Novel Mechanism of H^0 Dibaryon Production in Proton-Proton Interactions from Parton-Based Gribov-Regge Theory

M. Bleicher,[1,2] F. M. Liu,[1,2,3] J. Aichelin,[1] H. J. Drescher,[2,4] S. Ostapchenko,[5,6] T. Pierog,[1,7] and K. Werner[1]

[1]*SUBATECH, Laboratoire de Physique Subatomique et des Technologies Associées, University of Nantes–IN2P3/CNRS–Ecole des Mines de Nantes, 4 rue Alfred Kastler, F-44072 Nantes Cedex 03, France*

[2]*Institut für Theoretische Physik, Goethe Universität, Frankfurt am Main, Germany*

[3]*Institute of Particle Physics, Huazhong Normal University, Wuhan, China*

[4]*Physics Department, New York University, New York, New York USA*

[5]*Institut für Experimentelle Kernphysik, University of Karlsruhe, Karlsruhe, Germany*

[6]*Institute of Nuclear Physics, Moscow State University, Moscow, Russia*

[7]*FZK, Institut für Kernphysik, Karlsruhe, Germany*

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A novel mechanism of H^0 and strangelet production in hadronic interactions within the Gribov-Regge approach is presented. In this approach the H^0 is produced by the same mechanism as usual hadrons, namely, by disintegration of the remnant formed by the exchange of pomerons between the two protons. Rapidity and transverse momentum spectra of the observed hadrons are well described in this approach. In contrast to traditional distillation approaches, here the production of multiple (strange) quark bags does not require large baryon densities or a quark gluon plasma. We calculate the rapidity and transverse momentum distributions as well as the 4π multiplicity of the H^0 for $\sqrt{s} = 17$ GeV (Super Proton Synchrotron) and 200 GeV (Relativistic Heavy Ion Collider). In both cases the H^0, if it exists, should be observable by the present experiments.

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The existence or nonexistence of multiquark bags, e.g., strangelets and (strange) dibaryons is one of the great open problems of intermediate and high energy physics. Early theoretical models based on SU(3) and SU(6) symmetries [1,2] and on Regge theory [3,4] suggest that dibaryons should exist. More recently, QCD-inspired models predict dibaryons with strangeness $S = 0$, -1, and -2. The invariant masses range between 2000 and 3000 MeV [5–12]. Unfortunately, masses and widths of the expected 6-quark states differ considerably for these models. However, most QCD-inspired models predict dibaryons and none seems to forbid them.

Especially the search for a stable H particle is closely related to the study of Ξ and $\Lambda\Lambda$ hypernuclei (for very recent data on double Λ hypernuclei, see [13,14]). From these observations by the E906 [13] and the E373 [14] experiments a mass limit of the H^0 of the order of $m_H > 2m_{\Lambda\Lambda} - 8$ MeV is estimated with a 90% confidence level. This small binding energy is in strong contrast to the original estimate by Jaffe who suggested a mass difference of order ≈ -80 MeV. It should be noted that lattice studies of the H^0 mass indicate binding energies in excess of 200 MeV [15]. Therefore we will focus on binding energy ranges of the order of 10–200 MeV. The H is a six quark state ($uuddss$) coupled to an SU(3) singlet in color and flavor. Since its mass is smaller than $2m_\Lambda$ it is stable against strong decays. However, this object with baryon number two is not an ordinary nuclear state: the multiquark cluster contained in the H is deconfined. Thus, the H is the smallest strangelet or might even be seen as a small droplet of quark-gluon-plasma. While on the hadronic side, hypernuclei are known to exist already for a long time, e.g., double Λ hypernuclear events have been reported [13,14,16], no stringent observation of the H particle exists. Even today, decades after the first prediction of the $S = -2H$ dibaryon by Jaffe [5] the question of its existence is still open.

A major uncertainty for the detection of such speculative states is their (meta)stability. Metastable exotic multihypernuclear objects (MEMOs), for example, consists of nucleons, Λ's, and Ξ and are stabilized due to Pauli's principle, blocking the decay of the hyperons into nucleons. Only few investigations about the weak decay of dibaryons exist so far (see [12] for a full discussion and new estimates for the weak nonleptonic decays of strange dibaryons): In [16], the H dibaryon was found to decay dominantly by $H \to \Sigma^- + p$ for moderate binding energies. While the $(\Lambda\Lambda)$ bound state, which has exactly the same quantum numbers as the H dibaryon, was studied in [17]. Here, the main nonmesonic channel was found to be $(\Lambda\Lambda) \to \Lambda + n$. If the lifetime of the $(\Lambda\Lambda)$ correlation or H^0 particle is not too long, the specific decay channels might be used to distinguish between both states.

