PHYSICAL REVIEW D VOLUME 47, NUMBER 9 1 MAY 1993

BRIEF REPORTS

Brief Reports are accounts of completed research which do not warrant regular articles or the priority handling given to Rapid Communications; however, the same standards of scientific quality apply. (Addenda are included in Brief Reports.) A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.

String fusion in the dual parton model and the production of antihyperons in heavy-ion collisions

H.-J. Möhring and J. Ranft*
Fachbereich Physik, Universität Leipzig, Federal Republic of Germany

C. Merino and C. Pajares
Departamento de Física de Partículas, Universidade de Santiago de Compostela, Spain

(Received 16 July 1992)

String fusion is introduced into the Monte Carlo dual parton model for hadron-nucleus and nucleus-nucleus collisions. We find that already the fusion of a small fraction of quark-antiquark chains at present energies leads to a strong increase of antihyperon and antiproton yields at energies reached at the CERN SPS.

PACS number(s): 12.38.Mh, 13.85.Hd, 13.85.Ni, 25.75.+r

I. INTRODUCTION

Recent experimental results of the NA35, WA85, and NA36 Collaborations on heavy-ion collisions show a strong enhancement of strange particle (in particular, antihyperon) production as compared to proton-proton collisions [1–3]. These experiments are often interpreted as a hint to the formation of the quark-gluon plasma (QGP) [4].

Here we will return to the study of these features within the dual parton model (DPM) [5]. Strangeness production in nuclear collisions was recently studied within the DPM [6,7]. Good agreement was found with the rise of the relative strange particle yields. Only for $\overline{\Lambda}$ production does the model show some disagreement with the data from NA35 [1].

During the last years much attention has been devoted to the problem of string interactions [8]. In particular, Braun and Pajares [9] discussed the effects of string fusion within the DPM. Recently, string fusion was introduced by Merino, Pajares, and Ranft [10] into a two-component dual parton model for hadron-hadron collisions [11]. For this reaction it was predicted that at $\sqrt{s}=1.8$ TeV the fusion mechanism results in some increase of the $\overline{\Lambda}/\pi$ ratio as a function of the central rapidity density.

In heavy-ion collisions, a large number of quark-antiquark chains which could fuse already exist at the energies of the present experiments. The diquark-antidiquark chains formed in the fusion process are highly efficient in the production of baryon-antibaryon pairs. Therefore, we consider chain fusion to be a good candidate to explain the anomalous antihyperon production. In the present paper string fusion is studied within the framework of the Monte Carlo DPM DTUNUC, version 1.1, for heavy-ion interactions [6].

*Present address: Tarostrasse 13/905, D-0-7010 Leipzig, Germany.

II. STRING FUSION

The independence of the string fragmentation in models such as the DPM is a strong assumption, which might break down at least when the string density reached in the collisions becomes larger. Indeed, in the case of two electrical conductors it is well known that they attract (or repel) each other depending on whether the two conductors have the same current directions or opposite ones. In the case of color conductors we have little knowledge of what really happens and only very approximate models [12] about these nonperturbative effects have been elaborated. Naturally, it is reasonable to think that if two strings overlap in space they could fuse forming a new string with double color at the ends of the string. These new objects will fragment producing particles with larger transverse momentum and also with a larger heavy flavor content corresponding to the larger color charge at the ends of the strings [8]. The fusion of strings can be implemented in the Regge-Gribov [13] model for hadron-hadron collisions and in the Glauber-Gribov [14] model for hA and AB collisions in a consistent way satisfying unitarity [9,15]. The usual Glauber-Gribov weights are exchanged by other ones which depend on the probability of fusion, x. This probability of fusion is given by the ratio between the transverse size of the string and the total transverse surface $x\sim\pi/\langle p_T^2\rangle\sigma$.

For comparison with experimental data at present energies we use the DTUNUC Monte Carlo DPM [6] which has been successfully compared previously, without fusion of strings, to a large variety of data on hh, hA, and AB collisions.

At this stage, it is worth asking what relation, if any, this has with quark gluon plasma formation. In an independent string fragmentation model it is difficult to see how it could arise. One can interpret the string fusion as an intermediate stage towards quark gluon plasma forma-

TABLE I. Parameters of the chain fragmentation model BAMJET modified for the decay of fused chains.

