ANTINUCLEUS-NUCLEUS ANNIHILATION

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1 Abstract

A model for describing the collisions between an antinucleus and a nucleus is presented. It is based on the extension of the intranuclear cascade model for antiproton-nucleus interactions. The model is applied to exhibit some properties of antinucleus- nucleus collisions in the one GeV/nucleon incident energy range, in view of a possible analysis of special events in cosmic rays. In addition, the model does not support the possibility of a Leidenfrost effect, keeping the antinucleus and the nucleus fragments apart. event

2 Introduction

The detection of antimatter is of particular importance in particle physics and cosmology. Apparently, our Galaxy is overwhelmingly made of matter. Only a small fraction of antimatter, essentially antiprotons, is contained in the Cosmic rays. The total flux of antiprotons amounts to $\sim 10^{-4}$ times the total flux of the Cosmic rays (see Refs.[1,2] and other references therein), whose sources are believed to stand in our Galaxy. Very likely the ratio of the two fluxes is the same for other galaxies. In fact, it is largely believed that the Universe is predominantly made of matter. This picture is in striking conflict with the laws of particle physics, encrypted in the so-called standard model, which treats matter and antimatter on the same footing. Basically, two scenarios are usually proposed to get out of this conflicting situation. The first one, the so-called baryogenesis, assumes that the Universe was initially symmetric with respect to the particle-antiparticle conjugation and has afterward moved to a highly asymmetric configuration. Although the prerequisites for such a scenario, the so-called Sakharov conditions [3], are rather well known, the details of a successful picture of the development of this asymmetry has yet to be discovered. The second possible way to remove the conflict relies on the possibility of having presently a globally symmetric composition of the Universe in which initially equal amounts of matter and of antimatter have been split in distinct domains containing each only matter or only antimatter. These domains might correspond to galaxies or clusters of galaxies. Although the formation of such domains is possible in first order phase transitions, similar to the formation of domains in ferromagnetism, a precise description of this formation in the course of the expanding Universe, is still lacking. However the existence of such domains of antimatter cannot be readily discarded. The most probable signals coming from an hypothetical antimatter patch are expected to be identical to those coming from a matter patch since these signals are mainly of electromagnetic origin and thus are the same whether they come from antimatter or from matter. A more promising possibility may arise from the matter-antimatter interactions taking place at the boarder of two neighboring domains, one made of matter and the other of antimatter, when they possibly move to one another. This may generate large amounts of baryon-antibaryon annihilations generating copious emissions of gamma rays. These events are expected to be rare and highly transient, because high pressure may be built in the annihilation zone and may afterward clear up this zone by rejecting matter and antimatter in their respective original patches (Such a scenario was proposed already by Alfèn in Ref.[4]). A last possibility may arise when the annihilation in two touching patches is turbulent allowing finally substantial amounts of antimatter particles to escape from their original patch and travel until they reach our Galaxy. If these particles are antiprotons, they would probably be indistinguishable from the ones carried on by observed Cosmic rays. At the end, antinuclei may be the ultimate possible signal of the antimatter part of the Universe. Only very light antinuclei may have been detected so far and they may originate from spallation reactions taking place in our neighborhood. See Refs. [5–7] for a discussion of this presently well debated point. So heavy antinuclei (heavier than Carbon or Oxygen) may offer a promising signature. However, the shape of a nucleus-antinucleus annihilation event is not well known and such an event may escape the analyses. It is the main goal of this paper to give a simple presentation of a model able to generate such antinucleus-nucleus events and characterize them very simply. We plan to use the intranuclear cascade model that we proposed some time ago to describe antiproton annihilation on nuclei and that reproduces the data quite successfully. Of course we have adapted the model to this new case. We will mainly focus on the few GeV per nucleon incident energy domain, since this is the average energy of antimatter particles detected in the cosmic rays. Accessorily, we will pay attention to the so-called nuclear Leidenfrost effect [1]: in head-on nucleus-antinucleus collisions, a large amount of energetic pions are expected to be created in the touching zone. One may wonder whether the high pressure in the pion blob may or may not push on the remaining parts of the nucleus and the antinucleus, so terminating the global annihilation process prematurely.

