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How to search for primordial light gluinos

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Very light gluinos (constituent mass < 0.7 GeV) could be absolutely stable. After discussing that such an assumption is not in contradiction with existing experimental results, I study the phenomenology of light primordial gluinos in order to set limits on their abundance and to suggest new search strategies. The nuclear physics of hadronic gluino states and the fate of such states after their production in the big bang is studied. Depending on whether they bind to nuclei, relative concentrations of "anomalous isotopes" in the range of 10^{-10} to 10^{-18} or a "gluino atmosphere" around the Earth with a density at the surface of the Earth above about one particle/cm^3 are predicted. Techniques to search for these particles are proposed, based on accelerator mass spectroscopy, radiative capture on nuclei, annihilation in underground detectors, and a novel class of active cryogenic experiments. While it is quite possible that these particles have not been discovered until now, they are shown to be within the reach of present measuring sensitivities.

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I. INTRODUCTION

A. Very light strongly interacting particles

Recently there has been renewed interest in the possible existence of a light gluino with a mass < 4 GeV [1]. Such a gluino is theoretically well motivated [2,3] (though it does not appear in the simplest supersymmetric SU(5) grand unified theory [4]) and is one of our best hopes to find supersymmetry in nature in the immediate future.

Particularly interesting (though frequently just ignored) is the possibility of a very light gluino (constituent mass < 0.7 GeV) which is experimentally allowed if the squark mass is larger than about 100 GeV (window I in [5] and Fig. 5 in [6]). Such a very light gluino is also indicated by a detailed analysis of supersymmetry models at ordinary energies by Farrar and Weinberg [7] whose main worry is whether such a particle is already experimentally excluded.

A massless gluino is even more attractive as it would make the strong CP problem [8] trivial [9]. The observation of Eides and Vysotsky [10] that massless gluinos are excluded due to the existence of an unobserved very light R pion in this case depends on the assumption that R parity is broken by QCD anomalies. This is not necessarily true as pointed out by Farrar and Weinberg [7].

As the existence of any massless colored fermion would solve the strong CP problem, the experimental search for such particles is important, independent of supersymmetry. It is further possible that gluinos possess a Dirac mass term [11]. I will therefore consider not only Majorana particles but also colored, chargeless, weak-isospin singlet Dirac particles. These could also be, e.g., "new" quarks perhaps with a different color representation than the known ones (e.g., "shiny quarks" [12]).

This paper treats the consequences for astroparticle physics of the existence of a light strongly interacting particle, which is in addition absolutely stable. Previous experiments constrain the constituent mass of such a particle to be smaller than 0.7 GeV [5]. Various aspects of light and stable or long-lived gluinos have been previously discussed [13,14] but their fate after the big bang has not been studied up to now to my knowledge.

If the new particle is a new species of quark the assumption of stability is quite natural; in the framework of supersymmetry the new particle would only be stable either if the gluino is the lightest supersymmetric particle with the next heavier sparticle having a mass greater than the gluino-containing state or if the squarks mediating the decay of the gluino are superheavy. The latter assumption is ugly and implausible but the former is possible within the uncertainties of some popular supersymmetry (SUSY) scenarios [3].

The related subject of new stable very heavy quarks was investigated by Wolfram [15] and Dover, Gaisser, and Steigman [16]. The behavior of these objects during big-bang nucleosynthesis (BBN) was treated by Dicus and Teplitz [17]; note, however, that the smaller masses considered here make the results of this paper inapplicable for our case.

Stable gluinos will appear as remnants from the early Universe in confined states with normal quarks and/or gluons (collectively called R hadrons below). Astroparticle physics could set out to detect these preexisting primordial states in our surroundings. Primordial R hadrons may remind the reader of the well discussed case of primordial weakly interacting massive particles (WIMP's) [18]. These particles have a completely different phenomenology, however, because of their much weaker interactions with baryons (cross sections are typically some 14 orders of magnitude lower). Light strongly interacting particles come, e.g., much more

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quickly into thermal equilibrium with their surroundings than WIMP's and this requires new approaches for their detection.

The possibility of light *unstable* gluinos has to be tackled by "traditional" accelerator and cosmic-ray experiments. The important issue of what kind of new experiments and reanalyses of those already performed are best suited to this search is not addressed in this paper. As a stable gluino is most difficult to find in high energy experiments the different approaches complement each other.

In the rest of the Introduction I will review the likely properties of R hadrons and discuss whether a very light strongly interacting particle is ruled out by existing experimental results. Section II contains a treatment of the nuclear physics of remnant R hadrons. This somewhat technical paragraph can be skipped upon first reading, if the reader accepts the capture cross sections estimated there and the fact that there exists a critical atomic number A_{crit} (the value of which cannot be determined with present techniques) above which R hadrons bind to nuclei. In Sec. III I follow the fate of R hadrons after their production in the early universe. R hadron densities and concentrations are evaluated for both the case that R hadrons bind to stable nuclei ($A_{\text{crit}} < 238$) and the alternative that they remain free. Finally, in Sec. IV experimental techniques to detect these particles are proposed, and in Sec. V the message of this paper to the experimentalist is summarized.

B. Are very light stable gluinos already ruled out?

The possibility of an unknown very light (< 2 GeV) strongly interacting particle meets with great skepticism in the particle physics community out of the conviction that "such particles would have been discovered long ago." Indeed there have been many published claims that very light gluinos are experimentally excluded [19,20]. The most detailed case against a light *stable* gluino has been made by Voloshin and Okun [14]. I will briefly discuss why all of these assertions are unconvincing.