There are several searches in heavy-ion collisions for the H dibaryon [19,20] and for long-lived strangelets [21,22] with high sensitivities. Hypernuclei have been detected most recently in heavy-ion reactions at the Alternating Gradient Synchrotron by the E864 Collaboration [23].

In this Letter we study the formation of the H^0 dibaryon within a new approach called parton-based Gribov-Regge theory. It is realized in the Monte Carlo program NEXUS 3 [24,25]. In this model high energy hadronic and nuclear collisions are treated within a self-consistent quantum mechanical multiple scattering formalism. Elementary interactions, happening in parallel, correspond to underlying microscopic (predominantly soft) parton cascades and are described effectively as phenomenological soft Pomeron exchanges. A Pomeron can be seen as a (soft) parton ladder, which is attached to projectile and target nucleons via leg partons. At high energies one accounts also for the contribution of perturbative (high p_t) partons described by a so-called "semihard Pomeron"—a piece of the QCD parton ladder sandwiched between two soft Pomerons which are connected to the projectile and to the target in the usual way. The spectator partons of both projectile and target nucleons, left after Pomeron emissions, form nucleon remnants. The legs of the Pomerons form color singlets, such as q-$\overline{q}$, q-qq, or $\overline{q}$-$\overline{q}\,\overline{q}$. The probability of q-qq and $\overline{q}$-$\overline{q}\,\overline{q}$ is controlled by the parameter P_{qq} and is fixed by the experimental yields on (multi)strange baryons [25].

Particles are then produced from cutting the Pomerons and the decay of the remnants. As an intuitive way to understand particle production, each cut Pomeron is regarded as two strings, i.e., two layers of a parton ladder. Each string has two ends which are quark(s) or antiquark(s) from the two Pomeron legs, respectively. To compensate the flavor, whenever a quark or an antiquark is taken as a string end, a corresponding antiparticle is put in the remnant nearby.

Since an arbitrary number of Pomerons may be involved, it is natural to take quarks and antiquarks from the sea as the string ends. In order to describe the experimental yields on (multi)strange baryons [25], all the valence quarks stay in the remnants, whereas the string ends are represented by sea quarks. Thus, Pomerons are vacuum excitations and produce particles and antiparticles equally [26]. Only the remnants change the balance of particles and antiparticles, due to the valence quarks inside, resulting in the possibility to solve the antiomega puzzle [27] at the Super Proton Synchrotron (SPS).

This prescription is able to accumulate quarks and diquarks in the remnants depending on the number of exchanged Pomerons. In the most simple case of a single Pomeron exchange, the remnant may gain an additional diquark and a quark and is transformed into a six quark bag as discussed in the following.

The typical collision configuration has two remnants and one cut Pomeron represented by two q-$\overline{q}$ strings; see Fig. 1(a).

However, one or more of the q string ends can be replaced by a $\overline{qq}$ triplet state. To compensate the flavor, one of the remnants now has six quarks, cf. Fig. 1(b). This possibility occurs with a probability P_{qq}. These six quarks are the three valence quarks u, u, d plus three sea quarks, where each of them may have the flavor u , d, or s, with relative weights $1:1:f_s$. Both parameters, P_{qq} and f_s, are determined by multistrange baryon data in proton-proton scatterings at 160 GeV to be $P_{qq} = 0.05$ and $f_s = 0.26$. Thus, there is a small but nonzero probability to have a $uuddss$ flavor in a remnant, such that a H^0 dibaryon may be formed.

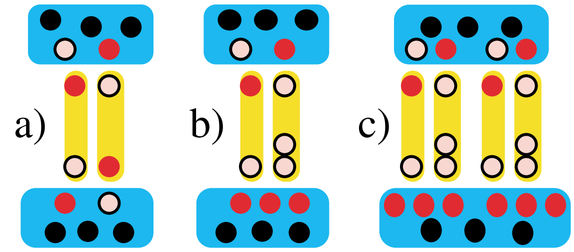

FIG. 1 (color online). (a) The typical collision configuration has two remnants and one cut Pomeron represented by two q-$\overline{q}$ strings. (b) One of the q string ends is replaced by a $\overline{qq}$ triplet state. To compensate the flavor, one of the remnants now has six quarks. In the case of a $uuddss$ flavor content a H^0 dibaryon can form. (c) Multiple Pomeron exchanges may lead to further accumulation of quarks in the remnant bag.

The remnants have mass distribution $P(m^2) \propto (m^2)^{-\alpha}$, $m^2 \in (m^2_{\rm min}, x^+ s)$, here s is the squared center of mass energy. With, $m_{\rm min}$ being the minimal hadron mass compatible with the remnant's quark content, and x^+ is the light-cone momentum fraction of the remnant which is determined in the collision configuration. In the present study, the parameter α is 2.25 for nondiffractive interactions and 1 for diffractive events. This remnant disintegrates into hadrons according to (microcanonical) phase space [28]. This approach describes quite well multiplicity, transverse momenta, and rapidity of all the observed hadrons [29] in pp collisions at energies between 40 and 160 GeV.

