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Experimental and Cosmological Implications of Light Gauginos

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Abstract: Gauginos may be nearly massless at tree level, with loop corrections giving a gluino mass of order 100 MeV and a photino mass of order 1 GeV. Relic photinos can naturally account for the observed dark matter, but their detection is more difficult than for conventional WIMPs. The lightest gluino-containing baryon could account for the recently observed ultra-high energy cosmic rays, which violate the GZK bound. The predicted mass and properties of the $\tilde{g}\tilde{g}$ boundstate agree with those of the $\eta(1410)$, a flavor singlet pseudoscalar meson which has proved difficult to reconcile with QCD predictions. Laboratory experiments presently exclude only a small portion of the interesting parameter space, although improvements expected in the next year may lead to complete exclusion or discovery.

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Introduction

Some supersymmetry (SUSY) breaking scenarios produce negligible tree-level gaugino masses and scalar trilinear couplings ($m_1 = m_2 = m_3 = A = 0$), and conserve R-parity. Such SUSY breaking has several attractive theoretical consequences such as the absence of the "SUSY CP problem"[1]. Although massless at tree level, gauginos get calculable masses through radiative corrections from electroweak (gaugino/higgsino-Higgs/gauge boson) and top-stop loops[2]. Evaluating these within the constrained parameter space leads to a gluino mass range $m_{\tilde{g}} \sim \frac{1}{10} - \frac{1}{2}$ GeV[1], while analysis of the η' mass narrow this to $m(\tilde{g}) \approx 120$ MeV[3]. The photino mass range depends on more unknowns than the gluino mass, such as the higgs and higgsino sectors, but can be estimated to be $m_{\tilde{\gamma}} \sim \frac{1}{10} - 1\frac{1}{2}$ GeV[1].

The gluino binds with quarks, antiquarks and/or gluons to make color-singlet hadrons (generically called R-hadrons[4]). The lightest of these is expected to be the gluino-gluon bound state, designated R^0. It is predicted to have a mass in the range $1.3 - 2.2$ GeV, approximately degenerate with the lightest glueball (0^{++}) and "gluinoball" (0^{-+}, $\tilde{g}\tilde{g}$)[5, 6]. An encouraging development for this scenario is the existance of an "extra" isosinglet pseudoscalar meson, $\eta(1410)$, which is difficult to accomodate in standard QCD but which matches nicely the properties of the pseudoscalar $\tilde{g}\tilde{g}$[7, 6].

Due to the non-negligible mass of the photino compared to the R^0, the R^0 is long lived. Its lifetime is estimated to be in the range $10^{-10} - 10^{-5}$ sec[1]. Prompt photinos[4] are not a useful signature for the light gluinos and the energy they carry[8]. Thus gluino masses less than about $\frac{1}{2}$ GeV are largely unconstrained[5][2]. Proposals for direct searches for hadrons containing gluinos, via their decays in K^0 beams and otherwise, are given in Refs. [5, 6]. Results of two new experiments are mentioned below. For a recent detailed survey of the experimental constraints on light gaugino scenarios, see [11].

[2]The ALPEH claim to exclude light gluinos[9] assigns a 1σ theoretical systematic error based on varying the renormalization scale over a small range. Taking a more generally accepted range of scale variation and accounting for the large sensitivity to hadronization model, the ALEPH systematic uncertainty is comparable to that of other experiments and does not exclude light gluinos[10, 11]. The claim of Nagy and Troscsanyi[12], that use of R_4 allows a 95% cl exclusion, has even worse problems. In addition to scale sensitivity, their result relies on using the central value of α_s. When the error bars on α_s are included, their limit is reduced to 1σ, even without considering the uncertainty due to scale and resummation scheme sensitivity.