[1] The Leidenfrost effect, in its simplest manifestation, is the physical phenomenon in which a liquid drop is deposited on the surface of another solid body that is significantly hotter than the liquid's boiling point and so creates an vapor layer that keeps the liquid from boiling rapidly. Owing to this repulsive force, a droplet stays slightly over the surface, avoiding a physical contact with it. The effect is named after the German doctor Johann Gottlob Leidenfrost, who described this phenomenon in "A Tract About Some Qualities of Common Water". Johann Gottlob Leidenfrost was born in Ortenberg in the County of Stollberg Germany on the 24th of November 1715. He died in 1794

3 The Intranuclear Cascade Model

3.1 The cascade model for antinucleon-nucleus interactions

There are several models of this kind. We use here the model developed by the author and his collaborators around the years 1990 and described in Refs.[8–13]. We simply mention the salient features here. The model aims to simulate the collision process in a way consistent with nuclear dynamics. Initially the particles are given position and momentum consistent with the incident antinucleon momentum and the Fermi gas picture of the target nucleus. The particles are set into motion, propagating freely until two of them reach their minimum distance of approach. At that precise moment, if this minimum distance of approach is small enough, in fact smaller than the quantity $\sqrt{\sigma(s)/\pi}$, where $\sigma(s)$ is the relevant collision cross section at the c.m. energy $\sqrt{s}$ of the colliding pair, the particles are forced to collide, i.e. they are given new momenta consistent with the available energy and the angular distribution of the produced particles. If the minimum distance of approach is too large, their free motion is not disturbed. Various types of elementary collisions are considered. In the purely hadronic sector (baryon number $B > 0$), $NN \rightleftharpoons NN$, $NN \rightleftharpoons N\Delta$ and $\pi N \rightleftharpoons \Delta$ collisions are considered. Conjugate processes ($B < 0$) with corresponding antiparticles are also taken into account. In the ($B = 0$) sector, $N\bar{N} \to n\pi$ annihilation, $N\bar{N} \to N\bar{N}$ elastic scattering and $N\bar{N} \to N\bar{N}m\pi$ inelastic scattering are introduced, as well as $N\bar{N} \rightleftharpoons N\bar{\Delta}$ and $N\bar{N} \rightleftharpoons \bar{N}\Delta$ inelastic scattering. In the use of this model, several other particles were included, like ρ, K and ω mesons and Λ and Σ hyperons were introduced. To keep the model as practical as possible for the extension to nucleus-antinucleus collisions, these complications leading to small effects in the energy range under interest were simply neglected. Similarly, isospin degrees of freedom were also neglected.

3.2 Extension to antinucleus-nucleus interactions

The main extension of the just described model for that purpose is the introduction in the initial state of an antinucleus, composed of a Fermi sea of antinucleons, boosted with the initial velocity. The simulation develops as in the antinucleon-nucleus case with the elementary collision cross-sections cited above. However, since in antinucleus-nucleus collisions a large number of pions are being created in a single event, we also took account of the pion-pion interactions, contrarily to the antinucleon-nucleus case. Pion-pion collision cross sections are not very well known. They are determined experimentally through final state interaction analyses of two-pion creation events, with simplifying assumptions. See for instance Ref.[16]. There are also theoretical indications based on chiral perturbation theory, like in Refs.[17,18]. One may summarize the information as saying that at low energy (less than a few hundred MeV kinetic energy), the elastic pion-pion cross-section lies between 10 and 30 mb. We chose to ascribe here the cross section to 40 mb. This choice is motivated by the fact that the effective pion-pion cross section in a pion gas is enhanced by the Bose factor (see for instance Ref.[19]), larger than unity, in contradistinction with the Pauli factor for fermion collisions [2]. Our choice is made as a first crude guess and is expected to depict approximately the maximum effect of the cloud of pions.