For the present study we have embedded the H^0 in the microcanonical approach to describe the disintegration of the remnant. It is therefore treated the same way as all the other hadrons. Since the mass of the H^0 is not known, we have performed the calculations for a set of three masses from $m_{H^0} = 2.1$ GeV to $m_{H^0} = 2.2$ GeV. Please note that the omission of many resonances with masses smaller than that of the H^0 will not change the result for the H^0 multiplicity as has been discussed in [29].

Contrary to the mechanism of [30], which needs high baryon densities to distill strangeness in heavy-ion collisions, the present approach works differently: It is independent of the baryon density and temperature. The presence of baryons enters only due to multiple scatterings. In addition, with increasing center-of-mass energy, multiple Pomeron exchanges gain importance. This results in an increased possibility to produce heavy quark bags around the target and projectile region of the collision as shown in Fig. 1(c).

Let us now study the multiplicities and momentum spectra of the calculated H^0's. Figure 2 depicts the

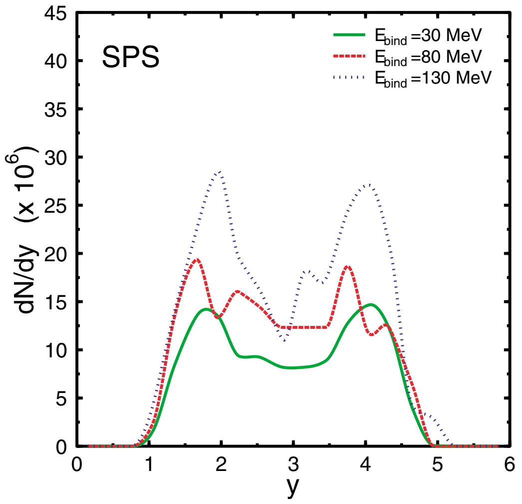

FIG. 2 (color online). Rapidity distributions of H^0's in pp interactions at $E_{\rm lab} = 160$ GeV. The different lines correspond to different binding energies: $e_{\rm bind} = 30, 80\,130$ MeV.

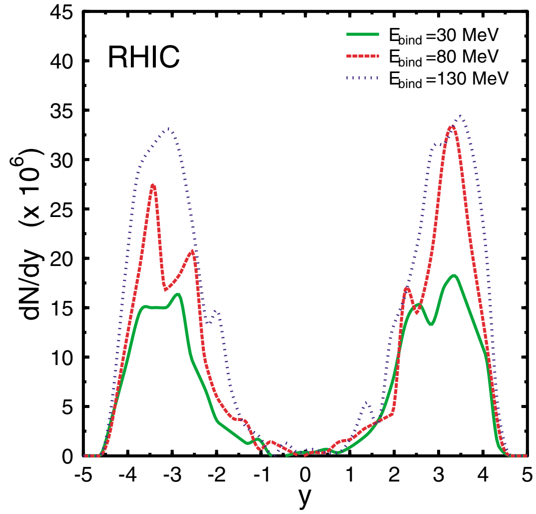

FIG. 4 (color online). Rapidity distributions of H^0's in pp interactions at $\sqrt{s} = 200$ GeV. The different lines correspond to different binding energies: $e_{\rm bind} = 30, 80\,130$ MeV.

rapidity distribution of the predicted H^0's at the top SPS energy for the three binding energies. One observes a forward-backward peak in the H^0 cross section flattening out with decreasing binding energy. The heavier the remnant the smaller is its rapidity. Therefore H^0's with a larger binding energy and hence a smaller mass are more forward/backward peaked. If the mass increases from 2.1 to 2.2 GeV the total multiplicity decreases from 6.9×10^{-5} to 3.71×10^{-5}. This multiplicity is about a factor of 10 lower than that for the multistrange $\bar{\Omega}$ baryon which has been well observed at this energy by the NA49 Collaboration. Thus with the presently accumulated statistics by the NA49 Collaboration the H^0 should be still visible.

Figure 3 depicts the transverse momentum spectra of the H^0's for the same masses. In Figs. 4 and 5 we show the rapidity and transverse momentum spectra at $\sqrt{s} = 200$ GeV, again for the different masses. Especially at Relativistic Heavy Ion Collider (RHIC) energies one clearly observes the pileup of dibaryons in the forward and backward hemisphere. In the midrapidity region the dibaryon yield vanishes. Figure 6 summarizes the integrated yields of H^0's obtained for the different sets of binding energies.