Relic Photinos

In the light gaugino scenario, photinos remain in thermal equilibrium much longer than in conventional SUSY, due to pion catalysis of their conversion to R^0's: $\tilde{\gamma}\pi \leftrightarrow R^0\pi$. The R^0's stay in thermal equilibrium still longer, because their self-annihilation to pions has a strong interaction cross section. The relic abundance of photinos depends sensitively on the ratio of the R^0 and $\tilde{\gamma}$ masses[13]. This is because the Boltzman probability of finding a pion with sufficient energy to produce an R^0 from a $\tilde{\gamma}$ decreases exponentially as the R^0 mass increases. This was studied in sudden approximation in ref. [13] using the most relevant reactions. The analysis has been refined in ref. [14] by integrating the coupled system of Boltzman equations for the reactions $\tilde{\gamma}\pi \leftrightarrow R^0\pi$, $R^0 \leftrightarrow \pi^+\pi^-\tilde{\gamma}$, $R^0\tilde{\gamma} \leftrightarrow \pi^+\pi^-$, and R^0R^0 total annihilation. Defining $r \equiv \frac{M(R^0)}{m_{\tilde{\gamma}}}$, ref. [14] finds that for relic photinos to give $\Omega h^2 \sim 0.25$ requires $1.3 \lesssim r \lesssim 1.55$. Assuming photinos are stable, their relic mass density would be unacceptably large unless $r \lesssim 1.8$. These values of r are consistent with the mass estimates quoted above for the R^0 and $\tilde{\gamma}$, which encourages us to take the possibility of light photinos seriously.

The detectability of relic dark matter is different for light $\tilde{\gamma}$'s than in the conventional heavy WIMP scenario for two reasons. The usual relation between the relic density and the WIMP-matter scattering cross section only applies when the relic density is determined by the WIMP self-annihilation cross section. In order to have the correct relic abundance, the rate of photino-removal from the thermal plasma must be greater than the expansion rate of the Universe until a temperature of order $m_{\tilde{\gamma}}/22$. In the light photino scenario, the photino relic density is determined by the $R^0 - \tilde{\gamma}$ interconversion cross section. When the dominant process keeping photinos in thermal equilibrium is interconversion ($\Gamma = n_\pi < \sigma_{R\pi\leftrightarrow\tilde{\gamma}\pi} v >$) the required cross section, now $\sigma_{R\pi\leftrightarrow\tilde{\gamma}\pi}$, is smaller than when equilibrium is maintained by photino annihilation ($\Gamma = n_{\tilde{\gamma}} < \sigma_{\tilde{\gamma}\tilde{\gamma}\leftrightarrow f\bar{f}} v >$), because $n_\pi >> n_{\tilde{\gamma}}$[13]. Furthermore, $\sigma_{R\pi\leftrightarrow\tilde{\gamma}\pi}$ is parametrically larger than $\sigma_{\tilde{\gamma}\tilde{\gamma}\leftrightarrow f\bar{f}}$ by the factor α_s/α and does not require a p-wave initial state. The photino-matter scattering cross section is therefore correspondingly smaller than in the usual WIMP scenario. Goodman and Witten in Ref. [15] discuss $\tilde{\gamma}$ detection through $\tilde{\gamma}$-nucleon elastic scattering. Using Eq. (3) of Ref. [15] and the parameters for light photinos, one finds event rates between 10^{-3} and 10 events/(kg day)[14].

Even if the event rate were larger, observation of relic light photinos would be difficult with existing detectors because the sensitivity of a generic detector is poor for the $\lesssim 1$ GeV photino mass relevant in this case, because WIMP detectors have generally been optimized to maximize the recoil energy for a WIMP mass of order 10 to 100 GeV.

The amplitudes for the reactions responsible for R^0 decay ($R^0 \leftrightarrow \pi^+\pi^-\tilde{\gamma}$) and for the photino relic density ($\tilde{\gamma}\pi \leftrightarrow R^0\pi$) are related by crossing symmetry. If the momentum dependence of the amplitude is mild, the R^0 lifetime and the photino relic abundance depend on a single common parameter in addition to the R^0 and $\tilde{\gamma}$ masses[14]. In that case, demanding the correct dark matter density determines the R^0 lifetime given the R^0 and $\tilde{\gamma}$ masses. The resulting lifetimes are shown in Fig. 1 from [14]. In actuality, the interconversion reaction $\tilde{\gamma}\pi \leftrightarrow R^0\pi$ is expected to have a resonance, so momentum-independence of the amplitudes is not a good assumption for all of parameter space. However this merely lengthens the R^0 lifetime in comparison with the crossing relation Fig. 1. The required lifetime range is consistent with both the experimental limits[5, 11] and with the predicted range of lifetimes, so relic light photinos pass an important hurdle.