The lightest (and therefore stable) R hadrons are probably the glueballino (gluon-gluino state) and perhaps the R baryon (gluino-baryon state). At present nonperturbative QCD calculations are not able to reliably predict the mass of the glueball; different theoretical results lie in the range 0.5–1.6 GeV [21]. A calculated value of the glueballino mass in the framework of the MIT bag model [22] yielded a similar mass range (0.3–1.0 GeV if one subtracts the "intrinsic" gluino mass from the glueballino mass for a rough comparison). For R baryons there is one calculation [23] (0.6–1.3 GeV) and an educated guess [14] (1.5 GeV); both numbers are for a massless gluino. It is thus currently impossible to reliably predict whether R baryons are stable in addition to glueballinos or decay into baryons and glueballinos. Even if they are stable it is not clear whether the lightest R baryon is charged. Voloshin and Okun [14] claim that it has to be positively charged in which case its existence would be excluded by searches for anomalous isotopes of hydrogen (see below, Sec. IV). Their argument relies critically on a SU(6) symmetry of hadronic states, whose validity for four-parton states remains unproven. Indeed Buccella, Farrar, and Pugliese [23], using the MIT bag model, find a neutral lightest R baryon (a state with a u, d, s quark and a gluino). I will assume in the following that the lightest R baryon is the state of Buccella, Farrar, and Pugliese [23] and that therefore all absolutely stable R hadrons are neutral. The major further argument of Voloshin and Okun [14] against light stable gluinos (others depend on astrophysical observations not confirmed since their paper was written) is that stable R baryon would have been seen in beam-dump and collider experiments (where states other than the ground state will also appear) as particles with anomalous mass/charge ratio.

The cross section for gluino production is not calculable for very light gluinos but can be guessed, e.g., to be tens of μb in hadronic collisions at 15 GeV incident energy if the lightest states have a mass of about a GeV [24]. It seems plausible (by analogy with quark fragmentation) that most of the produced gluinos fragment into glueballinos (three-parton states with gluinos are probably unstable to the strong interaction for constituent gluino masses < 0.8 GeV [22]). It is, however, completely impossible to estimate how many end up in four-parton states (R baryons) because the problem is nonperturbative and there is no analogous system known to us on which to base a guess. Hand-waving arguments are of no value here because there is no deep understanding as to why the naive nonrelativistic constituent quark picture works so remarkably well in $q\bar{q}$ and qqq systems. It might break down in the case of other combinations; indeed it is not completely clear why hybrid hadronic states are not prominent in the hadronic spectrum [25]. The production cross section of R baryons might thus be very small. While detailed phenomenological studies are necessary for the evaluation of individual experiments, it can be roughly guessed that charged weakly unstable R baryons would have surely escaped detection in hyperon beam, bubble-chamber, and collider experiments if their production cross section is about 100–1000 times smaller than the Λ production cross section [24].

This, together with the possibility that R baryons are unstable to strong decay into glueballino plus baryon (in which case they certainly would have escaped detection), makes it clear that R baryons may provide an interesting opportunity to search for gluinos, but that negative results cannot exclude the gluino's existence.

A glueballino in the favored mass range for a very light (possibly massless) gluino gets confused in particle experiments with the neutron and the K_0 which have quite similar properties (practically stable, strong-interaction cross section) and are more copiously produced in hadronic collisions (exactly by how much depends strongly on the target but it can be estimated to be always more than a factor of 10). The most sensitive beam-dump experiment sensitive to light neutral strongly interacting particles [26] gives no limits for R hadron masses below 2 GeV for this reason. Monte Carlo calculations simulating the effect of neutrons in collider environments have a precision which is not better than about 5% [27]. At large depths in the absorber the agreement get significantly worse. Fixed-target missing-mass experiments with hadronic projectiles are insensitive to glueballino and R baryon production because these particles have to be produced in pairs. Gluinoball production (two gluino state) is possible, but the unclear situation with respect to the similar glueball means that current missing-mass experiments cannot exclude the existence of such a state. A "second" stable neutron will thus escape detection even if it is produced with cross sections which are only somewhat smaller than that for ordinary neutrons.

A number of recent studies show that the existence of light stable gluinos would not be in contradiction with the results of precision experiments at e^+e^- colliders both in direct [28] and indirect searches [29]. There have been suggestions that there is evidence both for [1] and against [20] a light gluino from the running of the strong-interaction coupling constant α_s with the momentum transfer q. In my view all these analyses are not yet conclusive as there are still theoretical uncertainties in the determination of α_s at low q^2 which are on the same order of magnitude as the effect of a light gluino [30].

In conclusion, light stable gluinos could have easily (though not necessarily) escaped experimental detection up to now.

II. NUCLEAR PHYSICS OF R HADRONS

A fundamental question that arises in the study of primordial R hadrons is whether they get bound in nuclei and if so in which way (evaluation of capture cross sections). There is, as yet, no method to calculate even the low energy nucleon-nucleon interaction from QCD, therefore our discussion of the nuclear physics of R hadrons will have to remain semiquantitative. Hyperon physics is similar in some respects and allows some analogy conclusions. QCD-inspired phenomenological models [31] describe the short range repulsive part of the nucleon-nucleon interaction in terms of a one-gluon exchange. This part is therefore expected to be similar in the case of R hadrons. The medium and long range part of the interaction are described by σ- and π-meson exchange. Both the glueballino and the lightest R baryon are isospin singlets and therefore do not couple to the π. In the naive quark model (see Ref. [32] for a review of hyperon couplings) the R baryon can couple to the kaon and two pions similarly to the Λ, whereas the glueballino forms no meson couplings at all. More sophisticated methods to estimate hyperon couplings, based on flavor SU(3) symmetry, are not applicable to R hadrons. For the glueballino the long range coupling is therefore expected to be much weaker than for nucleons and hyperons and the net interaction could even be repulsive. For the R baryon it could be similar to the Λ, though it is not possible to estimate the effect of the fourth parton on the meson coupling (there is no known analogous case and our quantitative knowledge of meson-nucleon coupling depends completely on analogies). The scattering cross section with nuclei is roughly geometric in both cases because of the short range coupling.

Whether R hadrons bind to nuclei or not depends on the long range parts of their interaction. I introduce the effective coupling constant g_s of a R hadron to the nuclear mean potential to parametrize this part of the interaction. g_s is therefore the result of folding the effective two-body R-hadron–nucleon interaction (calculated, for example, with a Brueckner G-matrix approach [33]) with all the nucleons in the nucleus. I assume in the following a mean depth of the nuclear potential V_m of about 50 MeV [33], e.g., $g_s = 0.5$ then means that an R hadron experiences a well depth of 25 MeV in nuclei. This is a good approximation for an atomic number A larger than about 10. g_s cannot be calculated at present because the nucleon–R-hadron interaction is unknown, I view it as a free parameter and study the consequences of different values of it. Even in the case of hyperons it is not possible to reliably predict g_Λ theoretically (experimental information was necessary to decide whether the Ξ has a positive g [32]). For the Λ experimentally $g_\Lambda \simeq 0.6$ [32].