4 Illustrative results

4.1 Introduction

We give here only a few basic and illustrative results. We restrict to two cases. The first one concerns head-on collisions between an incident anti-^{16}O nucleus at 5 GeV/nucleon and a ^{16}O nucleus at rest. The second case refers to an anti-^{4}He impinging on a ^{16}O nucleus at 1 GeV per nucleon [3].

4.2 $\overline{^{16}O} - {}^{16}O,\ b = 0,\ E_{inc} = 5\ GeV/A$

We first focus on pion production. Fig. 1 gives the distribution of the pion multiplicity in head-on (impact parameter $b = 0$) collisions. One can see that on the average about 56.5 pions are produced at the end of the collision process. But, on the average, only 8 antinucleon-nucleon annihilations occur. At the incident energy considered here, each antinucleon-nucleon annihilation produces an average of 5 pions. The rest, about $\sim$ 17 pions, are produced by secondary reactions, mainly pion-nucleon and pion-antinucleon collisions.

More detail on the successive features of the collision can perhaps be provided by Fig. 2, which displays the time evolution of the spatial distributions of the baryons (nucleons and Delta's), of the pions and of the antibaryons, respectively, as the antinucleus-nucleus collision process develops. The left column of the figure represents the projections of the antibaryon density distribution on the reaction plane (same as the plane of the figure), as seen in the initial target rest frame, at four values of the time. The central part of Fig. 2 displays the pion density distribution in the same conditions. Finally, the right column gives the same information for the baryon density distribution. At t=0 (not shown in the figure), the Lorentz-contracted antibaryon density distribution of the antinucleus, coming from the left of the figure, is almost touching the extreme outskirts of the target, located at the origin of the coordinates. Actually the first row of Fig. 2 shows the distributions at $t = 4fm/c$ when the very first pions are just being created, as seen at the top of the central column in Fig. 2.

The examination of the distributions for the next snapshots reveals that the residue of the incoming $\overline{^{16}O}$ crosses the target with an almost undisturbed velocity (around 0.98 c) and basically keeps its shape during the whole collision process. This is not really surprising since half of the incoming antinucleons have been annihilated, leading to a mere $\sim$ 50% reduction of the density of the antinucleon

[2] This enhancement could be counterbalanced by medium effects produced in a hot pion gas, according to Ref.[20]

[3] These two cases are chosen for roughly corresponding to typical high and small incident energy conditions for the formation of a "fireball", respectively.