Variable	Standard chains	Fused chains
a_1	0.88	0.99
b_3	8.0	2.0
β	9.5	3.0

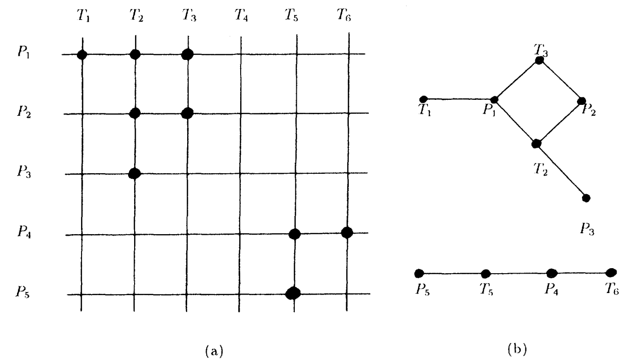

FIG. 1. (a) Example for the event structure in a heavy ion collision. (b) The event given in (a) in the form of a conventional diagram.

tion where many of its effects, such as enhancement of strangeness, heavy flavor, and rise of the transverse momentum, appear already [15].

As a first approach, we introduce chain fusion into DTUNUC in a simple way: At the (comparably low) energies of the present experiments the number of chains capable of fusing is not large and the fusion mechanism results only in a minor correction of the chain structure. Therefore, we do not apply the full apparatus proposed by Braun and Pajares [15]. Actually, only the fusion of two $q\bar{q}$ chains into one single qq-$\bar{q}\,\bar{q}$ string will be considered in the following.

Within DTUNUC the chain fragmentation model BAMJET [10] is applied. In BAMJET the fragmentation is controlled by several parameters originally adjusted to describe particle production in e^+e^- collisions. To simulate the fragmentation of fused strings we change the parameters a_1, b_3, and β as defined in Table I. This results in an increase of the average transverse momenta and the fraction of generated strange particles, as indicated in Table II for uu-$\bar{u}\,\bar{u}$ diquark-antidiquark chains.

III. TREATMENT OF CHAIN FUSION IN THE MONTE CARLO MODEL

Nucleon configurations within interacting heavy ions may be represented by diagrams as shown in Fig. 1(a), often used to demonstrate the results of a Monte Carlo simulation of the Glauber cascade [16]. For the discussion of chain fusion we prefer to redraw the diagrams in the conventional way [17], resulting in the example of Fig. 1(a) in one loop and one tree diagram represented in Fig. 1(b). Each link in these diagrams corresponds to an elementary nucleon-nucleon interaction, which is realized by a pair of parton-parton chains. The vertices represent the interacting nucleons. Since chains may be formed from valence as well as from sea quarks, each nucleon may undergo an arbitrary number of collisions. In fact, the corresponding diagrams may have much more complicated topologies than the planar ones shown in the example of Fig. 1.

An overlap in space-time is the basic requirement for the fusion of chains. Here we restrict ourselves to the fusion of two quark-antiquark chains in a single diquark-antidiquark chain. Quarks at chain ends may be either valence or sea quarks.

Chains originating from a single target or projectile nucleon are the most obvious candidates to satisfy the overlap requirement. This class of chains is easily identified in the Monte Carlo procedure. But also chains from disconnected diagrams could fuse if the interacting nucleons are sufficiently near in space-time. Although there is no basic technical problem to identify the candidates for chain fusion from disconnected diagrams, the procedure would be cumbersome. Since the present heavy-ion experiments are conducted at comparably low energies we restrict the actual procedure to the first class of fusion candidates originating from single vertices.

In order to decide which candidate chains actually undergo fusion (i.e., overlap in space) one could specify their transverse positions and sizes. Instead of this we use a simplified procedure: First we separately count at each vertex i the numbers of q-$\bar{q}$ and $\bar{q}$-q candidate chains, $n_{q\bar{q}}^{(i)}$ and $n_{\bar{q}q}^{(i)}$, respectively (the first parton always refers to the projectile, the second one to the target nucleon). In the second step, minimum numbers of nonfusing chains, $m_{q\bar{q}}^{(i)}$ and $m_{\bar{q}q}^{(i)}$, are chosen for each vertex and chain type. These numbers are sampled from a Poisson distribution with an average value C. This fusion cutoff parameter C is treated as a phenomenological parameter to be tuned according to the data. Fusion takes place if the number of candidate chains of a given type ($n_{q\bar{q}}$ or $n_{\bar{q}q}$), and at a given vertex, satisfies the requirement $n^{(i)} \geq m^{(i)}+2$. If fusion is allowed for an odd number of chains, $(m^{(i)}+1)$ chains of the given type remain unfused at the actual vertex i.