The assumption of a simple three-dimensional square well as a model for the shape of the mean field of a nucleus is sufficient for the following estimates in view of the large uncertainty in the R-hadron–nucleon interaction. In such a potential bound R hadron states occur if [34]

$$g_s > \frac{\pi^2\hbar^2}{2m_s V_m R^2}. \quad (1)$$

Here m_s is the effective reduced mass of the R hadron in the nuclear mean field and R the radius of the potential well which I approximate by $R = 1.3A^{1/3}$ fm. A possible difference between free and effective R hadron mass is neglected in the following for simplicity. For each positive value of g_s there will be a critical atomic number $A_{\rm crit}$ for nuclei above which R is large enough to allow bound states. The range of values of g_s for which $A_{\rm crit}$ lies between 1 and 238 is between about 8×10^{-3} ($m_s \simeq 2$ GeV, $A_{\rm crit} = 238$) and 0.8 ($m_s \simeq 0.3$ GeV, $A_{\rm crit} = 4$). For g_s smaller than the lower bound R hadrons do not bind to any stable nucleus.

Note that the Λ does not form a two-baryon bound state with protons and that ${}^3_\Lambda$H is the most weakly bound nuclear system known (binding energy 0.06±0.06 MeV [35]). Therefore there are very likely no "glueballino isotopes" of hydrogen. If g_s for the R baryon is only slightly smaller than that for the Λ it also will not form hydrogen isotopes.

For incoming energies E smaller than about 50 MeV (satisfied for the cases of interest here: big-bang nucleosynthesis $E \simeq 100$ keV, galactic halo velocities $E \simeq 400$ eV, and thermal energies 0.025 eV) the following expression can be used to evaluate the capture cross section σ_c [36]:

$$\sigma_c \simeq 300 \left(\frac{E}{\rm eV}\right)^{-1/2} g_s^{-1/2} \left(\frac{m_s}{\rm GeV}\right)^{-1/2} \frac{\Gamma_x}{\Gamma_s} \text{ barn}. \quad (2)$$

Γ_x is the width of the decay channel of the compound nucleus containing the R hadron to the bound state and Γ_s is its decay width back to the continuum. Single R hadron states will be single particle states in the nuclear mean potential with good precision because no state mixing can take place (as, e.g., in the case of an incoming neutron). To simplify the following expressions, I will assume that the binding energy is equal to the well depth of the R hadron ($g_s \times 50$ MeV); this is valid only for $A \gg A_{\rm crit}$. Near $A_{\rm crit}$ no simple analytical expressions are possible. For Γ_s we then obtain, under the assumption that the capturing continuum state has a width equal to the Wigner limit [37],

$$\Gamma_s \simeq 24.0 g_s^{1/2} \left(\frac{m_s}{\rm GeV}\right)^{-1} \left(\frac{10}{A}\right)^{1/3} \text{ MeV}. \quad (3)$$

Here A is the atomic number of the capturing isotope.

R hadrons can be captured via nucleon emission if g_s is large enough (roughly > 0.2), ${}^AZ(s,N)^{A-1}Z_s$, where ${}^AZ$ stands for a nucleus of atomic number A, N for a nucleon, and s for an R hadron. Γ_x depends on the value of g_s.

If nucleon emission can take place and the Wigner limit is assumed we have, for the nucleon decay width Γ_N,

$$\Gamma_x \simeq \Gamma_N \simeq 3.4 \left(\frac{g_s V_m - E_B}{\rm MeV}\right)^{1/2} \left(\frac{10}{A}\right)^{1/3} \text{ MeV}. \quad (4)$$

Here E_B is the binding energy of the emitted nucleon. Expressions (2), (3), and (4) combined typically lead to capture cross sections of about $300/(E/\text{eV})^{1/2}$ b.

Otherwise radiative capture ${}^AZ(s,\gamma)^AZ_s$ will dominate. Glueballinos have no magnetic moment at tree level; their dominant electromagnetic decay mode is therefore expected to be $E1$. Since $0 \to 0$ transitions are forbidden, the radiative capture can take place either via $L = 1$ capture into the ground state or via $L = 0$ capture into the first excited p state. The former case is suppressed for the low energies of interest by centrifugal barrier tunneling. $L = 0$ capture can only take place if the first p state is bound, which is the case if g_s is four times larger than the critical value of Eq. (1) [34]. If $8 \times A_{\rm crit} < 238$ there will be nuclei for which $E1$ radiative capture proceeds unhindered by barrier suppression.

For the R hadronic radiative transition amplitudes the Weisskopf values [33] are expected to be good approximations. The Weisskopf expressions are valid for nucleon transitions and have to be corrected for the case of R hadronic transitions. Single particle neutron electromagnetic transitions can occur because the neutral neutron deforms the mean nuclear potential. Nuclear matter (with net positive charge) fills the deformation and thus induces electromagnetic multipole moments, which are proportional to the density of this nuclear matter. I estimate that a neutron deforms the mean nuclear potential by a factor $1/g_s$ more than an R hadron does, and assume that for the density ρ_F of a Fermi gas $\rho_F \sim V^{3/2}$, where V is the depth of the deformed potential. This last expression is valid if V is proportional to the Fermi energy which is approximately true in nuclei. I then find that the transition multipole moments in the Weisskopf expressions have to be corrected by a factor $g_s^{3/2}$. Therefore the R hadronic transition amplitudes which are proportional to the square of the multipole moments vary as g_s^3. I then find, for the case in which the radiative transition width dominates,

$$\Gamma_x \simeq \Gamma_\gamma \simeq 0.1 \left(\frac{A}{10}\right)^{2/3} g_s^6 P \text{ MeV}. \quad (5)$$

Here P is the centrifugal barrier tunnel probability which can be calculated using standard formulas [34].