Using data from 1 day of running, KTeV[16] has placed limits on the production of R^0's and their subsequent decay via $R^0 \rightarrow \pi^+\pi^-\tilde{\gamma}$, as proposed in [6]. Their cut $m(\pi^+\pi^-) > 648$ MeV (designed to eliminate background from K_L^0 decays) restricts them to the study of the kinematic region $m(R^0)(1 - 1/r) > 648$ MeV. Subject to this constraint their limits are extremely good. Fig. 2 shows the mass-lifetime region excluded by KTeV, for two values of r. For the largest r allowed by cosmology, 1.8, KTeV is sensitive to $m(R^0) \gtrsim 1\frac{1}{2}$ GeV and considerably improves the previous limits[5]. However the sensitivity drops rapidly for lower r and the analysis is completely blind to the R^0 mass region of primary interest for $r \leq 1.4$. The experimental challenge will be to reduce the invariant mass cut, in order to obtain limits which are relevant to the photino-as-dark-matter question, for which $1.3 \lesssim r \lesssim 1.55$.

In order to naturally account for dark matter with light photinos as discussed in this section, all gaugino masses must be small. This means that some of the charginos and neutralinos (the eigenstates of the higgsino-gaugino mass matrix) must be lighter than the W and Z, so they can be pair-produced at LEP2 energies. Ref. [17] describes how this can be studied when the presence of light gluinos modifies the chargino and neutralino branching ratios usually assumed in SUSY searches.

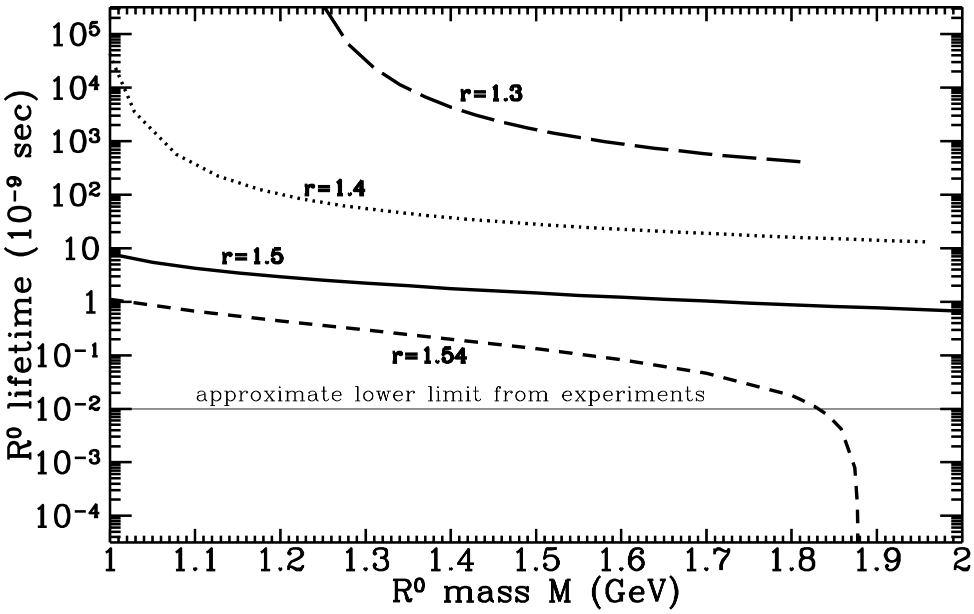


Figure 1: R^0 lifetime (strictly speaking, lower limit thereto) as a function of the R^0 mass, for several values of $r \equiv M_{R^0}/m_{\tilde{\gamma}}$, when $\Omega_{\tilde{\gamma}} h^2 = 0.25$.