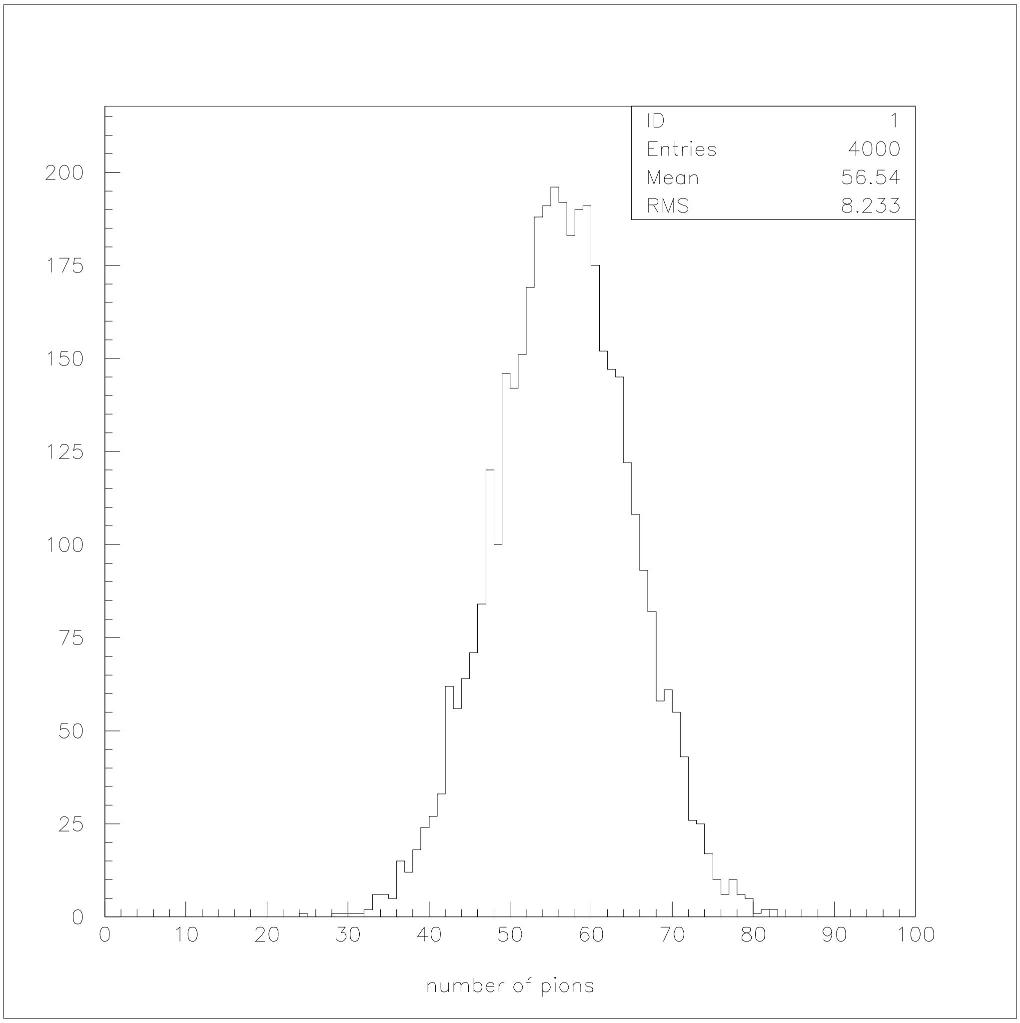

Fig. 1. Distribution of the pion multiplicity in head-on collisions of an incoming 5 GeV/nucleon $\overline{^{16}O}$ antinucleus with a ^{16}O nucleus at rest.

"cloud" (not really visible in Fig. 2, due to the scale of colors, a slight expansion is barely to be seen in the left lower panel). The most striking feature emerges from the comparison of the left and right panels of the lower row in Fig. 2. Clearly the antinucleon "blob" has passed through the target without too much trouble. At t=12 fm/c (lower row) it is located at the abcissa $x \approx 8$ fm, clearly on the right of the target, having so succeeded to cross the target while keeping the same form and the same velocity. Of course, as we said, its density has been reduced by about one half.

Let us say a few words about the pions. From the central part of Fig. 2, it appears that newly created pions are piling up in a "pion cloud", which travels throughout the target (see the two bottom panels), at about the same velocity as the antinucleon "cloud", as revealed by the comparison with the left column of Fig. 2. It may look strange that the pions are traveling with the same velocity as the antibaryon cloud. But this is quite natural since those antibaryons and those pions are highly relativistic when seen in the target rest frame. Indeed, in the cm frame of a typical antinucleon-nucleon annilihation, pions are emitted with an average kinetic energy of $\sim$ 100 MeV. When transformed in the target rest frame, the energy of these pions are well above the pion rest mass and the velocity