For R baryons $M1$ capture from an s wave could be important. For energies of interest in big-bang nucleosynthesis, this can be shown to have about an equal probability to that of p-wave $E1$ capture. Finally, for low energies where P becomes very small, internal conversion and pair conversion can become important for radiative capture from an s wave. Using simplified expressions [38] similar considerations to those in the case of the radiative transitions above lead to the following expression for internal conversion and pair conversion, respectively:

$$\Gamma_{\rm IC} = 1.8 \times 10^{-8} \left(\frac{Z}{5}\right)^3 \left(\frac{A}{10}\right)^{4/3} g_s^5 \text{ eV}, \quad (6)$$

$$\Gamma_{\rm PC} = 1.3 \left(\frac{A}{10}\right)^{4/3} g_s^8 \text{ eV}. \quad (7)$$

III. PRODUCTION OF R HADRONS IN THE EARLY UNIVERSE AND THEIR LATER FATE

A. Abundance of R hadrons in the present day Universe

The abundance of stable R hadrons relative to nucleons after decoupling, called N_s below, can be calculated with a standard procedure for baryons with particle-antiparticle symmetry, which is valid if R hadron decoupling occurs after QCD confinement. This condition is satisfied for R hadron constituents with a mass < 0.7 GeV. The final result is [39]

$$N_s = 9 \times 10^{-10} \frac{\langle v\sigma_{\rm geo}\rangle}{\langle v\sigma_{As}\rangle}. \quad (8)$$

Here σ_{As} and $\sigma_{\rm geo}$ are the R-hadron–R-hadron and geometric ($1/m_\pi^2$) annihilation cross sections, respectively, and multiplication by v in the angular brackets symbolizes thermal averaging in the usual way. Furthermore, a nucleon/photon density ratio of $\eta = 5.6 \times 10^{-10}$ corresponding to a Hubble constant $H_0 = 65$ km/sec Mpc and a baryonic mass fraction $\Omega_B = 0.05$ relative to the critical density Ω were assumed [39]. R hadrons do not have a long range one-pion exchange part in their strong-interaction potential (see below); therefore the geometric cross section is expected to be a reasonable approximation to the annihilation cross section (it will be assumed below that they are equal). Gluinos are probably Majorana particles and cannot develop a particle-antiparticle asymmetry; therefore 9×10^{-10} is the expected abundance of gluino-containing R hadrons relative to nucleons. Gluinos with a Dirac mass term or new quarks could have such an asymmetry, because we are currently unable to calculate it (as in the case of nucleons); higher abundances are possible in that case. This case is further discussed at the end of Sec. III C.

R hadrons that did not find their way into bound states with nuclei in the early Universe for whatever reason are expected to behave like cold dark mater (CDM). This is because for such particles in the galactic halo, even though they have geometric scattering cross sections with the nuclei of the interstellar medium, there is not enough dissipation to let them collapse to the disk [40]. To estimate the flux of free R hadrons near the earth I assume that the standard CDM scenario is correct. Even if this assumption should prove invalid, the estimate below is not expected to be off by more than an order of magnitude, because the R hadrons will form a galactic halo independent of other components (only the detailed values of the parameters "core radius" and "local density" are then uncertain). I obtain for the flux ϕ_s near the Earth, using the same values for the cosmological parameters as used for the evaluation of Eq. (8),

$$\phi_s \simeq 4.5 \times 10^{-4} \left(\frac{1}{\Omega_{\rm CDM}}\right) \left(\frac{\Delta v}{300 \text{ km/sec}}\right) \times \left(\frac{\rho_h}{0.3 \text{ GeV/cm}^3}\right) \frac{\langle v\sigma_{\rm geo}\rangle}{\langle v\sigma_{A\tilde{g}}\rangle} f \,\text{cm}^{-2}\,\text{sec}^{-1}. \qquad (9)$$

Here Ω_B and $\Omega_{\rm CDM}$ stand for the baryonic and the exotic fractions of the critical mass density of the Universe, respectively, Δv is the velocity dispersion in the galactic halo, ρ_h is the local density of the galactic halo, and f is the fraction of R hadrons that remains free after BBN. The dependence on $\Omega_{\rm CDM}$ follows from the assumption that the dark halo of our galaxy is formed by CDM and that the light gluinos behave dynamically similarly to the particles constituting CDM: if $\Omega_{\rm CDM} < 1$ the concentration factor in the galactic halo in order to supply the observed halo density and thus also the gluino density rises.

B. Case (a). *R* hadrons form bound states with nuclei

For samples collected on Earth there are three locations imporant for R hadron capture by nuclei (others can be shown to be negligible in comparison to these): during big-bang nucleosynthesis, in the interstellar medium, and on Earth. R hadron capture during BBN occurs if $A_{\rm crit} < 8$. Using experimental results for nuclear and Λ binding energies [35] one finds that, if the R hadron couples like the Λ hyperon, capture via nucleon emission is not possible for energetic reasons for any of the isotopes occuring in the early Universe ($A < 8$). The "closest" case is $^7\text{Be}(\Lambda, p)^7_\Lambda\text{Li}$, in which the final state is heavier by only 36 keV. For the equivalent reaction with helium the binding energy difference is 18.2 MeV. While it therefore seems certain that helium will not capture R hadrons via nucleon emission, for g_s only slightly larger than g_Λ, ^7_sLi could be thus produced. As the small R hadron concentration is not expected to disturb normal nucleosynthesis, I calculated the abundances of R hadronic isotopes in BBN by numerically integrating the expression

$$\frac{df(t)}{dt} = -N(t)f(t)\langle\sigma v\rangle \qquad (10)$$

over time. Here $\langle\sigma v\rangle$ is the thermally averaged capture cross section times the velocity, f is the remaining fraction of free R hadrons at time t, and N the instantaneous number density of the capturing isotope. For this integration I took the values of the abundances of the various isotopes and temperatures as a function of time from Fig. 4.3 in [39]. For the capture cross section I took a value of 1 b (calculated according to the formulas in Sec. II for energies during BBN). This procedure finally yields a fraction $f_b = 1 - f$ after nucleosynthesis of 5×10^{-6} and from that $^7_s\text{Li}/^7\text{Li} \simeq 10^{-4}$. This very high value is excluded by mass spectroscopic evidence (see below, Sec. IV) if the mass of the R hadron is not very near the nucleon mass.

