the excitation of highly excited strings is strongly dependent on the number of participating target and projectile nucleons. The probability of e.g. $\Delta\Delta$-interactions decreases drastically in asymmetric systems like dA. RQMD predicts an enhancement of several orders of magnitude in the antiproton yields when $Ne + NaF$ is compared to $d + Cu$.

Additionally one has to take into account the specific reabsorption rate of the antiprotons. Previous calculations by means of transport theory matched the data for $Si + Si$ at 2.1 GeV/u within a factor of 2, if the absorption is neglected[4]. Other calculations for $Ni + Ni$ at 1.85 GeV/u predict an annihilation of about a factor 1000, but these calculations can also fit the data[5]. The latter result is in striking contrast to our own investigations. Systematic studies of antiproton production and annihilation at $10 - 15$ GeV/u in the framework of RQMD established survival probabilities near 10% in Au+Au[14]. In $Ne + NaF$ the absorption rate is still 45%. The values vary with the number of participating nucleons, the impact parameter and -rather weakly- the beam energy. For the system $Ne + NaF$ at SIS-energies (2 GeV/u) RQMD predicts an absorption rate of 65% (Fig. 1). If the antiproton formation time is set to zero, absorption increases up to 90% at 2 GeV/u.

Antiprotons are produced rather isotropically in momentum space. This is due to the multiple collisions that are necessary for the excitation of heavy resonances in $Ne+NaF$ at $2GeV/u$. This result does not change due to absorption. Therefore we predict that future experiments at finite angles will exhibit a similar transverse momentum distribution as the observed $p_{||}$ distributions[3]. Figure 2 shows the rapidity integrated transverse momentum spectrum for initial and final antiprotons in minimum bias reactions of $Ne + NaF$. Strong annihilation is predicted at low p_t. This could be easily observed by experiments at finite angles. The mean p_t of the final yield ($< p_t >= 285GeV/c$) is only slightly higher than that of the initial yield ($< p_t >= 270GeV/c$).

Figure 3 shows the collision spectrum for $Ne + NaF$ at 1.9 GeV/u. The contributions of baryon-baryon (BB) and meson-baryon (MB) collisions add to 115 binary interactions in a central collision of which 80% are BB, 20% MB and $< 1\%$ MM. However, a BB collision requires a $\sqrt{s}$ of four nucleon masses to produce an anti-baryon whereas a MB collision requires only three nucleon masses. If the collisions above the particular threshold are considered, the MB collisions contribute with 60% and BB with 40%. We do not find evidence for any antiproton production via the MM channel (especially $\rho\rho$) at SIS-energies.

In conclusion we state a significant discrepancy in the antiproton absorption rates as predicted by different microscopic models. Further experimental and theoretical studies are needed for clarification.

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Figure Captions:

Figure 1

Rapidity distribution of initial (dashed line) and final antiprotons with $\tau = 0 fm/c$ (dotted line) and the default value $\tau \approx 1.5 fm/c$ (full line) in minimum bias reactions of $Ne + NaF$ at 2 GeV/u. Initial $\bar{p}$'s correspond to an infinite formation time.

Figure 2

Spectrum of transverse momentum of initial (dashed line) and final (full line) antiprotons in minimum bias reactions of $Ne + NaF$ at 2 GeV/u.

Figure 3

Collision spectrum of central $Ne + NaF$ collisions at 1.9 GeV/u. The contribution of meson-baryon (dashed line) and baryon-baryon (full line) collisions are shown. The thresholds for antiproton production are indicated.