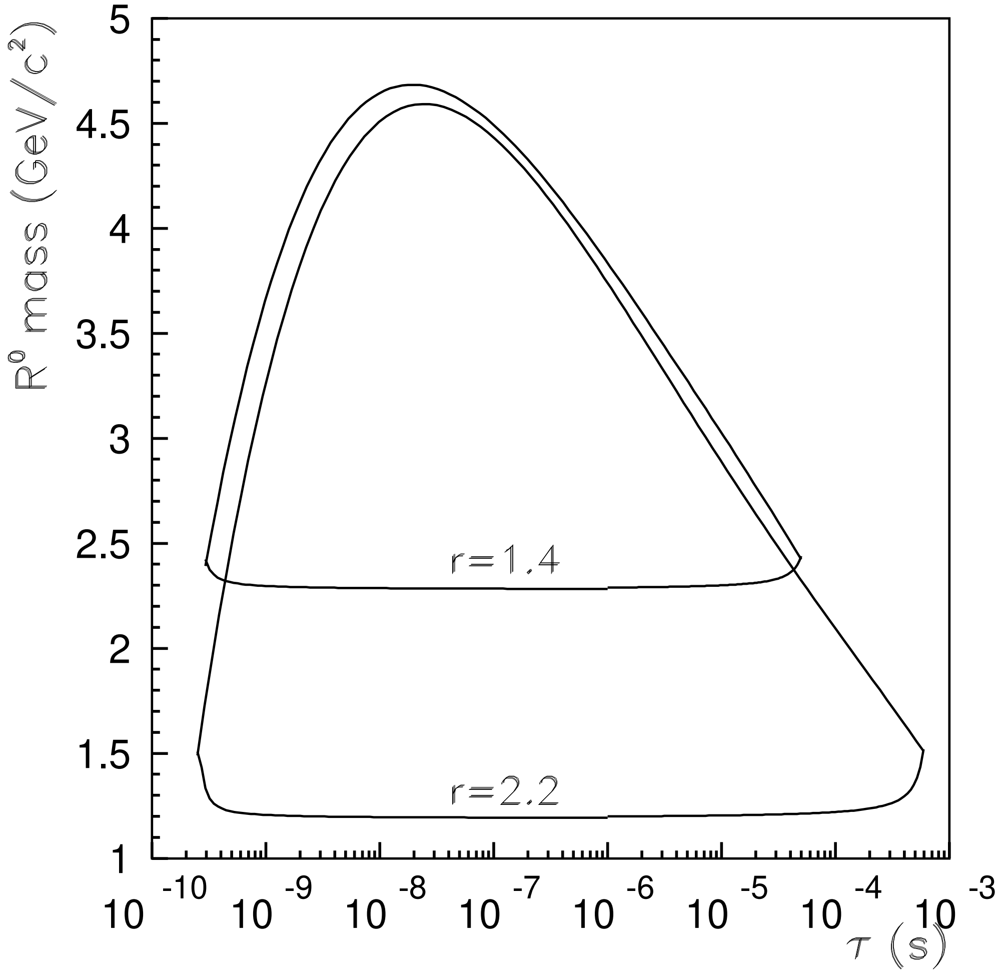


Figure 2: KTeV limits: inside the triangular regions is excluded[16].

Applying this technique, OPAL[18] has already completely excluded this scenario for the extreme case that all charginos and heavier neutralinos decay 100% of the time to purely hadronic final states. In the next year or so, improved statistical power and higher energy should either exclude or yield evidence in favor of the all-gauginos-light scenario for the general case of arbitrary final states[17].

The possibility that the anomalous 4 jet events observed by ALEPH[19] arise from pair production of a $\approx$ 55 GeV chargino, with the chargino decaying via a real or virtual squark to $q\bar{q}\tilde{g}$, has not yet been excluded. Under this interpretation, the excess events would in actuality contain 6 jets, which produce the peak in total dijet invariant mass because of the analysis procedure[20]. Due to the method of determining the dijet masses, such a peak would probably disappear with increasing energy, as has apparently occured in the data. A Monte Carlo of the 6-jet process is needed in order to decide the question. Of course the method described in the preceeding paragraph, when extended to arbitrary branching fractions, could also be used to exclude this possibility. The branching fraction required to account for the apparent cross section at 130 GeV, $\approx 1/2$ pb averaging over all 4 experiments, is too low to have been excluded by the OPAL analysis[18] discussed above.

Ultra-High-Energy Cosmic Rays

If the light gaugino scenario is correct, the lightest R-baryon, $S^0 \equiv uds\tilde{g}$, may be responsible for the very highest energy cosmic rays reaching Earth. Recall that the observation of several events with energies $\gtrsim 2\ 10^{20}$ eV[21] presents a severe puzzle for astrophysics[3]. Protons with such high energies have a large scattering cross section on the 2.7 K microwave background photons, because E_{cm} is sufficient to excite the $\Delta(1230)$ resonance[23]. Consequently the scattering length of such high energy protons is of order 10 Mpc or less. The upper bound on the energy of cosmic rays which could have originated in the local cluster, $\sim 10^{20}$ eV, is called the Greisen-Zatsepin-Kuzmin (GZK) bound.