In the more likely case that capture via nucleon emission is energetically forbidden it probably proceeds via p-wave $E1$ capture. S-wave capture seems difficult because, for example, in the case of ^{4}He and $m_s \simeq 1$ GeV g_s needs to be larger than about 1.0 for a bound p state to exist. For the energies occurring during BBN the centrifugal barrier penetration factor P is about 3×10^{-3} for helium. A plausible range for g_s is 0.24 (R hadron with about 1 GeV just bound to ^{4}He) to 0.6 (value of g_Λ). I then obtain for energies occurring during BBN and an R hadron mass of 1 GeV a radiative capture cross section according to Eqs. (2), (3), and (5) of $\sigma_\gamma \simeq 4$–400 nb. Using the same method as for Li above, this finally yields an expected abundance range for $^5_s\text{He}/^4\text{He}$ of 3×10^{-10} to 3×10^{-12}. f_b ranges from 0.02 to 2×10^{-4}. Even if R hadrons bind to nuclei they are *not all* expected to be bound to nuclei after BBN.

About half of the known matter in the solar neighborhood is in the form of interstellar medium (ISM) [41]. The galactic flux of R hadrons will transform some fraction of this to R hadronic nuclides. As the solar system formed from ISM about 5 billion years after the formation of the galaxy, matter found here is expected to contain a certain fraction N_s of R hadronic nuclides by number. This fraction is estimated according to

$$N_s \simeq \phi_s \sigma_c \Delta t, \qquad (11)$$

where ϕ_s is the R hadron flux according to Eq. (9), σ_c is the R hadron capture cross section, and Δt is the time during which the matter existed as ISM. If one estimates a typical age of 2.5 billion years for metals (elements with $Z > 2$) in the solar system and takes into account that they spend about half of this time as ISM, the latter time is estimated to be about 1.3 billion years. If capture via nucleon emission is allowed for heavier isotopes this expression together with Eq. (2) evaluated at energies arising in the galactic halo yields $N_s \approx 2 \times 10^{-10}$. On the other hand, for very small values of the capture cross section (values as low as 0.01 pb can occur for $g_s \simeq 0.01$ and p-wave radiative capture) N_s can become very small ($\simeq 2 \times 10^{-25}$).

In this case gravitational capture by the Earth and ensuing capture by terrestrial nuclei is the dominant R-hadronic–nuclei production process. We then have (see next section for details on the gravitational capture process)

$$N_s \simeq \frac{A_e \phi_s \Delta t}{N V_{\rm mix}}(1-\beta_e) \tag{12}$$

where A_e is the cross section of the Earth, ϕ_s the R hadron flux according to Eq. (9), Δt the age of the earth, N the number density of the capturing nucleus, $V_{\rm mix}$ the volume throughout which the R hadrons are mixed during their diffusion into the earth, and β_e the experimental R hadron albedo discussed in detail in the next subsection. A firm upper limit to $V_{\rm mix}$ is the volume of the whole Earth; in this case the value of N_s is about 10^{-18}. For a larger cross section (around 0.1 mb) all R hadrons are captured in the atmosphere and a typical value of N_s for nuclei in the atmosphere would be about 10^{-12}. In experimental searches xenon would be a preferred nucleus because it is chemically inert and of large atomic mass (probes possible large $A_{\rm crit}$).

The conclusion to case (a) is that the relative concentration of R hadronic to R hadron free nuclides most probably lies between about 10^{-10} and 10^{-18} depending on the detailed properties of the R-hadron–nucleon interaction potential.

C. Case (b). *R* hadrons remain free

If some R hadrons do not bind to nuclei (this seems possible, especially for glueballinos), their gravitational capture by the Earth will lead to a rise in the ambient R hadron density at the surface of the Earth. This process has some similarity to the gravitational capture of WIMP's by the Earth [42]. The detailed mechanism is different from WIMP capture, however, because the much larger scattering cross section of R hadrons allows them to quickly reach thermal equilibrium with their surroundings for densities encountered in the Earth. A similar process is possible for stars; I will not discuss this case further because I could not find observational consequences which are as important as the ones for the capture by the Earth. The present work has some parallels to research on charged dark matter [43] and technibaryons [44], though the quoted studies were generally concerned with particles of much higher masses.

When an R hadron enters the Earth's atmosphere it is moderated like a neutron via elastic collisions with the air nuclei. Once its velocity has fallen below the Earth-escape velocity it forms an "atmosphere" around the earth core. The "R hadron albedo" (i.e., the fraction of R hadrons hitting the earth that is reflected) can be calculated analogously to the experimental neutron albedo β_e [45]. For the number of elastic collisions n_s necessary to reduce the velocity of an R hadron from about 300 km/sec (galactic halo) to 11 km/sec (escape velocity) one has $n_s = u/\xi$, where u is the total change in lethargy and ξ is the lethargy change in a single scattering event. For example, for an R hadron with $m = 1$ GeV scattering on nitrogen, one gets $n_s = 51.2$. β_e can then be calculated according to [45]

$$n_s = \frac{4\beta_e}{(1-\beta_e)^2}. \tag{13}$$

For a 1 GeV R hadron we obtain an albedo of 0.76, i.e., about 24% of the R hadrons impinging on the atmosphere with the mean velocity are captured by the Earth. Since this value is quite high, it is not necessary to consider the effect of the low energy tail of the Maxwell velocity distribution (which is very important in the case of WIMP's where a single scattering event has to suffice to capture the particle). After they are captured the R hadrons quickly diffuse into Earth and finally form an atmosphere which is in thermal equilibrium with the surrounding baryonic matter. Its density distribution was calculated on the computer by integrating the R hadron density ρ_s from its value at the center of the Earth ρ_c to infinity, taking into account the density and temperature profile of the Earth according to the formulas [42]

$$\rho_s = \rho_c \exp(m_s \xi / T), \quad \xi = G \int_0^r M/z^2 dz. \tag{14}$$

Here G is the gravitational constant and M the mass of the earth within the radius r where ρ_s is evaluated. The density distribution used was the same as the one given by Krauss, Srednicki, and Wilezek [42]; for the temperature distribution I assumed 300 K at the surface, 1400 K at a depth of 100 km, and first 2000 and then 6000 K in the central region out to a 3400 km radius (the two values bracketing the present uncertainty in this value [46]). For intermediate depth values I interpolated linearly; this is a very good approximation for the region between the surface and a depth of 100 km [47]. For deeper regions the temperature distribution is not well enough known to warrant more sophisticated parametrizations. One typically finds that the R hadron density at the surface of the Earth is about 10^{-3} to 0.5 times less than at the center of the Earth, i.e., most R hadrons reside inside the earth. [For a central temperature of 2000 (6000) K the ratio ρ_c/ρ_s is 0.183 (0.42), 0.033 (0.187), and 0.006 (0.081) for $m_s = 0.5$, 1.0, and 1.5 GeV if ρ_s is evaluated at the surface of the Earth.] The loss of R hadrons from the Earth proceeds via evaporation and annihilation for particle-antiparticle symmetric R hadrons.

