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# Search for Light Gluinos via the Spontaneous Appearance of $\pi^+\pi^-$ Pairs with an 800 GeV/c Proton Beam at Fermilab

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We searched for the appearance of $\pi^+\pi^-$ pairs with invariant mass ≥648 MeV/c$^2$ in a neutral beam. Such an observation could signify the decay of a long-lived light neutral particle. We find no evidence for this decay. Our null result severely constrains the existence of an $R^0$ hadron, which is the lightest bound state of a gluon and a light gluino ($g\tilde{g}$), and thereby also the possibility of a light gluino. Depending on the photino mass, we exclude the $R^0$ in the mass and lifetime ranges of 1.2 – 4.6 GeV/c$^2$ and $2 \times 10^{-10}$–$7 \times 10^{-4}$ s, respectively.

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This Letter is motivated by recent discussions [1] of the possible existence of long-lived hadrons that contain light gluinos. In some theories where the breaking of supersymmetry is communicated to ordinary particles by the exchange of very heavy states, gauginos have small tree-level masses and are light compared to the squarks. The gluino($\tilde{g}$) and photino($\tilde{\gamma}$) masses are expected to be $\lesssim 1.0$ GeV/c$^2$. The gluons ($g$), gluinos, and quarks can form bound states, the lightest of which is a spin-1/2 $g\tilde{g}$ combination called the $R^0$. The approximate degeneracy of $R^0$ with the $0^{++}$ gluonia [1] suggests that the $R^0$ mass could be of the order of 1.3–2.2 GeV/c$^2$. The stable photino in this theory is a cold dark matter candidate [2]. Estimates from particle physics [1] and cosmology [2] place the $R^0$ lifetime in the $10^{-10}$–$10^{-5}$ s range. The $R^0$ decays into a $\tilde{\gamma}$ and hadrons. Because of the approximate $C$ invariance of supersymmetric QCD, the $R^0$ decay into $\rho\tilde{\gamma}$ is expected to be the dominant decay mode [1]; depending on the extent of $C$ violation, the $R^0$ may also decay into $\pi^0\tilde{\gamma}$ or $\eta\tilde{\gamma}$. The existence of a light gluino can have an impact on the running of the strong coupling constant $\alpha_s$. A phenomenological analysis of the perturbative running of $\alpha_s$ [3], in conjunction with the multijet analysis at LEP [4] has claimed an indirect exclusion of the light gluino scenario. However, a debate over the extent of this exclusion [5] underlines the necessity of a direct search for hadrons containing light gluinos.

The $R^0$'s can be produced in $pN$ collisions by processes such as quark-antiquark annihilation, gluon fusion, etc. Since squarks need not be involved, the $R^0$ production is in the realm of conventional QCD. Dawson, Eichten, and

Quigg [6] have calculated cross sections for gluino production in tree approximation. Their calculations suggest an order-of-magnitude cross section estimate [7] of $\sim 10$ $\mu$b per nucleon for the production of an $R^0$ with 2 GeV/c$^2$ mass in 800 GeV/c $pN$ collisions. This cross section corresponds to $\sim 10^{-3}$ $R^0$ to $K_L$ flux ratio in our experiment, as explained later. Assuming a $10^{-8}$ s lifetime and a 100% branching ratio for the decay of this $R^0$ into $\tilde{\gamma}\rho$, $\rho \to \pi^+\pi^-$, the KTeV experiment [8] has a per spill sensitivity of approximately $10^{-4}$ in terms of the $R^0$ to $K_L$ flux ratio with $3.5\times10^{12}$ 800 GeV/c protons delivered in a nominal spill. The results presented here are from the delivery of $1.9\times10^{15}$ protons.

In the KTeV experiment (figure 1), protons are incident on a 30 cm long beryllium oxide target at a vertical angle of 4.8 mr with respect to the neutral beam channel. The interaction products are filtered through a 50.8 cm beryllium absorber and a 7.6 cm lead absorber. Two neutral beams, each 0.25 $\mu$str in solid angle, emerge after collimation and sweeping. One of the beams passes through an active regenerator, but the decays from this beam are not used in this analysis. The beam transport and decays took place in an evacuated region with a vacuum of 0.5–$1.0\times10^{-4}$ torr.