Two of the highest energy cosmic ray events come from the same direction in the sky[22]; the geometrical random probability for this is $\sim 10^{-3}$. The nearest plausible source in that direction is the Seyfert galaxy MCG 8-11-11 (aka UGC 03374), but it is 62-124 Mpc away[24]. An even more plausible source is the AGN 3C 147, but

[3] For a recent survey and references see [22].

its distance is at least a Gpc[24]. The solid curves in Fig. 3, reproduced from ref. [25], shows the spectrum of high energy protons as a function of their initial distance, for several different values of the energy. Compton scattering and photoproduction, as well as redshift effects, have been included. It is evidently highly unlikely that the highest energy cosmic ray events can be due to protons from MCG 8-11-11, and even more unlikely that two high energy protons could penetrate such distances or originate from 3C 147.

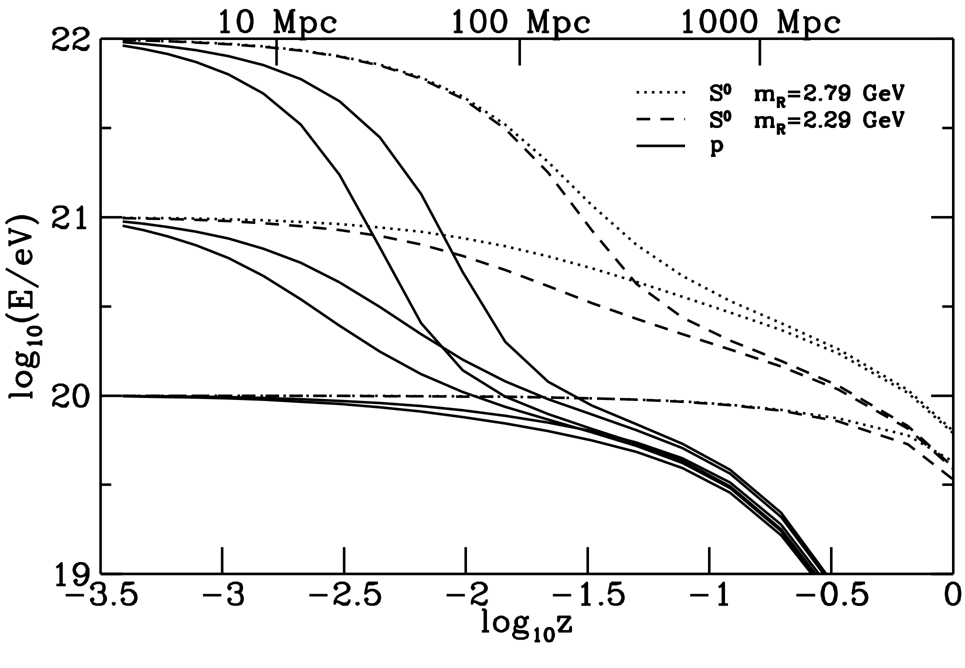
It is also unlikely that the UHECR primaries are photons. First of all, photons of these energies have a scattering length, 6.6 Mpc, comparable to that of protons when account is taken of scattering from radio as well as CMBR photons[24]. Secondly, the atmospheric showers appear to be hadronic rather than electromagnetic. The UHECRs observed via extensive air shower detectors have large muon content and Ref. [26] compared the shower development expected from a photon primary to that observed for the Fly's Eye event and concluded that the two are not compatible.

However the ground-state R-baryon, the flavor singlet scalar $uds\tilde{g}$ bound state denoted S^0, could explain these ultra-high-energy events[6]. On account of the very strong hyperfine attraction among the quarks in the flavor-singlet channel[27], the S^0 mass is about 210 ± 20 MeV lower than that of the lightest R-nucleons. As long as $m(S^0)$ is less than $m(p) + m(R^0)$, the S^0 must decay to a photino rather than R^0. It would have an extremely long lifetime since its decay requires a flavor-changing-neutral-weak transition. The S^0 could even be stable, if $m(S^0) - m(p) - m(e^-) < m_{\tilde{\gamma}}$ and baryon number is conserved[6].