At the outer edge of the gluino atmosphere the R hadrons can escape thermally. This escape flux F at a distance R from the center of the earth is calculated according to a formula well known in geophysics [46]:

$$F = \rho_s (kT/2\pi m_s)^{1/2}(1 + GMm_s/RkT) \times \exp(-GMm_s/RT), \tag{15}$$

where k is the Boltzmann constant. The temperature T (about 250 K) at 35 km above sea level was chosen, corresponding to one free path length of overlying matter for R-hadron–nitrogen scattering with a geometric

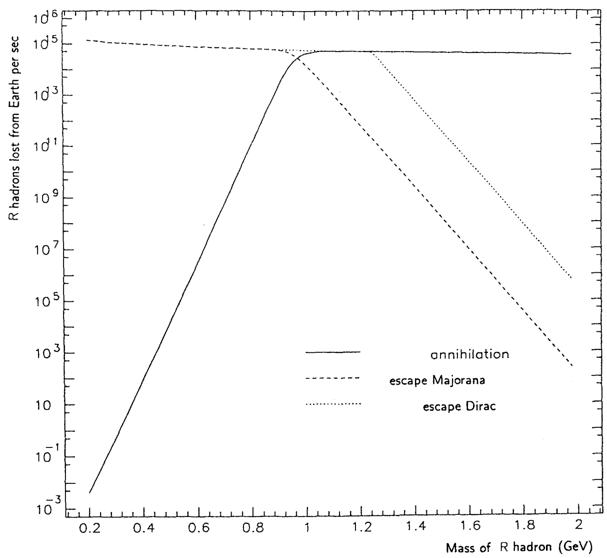

FIG. 1. The present loss of R hadrons per second from the Earth for a central temperature of 6000 K. The assumed incoming flux is the flux of Eq. (9) for the central value and $f = 1$. The continuous curve gives the loss due to annihilation under the assumption that the R hadrons are particle-antiparticle symmetric. The dashed and dotted curves give the loss rate due to thermal loss to outer space for symmetric (Majorana) and asymmetric (Dirac) R hadrons, respectively. The "Dirac" curves are to be regarded as lower limits to the true loss rate which depends on the unknown degree of the primordial particle-antiparticle asymmetry.

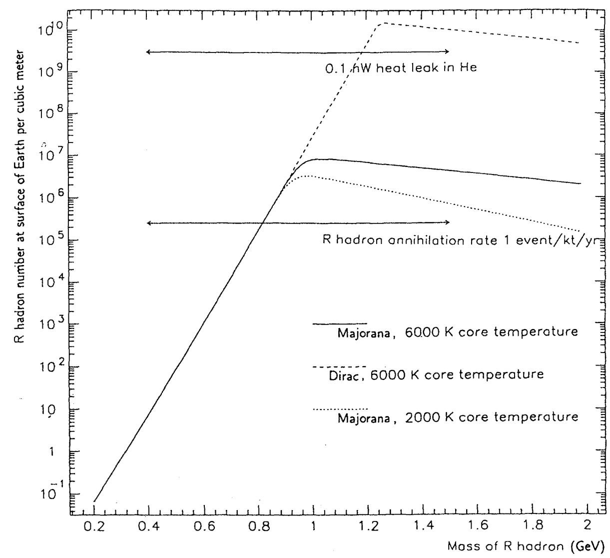

FIG. 2. The present R hadron density on the surface of the Earth. The unbroken and dotted curves are for a particle-antiparticle symmetric R hadron species for two different temperatures at the center of the Earth. The dashed curve is for a species which does not self-annihilate. Again the assumed incoming flux is the flux of Eq. (9) for the central values. The horizontal bars are very rough upper limits for two different classes of experiment; see text for details.

cross section ($\lambda_{\text{free}} \simeq 13$ g/cm^2). The resulting loss rate in equilibrium is displayed in Fig. 1. If the age of the Earth is not sufficient for equilibrium to be reached (for R hadrons above about 1.2 GeV) this is taken into account by reducing the loss rate accordingly.

The R hadron annihilation rate N_A for the whole Earth is calculated according to [42]

$$\dot{N}_A = \langle \sigma_A v \rangle \int \rho_s^2 d^3 r. \tag{16}$$

It is seen in Fig. 1 to take over as the dominant loss mechanism for particle-antiparticle symmetric R hadrons above about 1 GeV. Finally the capture rate C according to $C = \phi A_e (1 - \beta_e)$, where A_e is the cross section of the Earth, is equated to the loss rate of R hadrons from the Earth, which is the sum of Eqs. (15) and (16). The resulting quadratic equation is solved to get the various R hadron densities in equilibrium. The resulting R hadron densities at the present time at the surface of the Earth are displayed in Fig. 2.

In the case of Dirac particles a particle-antiparticle asymmetry is possible, and the given concentration is really only a lower limit on the possible concentration. (This is also true for the concentration of possible anomalous isotopes.) In this case there is even a remote possibility that unbound R hadrons form the dark matter of cosmology [18]. For R hadron masses below 1 GeV there are no known limits on strongly interacting dark matter [48] and for masses below about 400 MeV the expected concentration on the surface of the Earth could also be low enough to pass the experimental constraints discussed in the next section. This possibility needs further study. It does not seem attractive because it involves the arbitrary tuning of some parameters to implausible values, but it cannot be logically excluded at the moment.