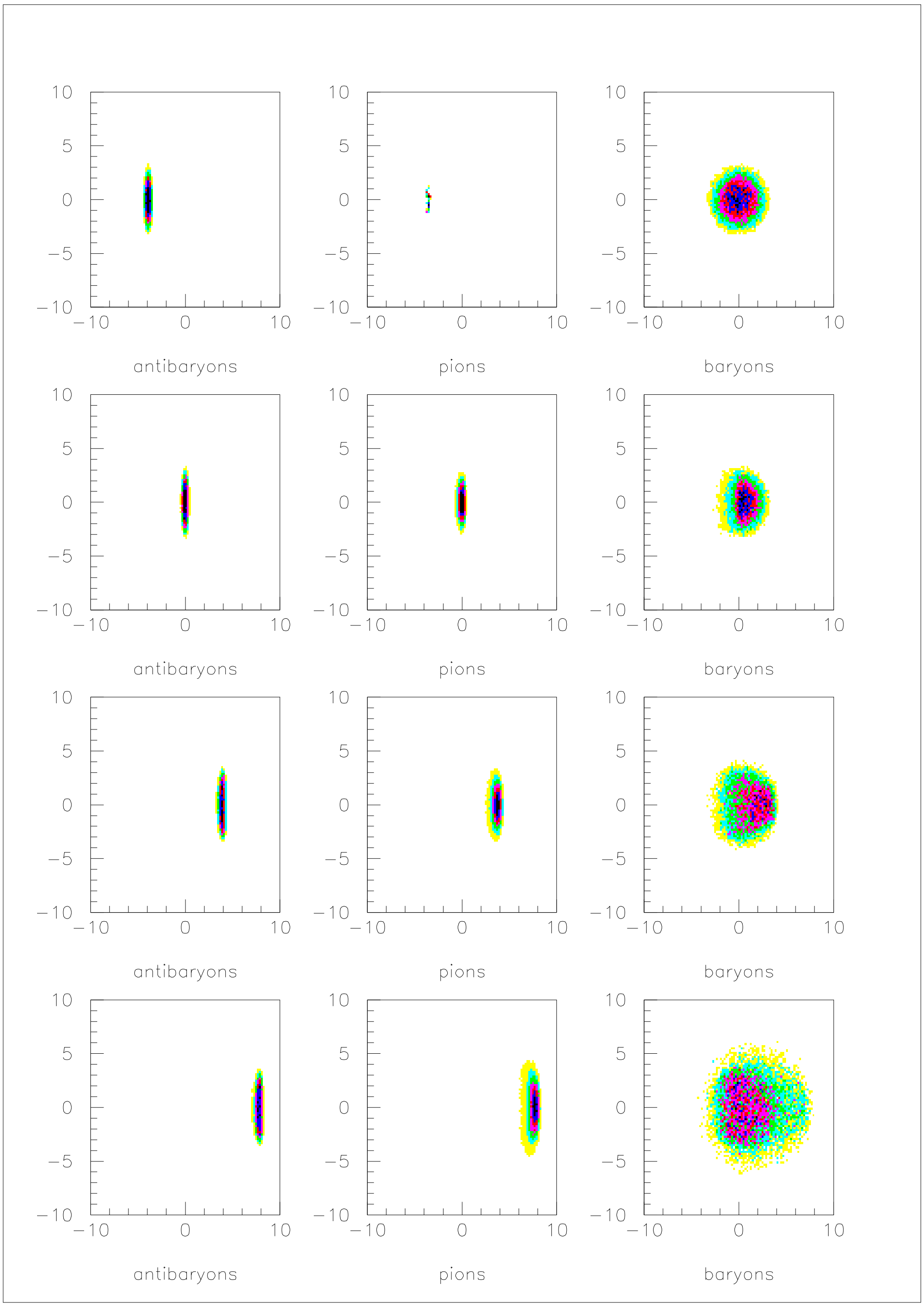

Fig. 2. Projections on the reaction plane of the antibaryon (left), pion (center) and baryon (right) density distributions during a head-on ($b = 0$) collision between an incoming 5 GeV/nucleon $\overline{^{16}O}$ antinucleus and a ^{16}O nucleus at rest. The successive rows show the situation at four values of the time, corresponding to $t = 4, 8, 12$ and $16 fm/c$, respectively. At the time $t = 0$ (not shown in the figure), a little bit before the situation corresponding to the first row, the target ^{16}O is sitting at rest at $x = 0fm, y = 0, z = 0$, x and y being the coordinates in the reaction plane, respectively. At the same time, the center of the $\overline{^{16}O}$ projectile is located at the point with $x = -8fm, y = 0$ coordinates. It is flying along the (horizontal) y axis with a total kinetic energy of $5GeV/nucleon$. At that very moment, the projectile is almost touching the target.

of these pions is close to the velocity of light. What happened to the target is basically described in the third column of Fig. 2. The initially spherical target suffers a depopulation of the nucleon density which is more marked on the left side of the target where the annihilations are occurring predominantly. The remaining nucleons are pushed on the right due to pion-nucleon collisions.