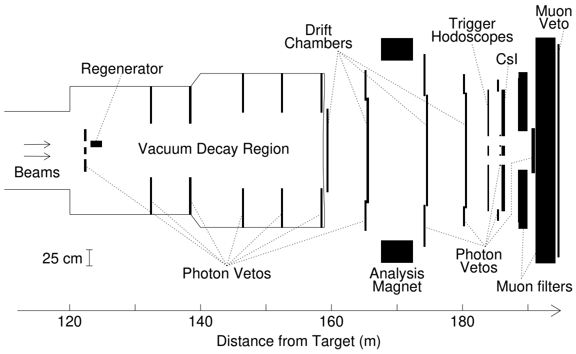


FIG. 1. KTeV detector configuration for this measurement. Note the highly compressed scale along the beam direction.

The most crucial detector element for this analysis, the charged spectrometer, consists of four planar drift chambers, two on either side of an analyzing magnet. Each chamber measures positions in two orthogonal views. Each view consists of two planes of wires, with cells arranged in a hexagonal geometry. Each chamber has approximately 100 $\mu$m single-hit position resolution per plane. The spectrometer magnet has a 2 m by 1.7 m fiducial region over which a transverse momentum impulse of 411 MeV/c is imparted to the charged particles. A set of helium bags integrated into the spectrometer system minimizes multiple scattering. The invariant mass resolution for the decay $K_L \to \pi^+\pi^-$ is better than 2 MeV/c$^2$.

A pure CsI electromagnetic calorimeter of dimension 1.9 m by 1.9 m is used to reconstruct photon and electron energies to better than 1% precision. The calorimeter is used to match the orthogonal track views and to reject background from $K_{e3}$ decays. A set of 12 photon vetos provides hermetic photon coverage up to angles of 100 mr. A counter bank (muon veto) located at the downstream end of the detector is used to reject $K_{\mu3}$ decays. The event trigger is initiated by signals from two scintillator hodoscopes located downstream of the spectrometer. The primary trigger requires two hits in these counters consistent with two oppositely charged tracks, at least one hit in each of the two upstream drift chambers, and lack of hits in the muon veto bank. Next, a set of fast trigger processors requires two straight tracks in the non-bend view from two hits in each drift chamber.

A combination of online and offline cuts in the $\pi^+\pi^-$ analysis required two oppositely charged tracks matched to clusters in the calorimeter to within 4.6 cm. Individual track momenta were required to be more than 8 GeV/c, and the scalar sum of two track momenta was required to be between 30 GeV/c and 160 GeV/c. A longitudinal vertex position between 126 m and 155 m downstream of the target defined the fiducial region. Electrons were rejected by requiring the energy deposited in the calorimeter to be less than 80% of the particle momentum, as measured in the spectrometer. The signals in various veto devices were required to be no more than those due to accidental activity. The two tracks were required to project within the active fiducial area of the muon banks. After making all other cuts, the momentum ratio of the two tracks was required to be between 0.2 and 5, which curtailed the high-side tail of the $\pi^+\pi^-$ mass distribution by moving its end point from $\sim$640 MeV/c$^2$ to $\sim$600 MeV/c$^2$. Figure 2 shows the $m_{\pi^+\pi^-}$ distribution for the events surviving all cuts. Note the peak corresponding to the $K_L \to \pi^+\pi^-$ candidates and the rapidly falling background to the right of the kaon peak. The figure also shows the $m_{\pi^+\pi^-}$ distribution for an $R^0$ with mass $m_{R^0}$=1.75 GeV/c$^2$ and photino mass $m_{\tilde{\gamma}}$=0.8 GeV/c$^2$. There are no $R^0$ candidates in the signal window between 648 MeV/c$^2$ (i.e. 150 MeV/c$^2$ above the kaon mass) and 1.0 GeV/c$^2$. For the simulated $R^0$ shown, 91% of the decays are contained in the signal window.

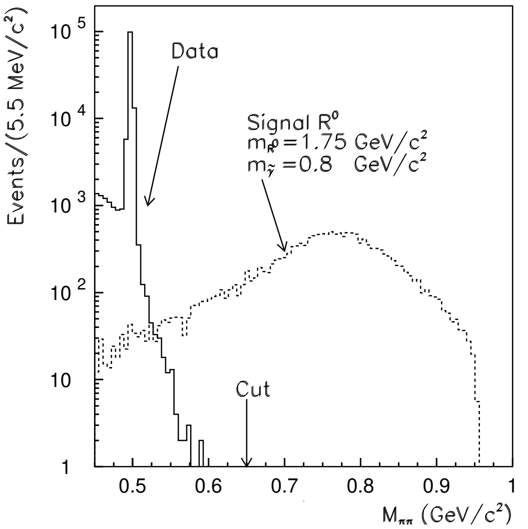


FIG. 2. $m_{\pi^+\pi^-}$ distribution for the data (solid) and $R^0$ signal Monte Carlo (dashed, arbitrary scale). The peak at 500 MeV/c$^2$ corresponds to $K_L \to \pi^+\pi^-$ decays. The sharp cutoff at 0.95 GeV/c$^2$ ($=m_{R^0} - m_{\tilde\gamma}$) is due to the kinematic limit for the $R^0$ shown.