IV. EXPERIMENTAL DETECTION OF PRIMORDIAL R HADRONS

A. Case (a) (bound). Accelerator mass spectroscopy and Ge(Li) detectors

Concentrations of anomalous isotopes as calculated in the previous section are below the sensitivity of normal spectrometers as routinely used (e.g., in geochemistry) of about 10^{-6}–10^{-9} for the number ratio of a detected isotope to the neighboring more abundant isotopes [49]. They are, however, within reach of the much more sensitive accelerator mass spectroscopy (AMS) methods [50] which reach sensitivities down to 10^{-18} depending on the element studied. A summary of limits for concentrations of anomalous isotopes is given in [51]. Except for hydrogen and helium there are no published AMS limits for any element in the relevant mass region from A to about $A + 2$. We have seen in Sec. II that R hadrons probably do not form isotopes of hydrogen and that A_{crit} is as small as 4 is also doubtful. The limit on helium comes from the measurement of Klein, Middleton, and Stevens [52] who quote an upper limit on the ratio $^5He_s/He$ in the relevant mass range of 2×10^{-14} (note that their helium measurement is misrepresented in the summary diagram in [51]). The helium used by them was atmospheric helium which has a content of primordial helium of about 0.3% [53] (the rest consists of radiogenic helium which was formed via radioactive decay of heavy elements in the Earth). Therefore their upper limit on the ratio $^5He_s/He$ in primordial helium is about 6×10^{-12} which is not even sufficient to rule out R hadrons which bind to helium. The formation of ^5He_s at later times probably leads to very small concentrations ($\simeq 10^{-16}$ in the ISM with σ_γ at the upper end of the plausible range calculated as explained in Sec. III B).

To my knowledge there has been only one series of experiments on anomalous isotopes with relevance to small masses since the work of Hemmick *et al.* [51]; the search for a violation of the Pauli principle by Nolte and colleagues [54]. Unfortunately, these authors only searched in a mass region from the expected mass of ^5He to about 40 MeV less, which is more than an order of magnitude too small in a search for R hadrons. In heavier elements they only searched at the exact expected masses of known isotopes. They obtained an upper limit of 2×10^{-15} for $^5He/He$ (raw result without correction for the primordial fraction which was low in their sample), 6×10^{-18} for $^{20}F/F$, and 8×10^{-16} Cl/Cl. From this it is clear that this group has the experimental means at its disposal to discover R hadronic isotopes if R hadrons exist and bind to nuclei. A serendipitous discovery of R hadron mass peaks in AMS studies seems improbable because in quantitative studies of concentrations it is of the utmost importance in these experiments to go as quickly as possible from one mass peak to the other to maintain stable conditions in the accelerator, i.e., the intermediate mass region is never slowly scanned as would be necessary in a search for R hadronic bound states.

The question of whether R hadronic isotopes exist is therefore still open at present but could be answered in a very short time by AMS measurements. Preferred isotopes in such a study would seem to be the following.

^5_sHe because its cosmological origin is well understood. One should choose helium extracted from magnetic deep-sea sediments, which is expected to be fairly pure primordial helium [53].

^7_sLi is a special case as discussed in Sec. III and could be very abundant. ^8_sLi is the heaviest R hadronic isotope formable with BBN nuclides.

A heavy isotope in case $A_{\rm crit}$ is large. Xenon is an interesting candidate for the reasons stated in the previous section, but noble-gas AMS is still in the development stage.

Experimenters should be cautious to use isotopically enriched samples. While in general the simple picture that the R hadrons bind to the more or less unchanged nucleus will be correct because of the relatively small expected binding energy of the R hadrons, there can be cases in which the R hadronic isotope is β unstable and will decay into a $Z+1$ nucleus. In this case there will be no R hadronic isotope heavier than the heaviest isotope of a given element. An example is ^{136}Xe where the β decay into ^{136}Cs is forbidden by only 67 keV which could be easily supplied by the bound R hadron. Probably the best strategy is to search over a relatively wide mass range for all isotopes (also at masses smaller than a given isotope).

We have seen that a large fraction of R hadrons exists as free particles today even if they can bind to nuclei. Therefore radiative capture on nuclei of ambient R hadrons could be directly observed, e.g., in Ge(Li) detectors. The detailed calculation of the R hadron flux at the surface of the Earth for R hadrons binding to nuclei is a complicated problem in nonequilibrium thermodynamics which I leave for the time when a few more free parameters are fixed. For a first estimate I assume that the R hadron flux ϕ_s of Eq. (9) (assuming central values and $f = 1$) impinges on a 200 cm^3 Ge(Li) detector. With the optimistic estimate of a 0.1 mb radiative capture cross section on Ge (for a much larger cross section the R hadrons would not reach the surface of the Earth) I get 4×10^{-7} captures/sec. Assuming a γ-detection efficiency of 2% this corresponds to 5×10^{-4} events/day in the R hadron capture line. This has to be compared with a background of about 10–20 events/day keV with such a state of the art detector at the surface of the Earth and 1–2 events/day keV at a moderate shielding depth of 15 meter water equivalent [55] for the relevant energy range of up to about 8 MeV. For much larger capture energies nucleon emission becomes possible. This leads to cross sections in the barn range and the R hadrons do not reach the surface of the Earth. It is seen that the nonexistence of "unexpected lines" in present detectors [56] does not go against the existence of R hadron capture. Large Ge(Li) experiments at not too large shielding depths should search for these "unexpected lines" in the stated energy range. Note that experiments searching for the recoil of nuclei from the collision with very heavy strongly interacting particles at galactic velocities [57] do not bear on this point because they search for an enhanced counting rate at very low energies, not for unexpected isolated lines.

B. Case (b) (unbound). Proton decay experiments and cryogenic devices

R hadron annihilation in the center of the Earth and in the Sun might lead to a neutrino flux detectable by proton decay experiments (analogously to the case of WIMP's). The lack of heavy quarks or leptons in the final state (which could lead to prompt neutrinos as in the case of WIMP's) suppresses this observational mode, however. Because of the small masses of R hadrons as compared to WIMP's, their spatial distribution is less concentrated towards the center of the Earth and the observation of R hadron annihilations directly inside the underground detector should be a better signal. This signal is proportional to the volume of the detector rather than its mass, so water based detectors are favored over iron calorimeters, though in the latter case there seems to be a chance to discriminate between the R hadron annihilation and the atmospheric neutrino background by selecting events which have their vertex in the air rather than in more dense matter.