The collision pattern that we obtained may appear as lacking some symmetry. We refer to the symmetry under the interchange between baryons and antibaryons. Obviously, such a symmetry is not revealed in Fig.2: the fate of the $\overline{^{16}O}$ nucleus looks very different from the one of the ^{16}O nucleus. Actually, this is due to the fact that the colliding $\overline{^{16}O} - {}^{16}O$ system is viewed in the rest frame of the ^{16}O nucleus. To judge of the symmetry between baryons and antibaryons, it is indicated to look in the c.m. frame (of the original system) or alternatively to turn to the rapidity distributions rather than the velocity distributions. This is realized in Fig.3. Since rapidity is an additive variable, these distrributions now show now a clear symmetry between target and projectile (or between baryons and antibaryons), though not perfectly. This is due to the relativistic properties of our intranuclear cascade model. We seize the opportunity to elaborate a little bit on this point. In our model, all particles are moving with relativistic kinematics. However, the time coordinate is the same for all the particles. So the relativistic invariance of the calculation is broken (time cannot be the same for all particles and for all Lorentz frames). This is responsible for the slight distortion in the symmetry between target and projectile. If our model respected relativistic invariance, the results would show a perfect mirror symmetry around the vertical line with an abscissa equal to 1.3135 [4]. For the same case, we observed also that the average number of pions is almost the same in the lab and in the c.m. frames, 56.00 and 56.63, respectively. Similarly the average number of annihilations are 8.25 and 8.37, respectively. Globally, one may say, on the basis of these typical observables that the observed discrepancies are limited to 2-3 % , up to a few GeV/A. This maximal discrepancy may reach 10-15 % above 10 GeV/A, for some observables, but not in general.

4.3 $\overline{^{4}He} - {}^{16}O, b = 0, E_{inc} = 1GeV/A$

One may wonder whether there are more favorable conditions for having an incoming antinucleus to be pushed back by the creation of pions. Going higher in energy is not really a promising choice, since the annihilation nucleon-antinucleon cross section is decreasing with increasing energy. So, going to smaller energy is probably better, for the same reason. However, the pressure built in the pion cloud will be smaller. Considering a lighter antinucleus may be helpful. In any case, the presence of antinuclei heavier than $\overline{^{16}O}$ in the cosmic rays is very doubtful. For illustrative purposes, we show results of our calculation for head-on $\overline{^{4}He} - {}^{16}O$ collisions at 1 GeV/A, in Fig.4. In 60 % of the events, the antinucleus is totally annihilated. In the remaining events, on the average, an antinucleon survives once out of 6 events. But it succeeds to go through the target, as can be seen in the rapidity distribution of the antinucleons. At 50 MeV/A (not shown), the "surviving" antinucleon cannot go through the nucleus, it is stopped by the latter.

[4] In the example of Fig.2, the incident velocity β_{inc} = 0.9896. The incident rapidity is y_{inc} = 2.627 and thus the c.m. rapidity is $y_{c.m.}$ =1.3135.