TABLE II. Properties of BAMJET chain decay for standard and fused qq-$\bar{q}\,\bar{q}$ chains.

	$\langle p_T \rangle$		K^+/π^+		$\bar{\Lambda}/\pi^-$		$\langle n_{ch} \rangle$	
$\sqrt{s}$	stand.	fused	stand.	fused	stand.	fused	stand.	fused
10	0.32	0.53	0.085	0.146	0.05	0.068	6.06	6.40
30	0.32	0.63	0.099	0.182	0.057	0.080	9.48	9.82

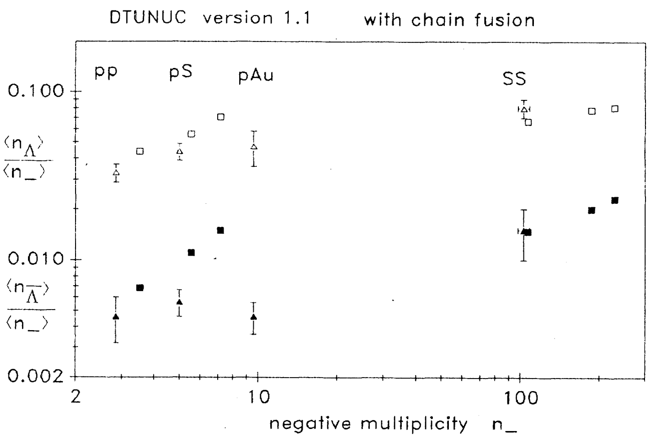

FIG. 2. Ratios of the integrated average multiplicities of Λ and $\overline{\Lambda}$ over the total average negative multiplicity $\langle n_- \rangle$ obtained by taking into account in DTUNUC 1.1 the possibility of chain fusion ($C=2.2$), for different proton-nucleus and nucleus-nucleus collisions at 200 GeV/c per nucleon. Experimental data from Ref. [1].

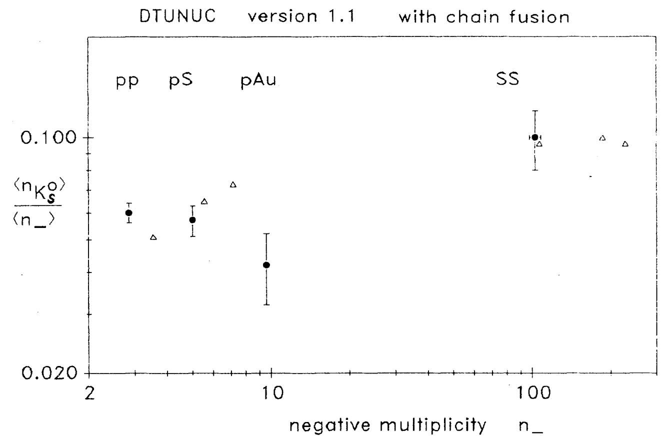

FIG. 3. Ratio of the integrated average multiplicities of K^0 over the total average negative multiplicity $\langle n_- \rangle$ obtained in DTUNUC 1.1 with chain fusion ($C=2.2$), for different proton-nucleus and nucleus-nucleus collisions at 200 GeV/c per nucleon. Experimental data from Ref. [1]. These ratios are nearly the same as in the model without fusion [6].

IV. RESULTS

We have generated 10 000 events with DTUNUC 1.1 for different proton-nucleus collisions at 200 GeV/c, and 5000 events for several central nucleus-nucleus collisions at 200A GeV/c. We compare the calculated ratios between the average multiplicities of Λ, $\overline{\Lambda}$, K^0, $\bar{p}$, and Ξ, the average total negative multiplicity $\langle n_- \rangle$ with the available experimental data [1], and with the results obtained for these ratios in the DPM without fusion [6].