If the S^0 lifetime is longer than $\sim 10^5$ sec,[4] it is a good candidate to be the UHECR primary[6, 25]. The GZK bound for the S^0 is several times higher than for protons. Three effects contribute to this: (a) The S^0 is neutral, so its interactions with photons cancel at leading order and are only present due to inhomogeneities in its quark substructure. (b) The S^0 is heavier than the proton. (c) The mass splitting between the S^0 and the lowest lying resonances which can be reached in a γS^0 collision (mass $\equiv M^*$) is larger than the proton-$\Delta(1230)$ splitting.

The threshold energy for exciting the resonances in γS^0 collisions is larger than in γp collisions by the factor[6] $\frac{m_{S^0}}{m_p}\frac{(M^*-M_{S^0})}{(1230-940)\mathrm{MeV}}$. We can estimate M_{S^0} and $M^* - M_{S^0}$ as follows. Taking $m(R^0) = 1.3 - 2.2$ GeV, $m_{\tilde{\gamma}}$ must lie in the range $\sim 0.9 - 1.7$

[4]This is the proper time required for a few 10^{20} GeV particle of mass ~ 2 GeV to travel ~ 100 Mpc.



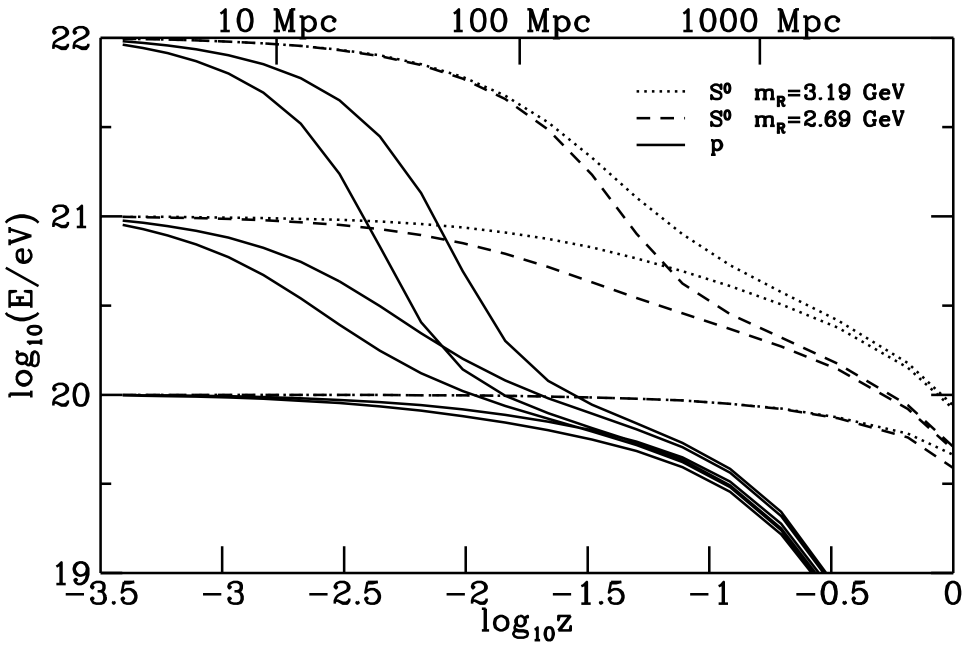


Figure 3: The figures show the primary particle's energy as it would be observed on Earth today if it were injected with various energies ($10^{22}eV$ eV, 10^{21} eV, and 10^{20} eV) at various redshifts. The distances correspond to luminosity distances. The mass of S^0 is 1.9GeV in the upper plot while it is 2.3GeV in the lower plot. Here, the Hubble constant has been set to 50 km sec^{-1} Mpc^{-1}.

GeV if photinos account for the relic dark matter. In order that the S^0 be stable or very long lived we require $m_{S^0} \lesssim m_p + m_{\tilde{\gamma}}$. On the other hand, the S^0 is unlikely to be lighter than $m_{\tilde{g}} + m(\Lambda(1405)) \approx 1.5$ GeV, assuming the cryptoexotic baryon $udsg$ is either the $\Lambda(1405)$ as conjectured in [6], or heavier. This leads to the favored mass range $1.5 \lesssim m(S^0) \lesssim 2.6$ GeV. Since the photon couples as a flavor octet, the resonances excited in $S^0\gamma$ collisions are flavor octets. Since the S^0 has spin-0, only a spin-1 R_Λ or R_Σ can be produced without an angular momentum barrier. There are two R-baryon flavor octets with $J = 1$, one with total quark spin 3/2 and the other with total quark spin 1/2, like the S^0. Neglecting the mixing between these states which is small, their masses are about 385-460 and 815-890 MeV heavier than the S^0, respectively[27]. Thus one qualitatively expects that the GZK bound is a factor of 2.7 - 7.5 higher for S^0's than for p's, depending on which R-hyperons are strongly coupled to the γS^0 system. A more detailed calculation of S^0 scattering on microwave photons can be found in [25]. The results for a typical choice of parameters are shown in Fig. 3, confirming the crude treatment given above following ref. [6].