The R hadron annihilations are not expected to have very specific signatures (a decay into a few pions will probably be typical) so we have to compare the expected rate with the neutrino background which is about 100 events/kton yr [58]. In view of this rate it seems certain that a rate below 1 event/kton yr would not have been serendipitously discovered in ongoing experiments. The R hadron density necessary for this rate is indicated in Fig. 2. The annihilation rate was taken to be the one of Eq. (16), and the density of the detector was assumed to be 1 g/cm^3. It can be seen that underground experiments are most sensitive to R hadron annihilation just about in the favored mass range for glueballinos, so a more detailed analysis of archival data by the experimentalists might be interesting.

There is another way to detect R hadrons independent of their particle-antiparticle symmetry: because of their large free path length (of the order of centimeters in condensed matter) they conduct heat through walls [59]. An elementary calculation gives for the heat conduction per unit mass P_t into a vessel "closed" to conventional means of heat conduction

$$P_t = 3 \times 10^{-14} \left(\frac{\rho_s}{1/\mathrm{cm}^3}\right) \left(\frac{\sigma_{\mathrm{sc}}}{0.8\ \mathrm{b}}\right) \left(\frac{v}{2200\ \mathrm{m\,sec}}\right)^3 \times \left(\frac{m_s}{m_s + m_t}\right)^2 \ \mathrm{W/kg}, \tag{17}$$

where ρ_s is the ambient number density of R hadrons (from Fig. 2), σ_{sc} is the geometrical scattering cross section of R hadrons on the material inside the vessel (0.8 b is the value for helium), v is the mean velocity of the R hadron (2200 m/sec, for a 1 GeV R hadron, if it is room temperature outside the vessel), and m_t is the mass of a "target" nucleus of the material inside the vessel. For comparison the heat leak of a state of the art experiment [60] (0.1 nW/kg) is indicated in Fig. 2 for the case of helium as the material inside the vessel (the most favorable case except for hydrogen). Note that in Pobell's [60] cryostat the target material was much heavier, so at present there is probably no limit on the R hadron flux to be obtained by considering published heat leaks. A fundamental problem is that cosmic-ray muons deposit about 5×10^{-12} W/kg into cryostats at the surface of the Earth. To detect R hadrons via heat leaks, it therefore seems necessary to work in an underground laboratory. A lot of work has been done recently on the measurement of small recoil energies in cryostatic detectors in connection with the search for dark matter and coherent neutrino interactions [61]. A major problem in this work is how to scale up small prototype detectors in order to allow the detection of WIMP's which have very small scattering cross sections. These prototype detectors seem, however, already promising for the detection of recoiling nuclei from collisions with R hadrons with their much larger cross sections. In order to reach high enough recoil energies it is necessary to accelerate the ambient R hadrons by some means. This possibility leads to a novel class of experimental techniques in which preexisting remnant particles from the big bang are detected by active experiments. One possibility is to heat the surroundings of the detector on a scale of centimeters so that the R hadrons in equilibrium get higher thermal energies. Such a heating would also raise v in Eq. (17) and ease the detection of the "R hadronic heat leak."

If the surroundings of the detector were at a temperature of 3000 K (higher temperatures are not easy to realize technically in matter with a reasonably high mass density) one would have a scattering rate of about $N_{\tilde{g}}\phi\sigma_{\mathrm{sc}} \simeq 3\times 10^5$/mole sec for an ambient R hadron density of 1/cm^3. If the "scattering target" in the cryostat is, e.g., helium, the energy transfer per scatter is about 0.08 eV on average. Using the Maxwell velocity distribution it is easy to estimate that there would be about 3 events/mmole day with an energy transfer of > 1.4 eV. The detection of these events therefore seems possible even with very small (mg size) detectors if their energy threshold is low enough. R hadron detection seems to offer a challenge to designers of dark matter experiments to do fundamental physics even with their prototype detectors.

Finally, another possibility of R hadron acceleration deserves further study. The beam of a high current low energy heavy ion accelerator which passes through a vacuum chamber will collide with the ambient R hadrons and accelerate them into a 45° forward cone for the limiting case of very small target to projectile mass ratios. Low energies are necessary to prevent neutron-producing background reactions. Heavy ions are preferable because of their high Coulomb barrier, preventing neutron-producing nuclear reactions; moreover, they present higher geometric cross sections for scattering on R hadrons. These accelerated R hadrons could be detected in conventional Si(Li) or cryogenic detectors via their recoil as they slow down. One gets, for the rate of accelerated R hadrons C_a,

$$C_a = (10/\mathrm{yr}) \left(\frac{I}{1\ \mathrm{mA}}\right) \left(\frac{l}{0.1\ \mathrm{m}}\right) \left(\frac{\sigma}{4\ \mathrm{b}}\right) \left(\frac{\rho_s}{1/\mathrm{cm}^3}\right). \tag{18}$$

Here I stands for the current of the accelerator (1 mA is readily reached in commercial ion implanters), l is the length of the vacuum vessel, and σ_{sc} is the scattering cross section (4 b is the value for silicon). Given an R hadron density higher than about 100/cm^3 (possible for particles possessing a particle-antiparticle asymmetry as seen in Fig. 2) the experiment could be feasible. In this connection it is interesting to note that there is a project to install low energy accelerators in the Gran Sasso underground laboratory [62] where there are already several recoil detectors. It seems that proton decay experiments should be able to find a particle-antiparticle symmetric R hadron species, whereas the various scattering and capture experiments have a chance of finding particle-antiparticle asymmetric states.

V. CONCLUSION

Very light, possibly massless, stable gluinos or gluino-like particles are an attractive possibility from a theoretical standpoint. They exist after the big bang in bound states with gluons and/or quarks. Depending on the properties of the R-hadron–nucleon interaction either they are to some extent incorporated in existing nuclei or they remain free and in this case form an atmosphere around the Earth's core. Accelerator mass spectroscopy experiments should search for the "R hadronic isotopes" as concentrations predicted in this paper, under the assumption that R hadrons bind to nuclei, are within their reach. Independent of the outcome of this search, proton decay experiments, Ge(Li) detector experiments, and especially cryogenic experiments could hunt the primordial free R hadron in uncoventional ways.

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