The numerical results, obtained by using a value of $C=2.2$, are presented in Table III and Figures 2–4. We find that the implementation of chain fusion in the formalism strongly increases, both for proton-nucleus and nucleus-nucleus collisions, baryon and strangeness production in general, and especially the $\overline{\Lambda}$ and $\overline{\Xi}$ yields in the total phase space. This behavior agrees with the experimental data and to the expectations for a quark gluon

TABLE III. Numerical values of the integrated multiplicities of negative particles, $\bar{p}$, $\Lambda+\Sigma^0$, $\overline{\Lambda}+\overline{\Sigma}^0$, K^+, $K^-K^0_S$, Ξ^-, and $\overline{\Xi}^-$ obtained in DTUNUC 1.1 for various nuclear reactions at $E_{\text{lab}}=200$ GeV/nucleon by taking into account chain fusion with a fusion cutoff parameter $C=2.2$ (in brackets are the experimental values).

Reaction	$\langle n_- \rangle$	$\bar{p}$	$\Lambda+\Sigma^0$	$\overline{\Lambda}+\overline{\Sigma}^0$
pp	3.52	0.081	0.155	0.024
(nondiffractive)	(2.85±0.04)		(0.095±0.010)	(0.013±0.004)
p-S	5.54	0.11	0.32	0.060
	(5.0±0.2)		(0.22±0.02)	(0.028±0.004)
p-Pb	7.15	0.15	0.51	0.11
S-S centr.	107.0	1.96	7.18	1.57
	(103±5)		(8.2±0.9)	(1.5±0.4)
S-Ag centr.	186.9	3.87	14.06	3.65
S-Pb centr.	228.2	5.11	18.39	5.27

Reaction	K^+	K^-	K^0_s	Ξ^-	$\overline{\Xi}^-$
pp	0.23	0.14	0.18	0.0021	0.0012
(nondiffractive)	(0.24±0.06)	(0.17±0.05)	(0.17±0.01)		
p-S	0.47	0.29	0.36	0.003	0.006
			(0.28±0.03)		
p-Pb	0.64	0.43	0.52	0.007	0.018
S-S centr.	12.05	8.74	10.24	0.12	0.21
	(12.5±0.4)	(6.9±0.4)	(10.7±2.0)		
S-Ag centr.	21.8	16.1	15.73	0.21	0.58
S-Pb centr.	25.57	18.85	21.98	0.27	0.82

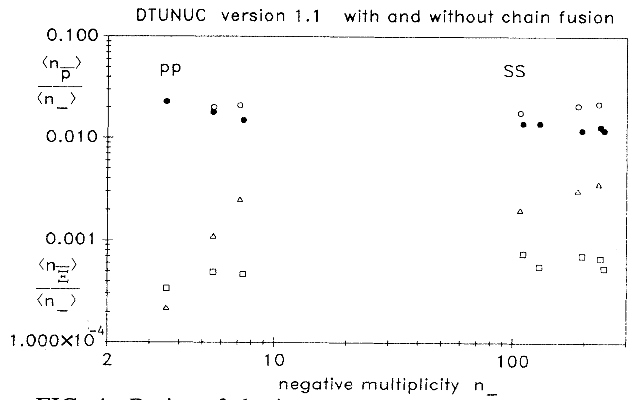

FIG. 4. Ratios of the integrated average multiplicities of $\bar{p}$ and $\bar{\Xi}$ over the total average negative multiplicity, $\langle n_- \rangle$, obtained with and without taking into account in DTUNUC 1.1 the possibility of chain fusion ($C=2.2$), for different proton-nucleus and nucleus-nucleus collisions at 200 GeV/c per nucleon.

plasma scenario.

This rise in the production of $\bar{\Lambda}$ and $\bar{\Xi}$ occurs without spoiling the results for Λ and K_S^0 which fit already to the experimental data in the model [6]. However, the increase of the K^0 and $\bar{\Lambda}$ ratios obtained in proton-nucleus collisions disagrees with the current experimental data which look mainly flat (see Figs. 2 and 3).

In Fig. 4 one can see how the chain fusion leads to a large increase of the baryon production, by comparing the ratios of the average $\bar{p}$ and $\bar{\Xi}$ yields to the average total negative multiplicity, with those from the model without fusion.

V. CONCLUSIONS

The chain fusion mechanism was already used to explain the large rise of $\langle p_T \rangle$ of $\bar{p}$ in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV [10]. Here we introduce chain fusion into the DPM Monte Carlo code DTUNUC (version 1.1) for nucleus-nucleus collisions. This accounts for the strong rise of integrated strangeness production, especially $\bar{\Lambda}$ and $\bar{\Xi}$, detected by several experimental collaborations. So, chain fusion might indeed be an intermediate stage towards the QGP formation.