As the above discussion makes clear, any stable hadron with mass larger than a few times the proton mass will avoid the problem of the GZK bound. However as pointed out in [25], there is also an upper bound on the allowed mass. This comes about because the fractional energy loss per collision with atmospheric nuclei is of order m_p/m_U, where m_U is the mass of the UHECR primary. If the energy loss per collision is too small, the shower development will not resemble that of a nucleon. Detailed Monte Carlo simulation is necessary to pin down the maximum acceptable mass[28], but it seems unlikely to exceed tens of GeV. Therefore new heavy colored particles predicted in many extensions of the standard model, whose masses are $\gtrsim 100$ GeV, could not be the UHECR primaries even if they were not excluded on other grounds. It is quite non-trivial that the mass of the S^0 in the all-gauginos-light scenario fortuitously falls in the rather narrow range required to explain the UHECR's.

The question of production/acceleration of UHECR's is a difficult one, even if the UHECR primary could be a proton. The mechanisms which have been considered are reviewed in ref. [29]. I merely note here that most of the mechanisms proposed for protons have variants which work for S^0's. Indirect production via decay of defects or long-lived relics of the big bang proceeds by production of extremely high energy quarks (or gluinos). Since all baryons and R-baryons eventually decay to protons and

S^0's respectively, the relative probability that a quark or gluino fragments into an S^0 compared to a p can be expected to be of order $10^{-1}-10^{-2}$. This estimate incorporates the difficulty of forming hadrons with increasingly large numbers of constituents, as reflected in the baryon to meson ratio in quark fragmentation which is typically of order 1:10. To be conservative, an additional possible suppression is included because the typical mass of R-baryons is greater than that of baryons.

Mechanisms which accelerate protons also generate high energy S^0's, via the production of R_p's ($uud\tilde{g}$ bound states) in pp collisions[25]. In fact, a problem with most acceleration mechanisms which is overcome here is that astrophysical accelerators capable of producing ultra high energy protons have such high densities that the protons are unlikely to escape without colliding and losing energy. In the scenario at hand, this high pp collision rate is actually advantageous for producing R_p's. These R_p's decay to $S^0\pi^+$ via a weak interaction, with lifetime estimated to be $2\ 10^{-11} - 2\ 10^{-10}$ sec[6]. The S^0 cross section is likely to be smaller than that of a nucleon by up to a factor of 10[6]; if so, the S^0's escape without further energy loss.

Laboratory experiments can be used to get upper bounds on the production of R_p's, which may be helpful in deciding whether this S^0 production mechanism is plausible. The E761 collaboration at Fermilab searched for evidence of $R_p \to S^0\pi^+$[30]. Their result is shown in Fig. 4. If the lifetime of the R_p is of order nanoseconds, these limits would make it difficult to produce sufficient high energy S^0's via R_p's. But for a lifetime of order $2\ 10^{-1} - 2\ 10^{-2}$ ns as estimated in [6], the E761 limits are too weak to be a constraint. As detailed in [11], a second generation experiment of this type would be very valuable.

Finally, I note that the predicted time-dilated lifetime of a $\sim 3\ 10^{20}$ eV R_p, is of order seconds – a characteristic timescale for Gamma Ray Bursts. Mechanisms for producing ultra high energy protons in GRB's would translate to the production of R_p's[31].

With the much larger sample of ultra-high-energy cosmic rays expected from HiRes and hopefully the Auger Project, the prediction of a GZK cutoff shifted to higher energy can be tested. The S^0's are not deflected by magnetic fields so they should accurately point to their sources[5]. That means UHECR's should cluster about certain directions in the sky, if S^0's are the primaries and the sources are not intermittant.