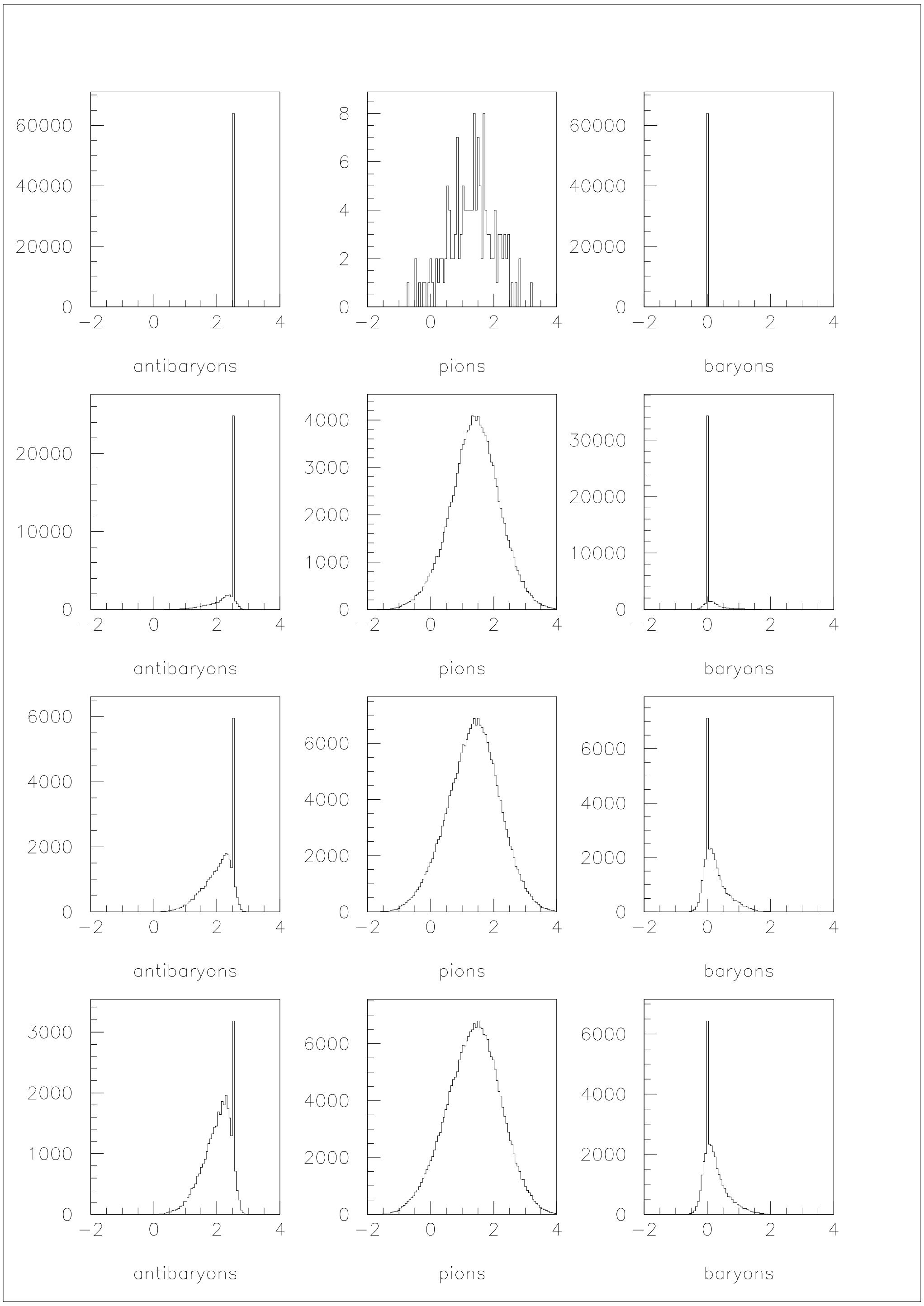

Fig. 3. Same as Fig.2, but the distributions are plotted versus the rapidity of the particles in the initial target frame. Note that the first and the third columns have been produced, for practical reasons, with bins of slightly different widths. The corresponding histograms are of course normalized in the same way.