Figure 1

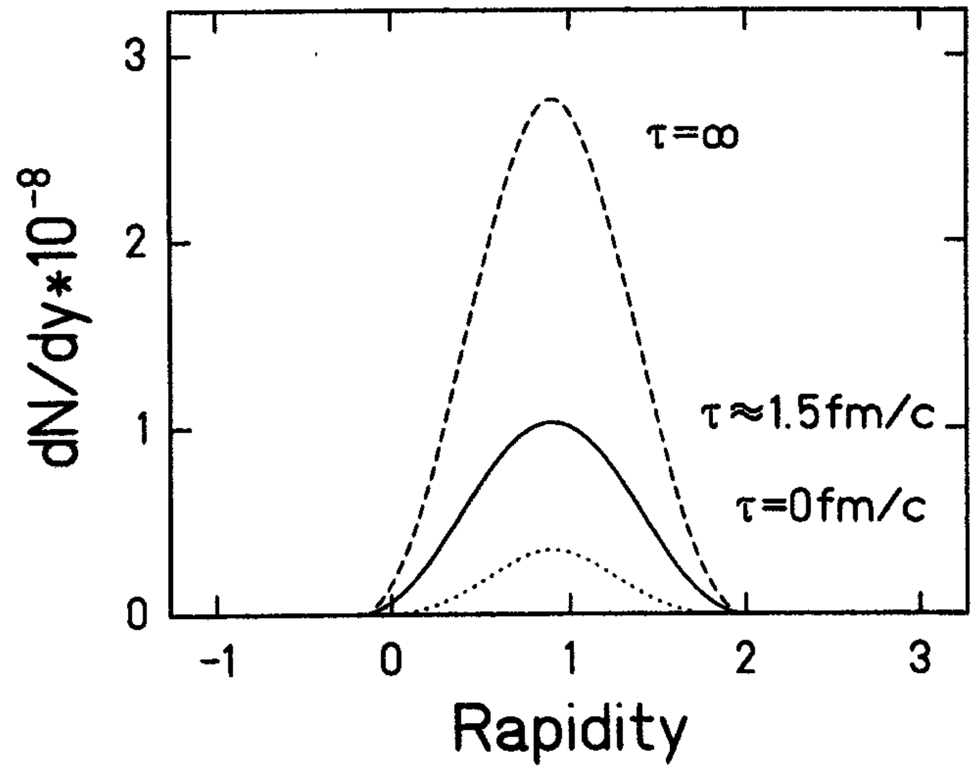

Figure 2

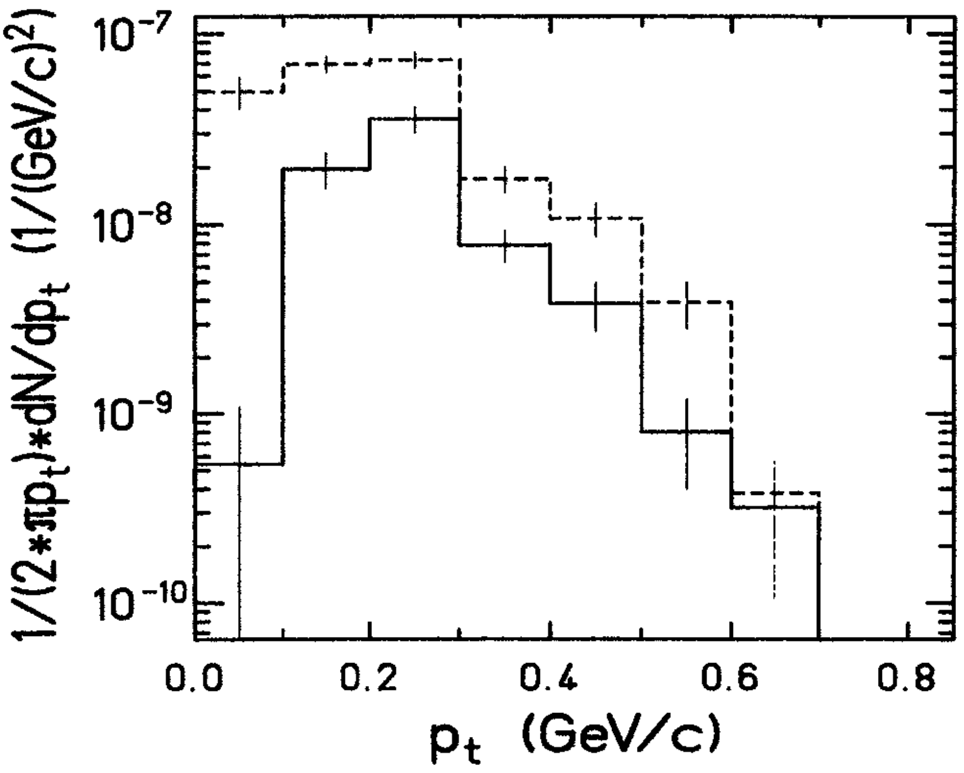

Figure 3