[5]Since the S^0 is a neutral spin-0 particles, even its magnetic dipole moment vanishes.

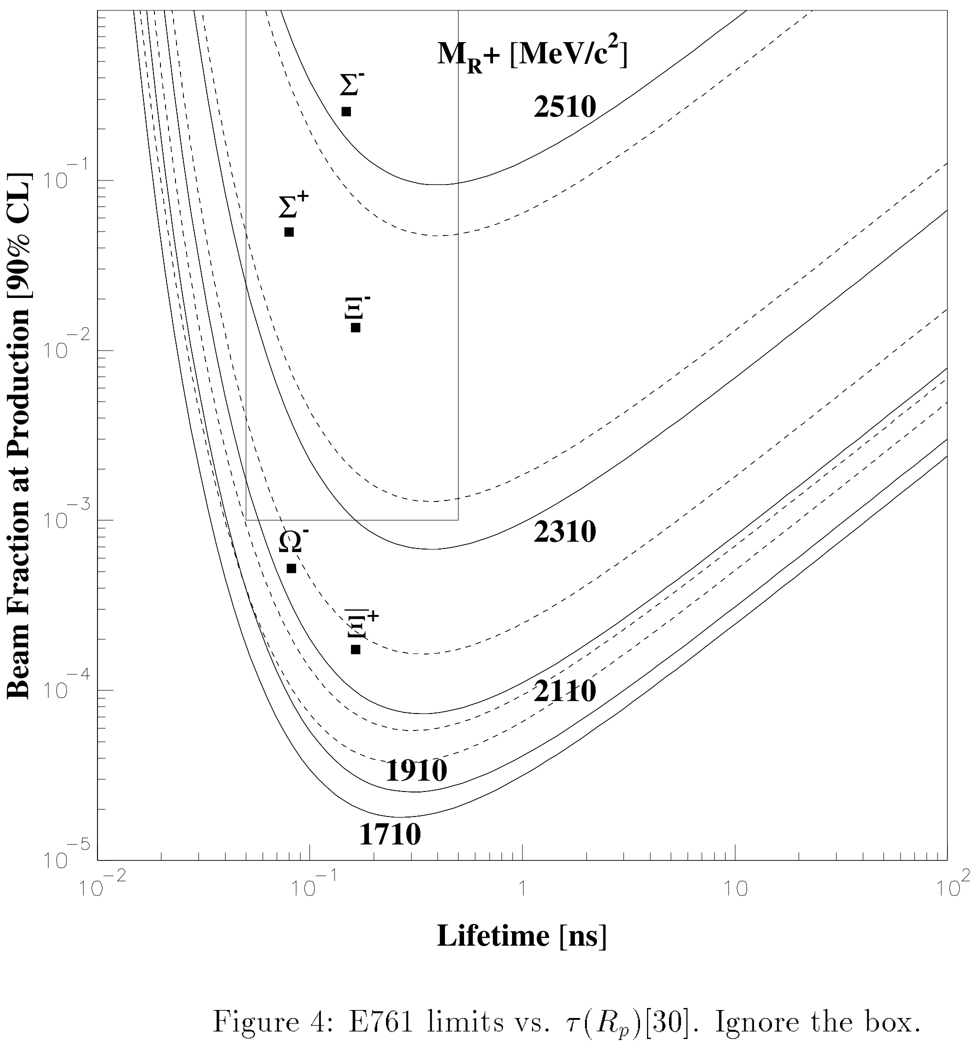


Figure 4: E761 limits vs. $\tau(R_p)$[30]. Ignore the box.

Summary

• Light photinos can account for the relic dark matter, if the R^0 (glueballino) mass is between 1.3 and 1.55 times the photino mass. This is consistent with the predicted mass ranges and present experimental constraints.
• If dark matter is due to relic photinos, one can expect $10^{-3} - 10$ interactions per kg per day in a WIMP detector. However since the photino mass is of order 1 GeV in this scenario, they will not deposit significant energy in detectors based on heavy nuclei.
• The cosmic ray events whose energy is above the GZK bound may be due to the lightest gluino-containing baryon, a $uds\tilde{g}$ bound state called the S^0. A cutoff in the spectrum at a somewhat higher energy is predicted, as is sharp pointing to the sources.
• Three new laboratory searches are described. At present their sensitivity is insufficient to test this picture, but that should change in a year or two.

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