Note added. After finishing this paper we learned about a paper [18] in which similar ideas are implemented in a different model with similar results to ours.

ACKNOWLEDGMENTS

We acknowledge support from the Acciones Integradas Hispano-Alemanas Spanish-German scientific exchange.

[1] NA35 Collaboration, J. Bartke *et al.*, Z. Phys. C **48**, 191 (1990).
[2] WA85 Collaboration, S. Abatzis *et al.*, Phys. Lett. B **270**, 123 (1991).
[3] NA36 Collaboration, E. Andersen *et al.*, Phys. Lett. B **294**, 727 (1992); in *Quark Matter '91,* Proceedings of the Ninth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Gatlinburg, Tennessee, edited by T. C. Awes *et al.* [Nucl. Phys. **A544** (1992)].
[4] P. Koch, B. Mueller, and J. Rafelski, Phys. Rep. **142**, 167 (1986).
[5] A. Capella, U. Sukhatme, Ch.-I. Tan, and J. Tran Thanh Van, Phys. Lett. **81B**, 68 (1979); in *Hadronic Multiparticle Production,* edited by P. Carruthers (World Scientific, Singapore, 1988), p. 428; A. Capella and J. Tran Thanh Van, Z. Phys. C **10**, 249 (1981); Phys. Lett. **114B**, 450 (1982).
[6] H.-J. Möhring and J. Ranft, Z. Phys. C **52**, 643 (1991).
[7] H.-J. Möhring, J. Ranft, A. Capella, and J. Tran Thanh Van, this issue, Phys. Rev. D **47**, 4146 (1993).
[8] T. S. Biro, H. B. Nielsen, and J. Knoll, Nucl. Phys. **B245**, 449 (1984); M. Gyulassy and A. Iwazaki, Phys. Lett. **165B**, 157 (1985); A. K. Kimman, T. Matsui, and B. Svetitsky, Phys. Rev. Lett. **56**, 219 (1986); B. Andersson and P. A. Henning, Nucl. Phys. **B82**, 335 (1991); M. Gyulassy, in *Quark Gluon Plasma,* edited by R. Hwa (World Scientific, Singapore, 1991), p. 223.
[9] C. Pajares, Phys. Lett. B **258**, 461 (1991); in *Quark Gluon Plasma Signatures,* Proceedings of the International Workshop, Strasbourg, France, 1990, edited by V. Bernard *et al.* (Editions Frontieres, Gif-sur-Yvette, 1991); M. Braun and C. Pajares, Nucl. Phys. **B390**, 542 (1993).
[10] C. Merino, C. Pajares, and J. Ranft, Phys. Lett. B **276**, 168 (1992).
[11] P. Aurenche, F. W. Bopp, A. Capella, J. Kwiecinski, J. Marie, J. Ranft, and J. Tran Thanh Van, Phys. Rev. D **45**, 92 (1992).
[12] M. Grabiak, J. Casado, and M. Gyulassy, Z. Phys. C **49**, 283 (1991).
[13] V. N. Gribov, Zh. Eksp. Teor. Fiz. **53**, 654 (1967) [Sov. Phys. JETP **26**, 414 (1967)].
[14] R. J. Glauber, in *Lectures in Theoretical Physics,* edited by W. E. Britten (Interscience, New York, 1959), Vol. I, p. 315; V. N. Gribov, Zh. Eksp. Teor. Fiz. **56**, 986 (1969) [Sov. Phys. JETP **29**, 532 (1969)]; **57**, 1306 (1969) [**30**, 709 (1969)].
[15] M. Braun and C. Pajares, Nucl. Phys. **B390**, 559 (1993).
[16] S. Yu. Shmakov, V. U. Uzhinskii, and A. M. Zadorozhny, Comput. Phys. Commun. **54**, 125 (1989).
[17] A. Kaidalov, in *Quark Matter '90,* Proceedings of the Eighth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Menton, France, edited by J. P. Blaizot *et al.* [Nucl. Phys. **A525**, 39c (1991)].
[18] H. Sorge, M. Berenguer, H. Stöcker, and W. Greiner, Los Alamos Report No. LA-UR-92-1078, 1992 (unpublished).