One should note that the suggested scenario allows for H^0 production without a distillation mechanism,

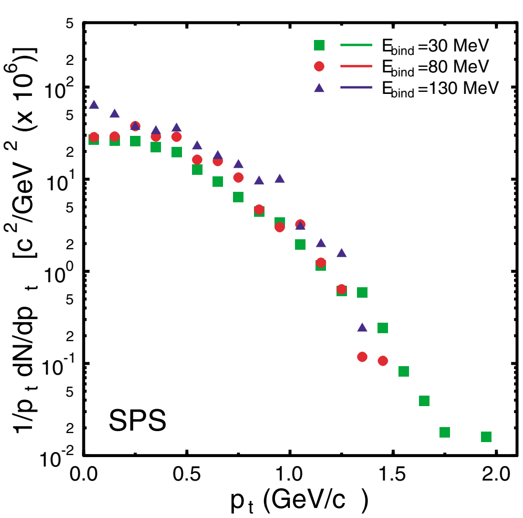

FIG. 3 (color online). Transverse momentum distributions of H^0's in pp interactions at $E_{\rm lab} = 160$ GeV. The different symbols correspond to different binding energies: $e_{\rm bind} = 30, 80\,130$ MeV.

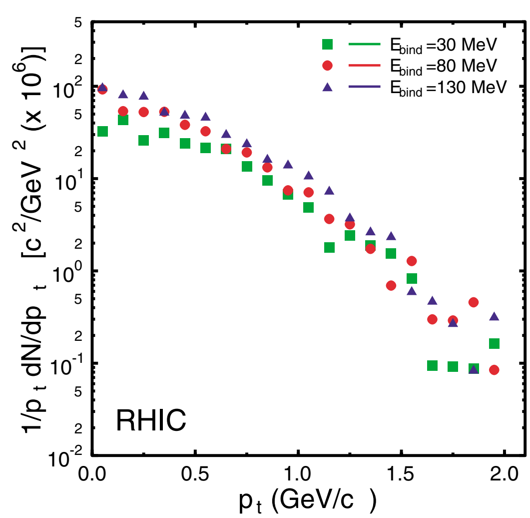

FIG. 5 (color online). Transverse momentum distributions of H^0's in pp interactions at $\sqrt{s} = 200$ GeV. The different symbols correspond to different binding energies: $e_{\rm bind} = 30, 80\,130$ MeV.

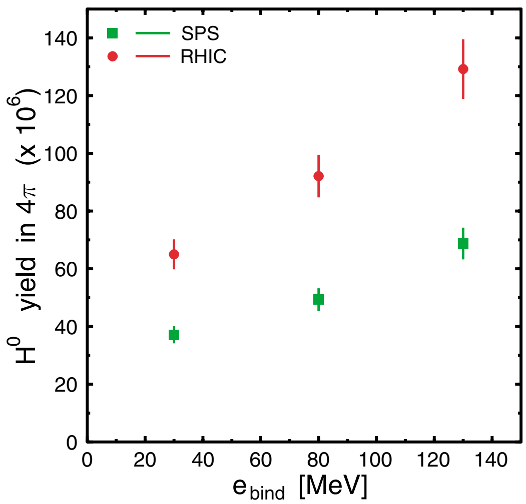

FIG. 6 (color online). Integrated amounts of H^0 as a function of the binding energy for SPS (squares) and RHIC (circles) energies.

e.g., in the discussed pp case. While this mechanism is also at work in nucleus-nucleus interactions, its absolute magnitude is small (order 10^{-3}–10^{-2} H^0 per central nucleus-nucleus collision if scaled by the number of partcipants) compared to the estimates for a thermalized QGP/hadron gas (~ 0.1–1 H^0 per central nucleus-nucleus event [32,33]). Thus, such a large H^0 yield—referring to expectations of a thermal distribution—can still provide evidence for distilation in a heavy-ion environment.

In conclusion, we have presented a novel production channel of H^0 dibaryons in pp collisions from parton-based Gribov-Regge theory. All model parameters are fixed by multistrange baryon data at 160 GeV.

Multiplicities, rapidity, and transverse momentum spectra are predicted for pp interaction at $E_{\rm lab} = 160$ GeV and $\sqrt{s} = 200$ GeV. At SPS, the cross section for H^0 production in the present study is found in the same order of magnitude as the Ω production cross section if the binding energy is of the order of 100 MeV. For binding energies restricted by the recent data, we expect 3–5 $\times 10^{-5}$ H^0 per event at SPS/RHIC. Our predictions are accessible in the $\Sigma^- p$ channel by the NA49 experiment at CERN and the STAR experiment at RHIC.

In contrast to previous works, the proposed mechanism does not require the production of a deconfined state, neither does it need high baryon densities.

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