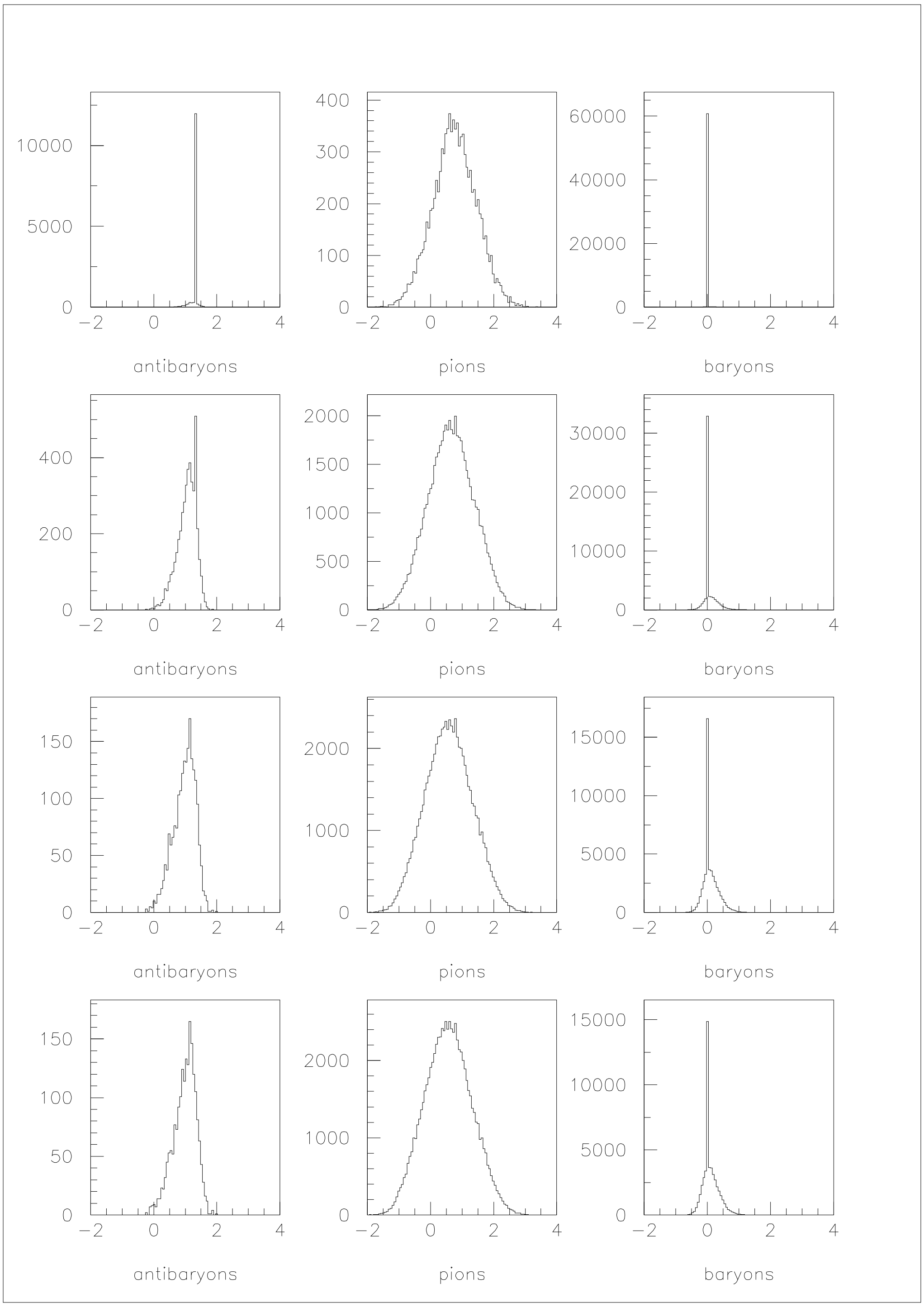

Fig. 4. Same as Figure 3 for a head-on ($b = 0$) collision between an incoming 1 GeV/nucleon $\overline{^4He}$ antinucleus and a ^{16}O nucleus at rest.

5 Conclusion

We have presented a model able to describe collisions between an antinucleus and an ordinary nucleus. This model may be useful for detection and analyses of antimatter in cosmic rays and for the study of the presently debated question of the importance of this presence for cosmological issues. We have also indicated that such collisions in the typical energy range of the flow of particles in the cosmic rays, namely around the GeV/nucleon are not really the seat of a typical Leidenfrost nuclear effect.

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