The absence of signal in the data can be expressed in terms of upper limits on the $R^0$ flux. We define the $R^0/K_L$ flux ratio to be the ratio of the number of $R^0$'s to the number of $K_L$'s exiting the beam absorbers, calculated with the assumptions that the $R^0 \to \tilde\gamma\rho$, $\rho \to \pi^+\pi^-$branching ratio is 100% and that the photino does not interact significantly in the detector material. For the $R^0$ spectrum shape, we use the invariant cross section for $\Lambda$ production in $pBe$ interactions [9]. We make this choice because the $R^0$ mass is in the proximity of the $\Lambda$-$\Xi^0$-$D^0$ mass range. For our experiment, the function $(1-x_F)^a \exp(-bp_\perp^2)$ with $a = 1.0$ and $b = 2.3(\mathrm{GeV/c})^{-2}$ is a good approximation for the cross section shapes given in [9] for both $\Lambda$ and $\Xi^0$. The limits are not very sensitive to the spectrum shape; if we use the values $a = 6.1$ and $b = 1.08(\mathrm{GeV/c})^{-2}$ which are applicable to $D^0$ production [10], the limits change by $\sim$5-10% for $R^0$ lifetime of $10^{-8}$ s.

The $K_L$ flux was determined using a total of 116,552 $K_L \to \pi^+\pi^-$ candidates with two-body transverse momentum squared ($p_t^2$) less than 250 MeV$^2/c^2$ and $m_{\pi^+\pi^-}$ within 10 MeV/c$^2$ of the $K_L$ mass. The detector acceptance for the $K_L \to \pi^+\pi^-$ decays was calculated using a Monte Carlo simulation of the beam and the detector. We calculate a

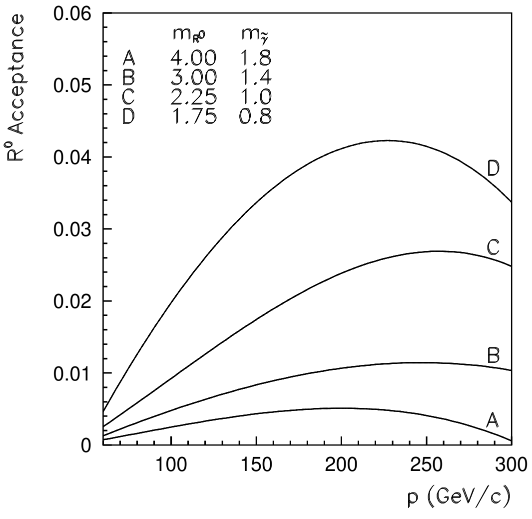


FIG. 3. Geometrical acceptance of the detector in the fiducial region for various $R^0$ masses as a function of the $R^0$ momentum. $m_{R^0}$ and $m_{\tilde\gamma}$ are in GeV/c$^2$. ($R^0$ lifetime = $10^{-8}$s)

total of $1.33 \times 10^{10}$ $K_L$'s of all energies exiting the absorbers. To calculate the detector acceptance for $R^0$'s, the $R^0 \to \tilde{\gamma}\rho$, $\rho \to \pi^+\pi^-$decays were simulated for various values of $m_{R^0}$ and $m_{\tilde{\gamma}}$ assuming isotropic angular distributions of the decay products in the center of mass frame. Figure 3 shows the geometric acceptance of the detector in the fiducial region for various $R^0$ masses as a function of the $R^0$ momentum. Figure 4 shows the 90% confidence level upper limits on the $R^0/K_L$ flux ratio as a function of $m_{R^0}$ with a $10^{-8}$ s $R^0$ lifetime for two values of the mass ratio $r = m_{R^0}/m_{\tilde{\gamma}}$. The sharp loss of sensitivity for small $m_{R^0}$ for a given $r$ is because an $R^0$ with mass less than $0.648r/(r-1)$ GeV/c$^2$ can not produce a $\tilde{\gamma}$ with mass $m_{R^0}/r$ together with a $\pi^+\pi^-$ pair having invariant mass greater than 648 MeV/c$^2$.

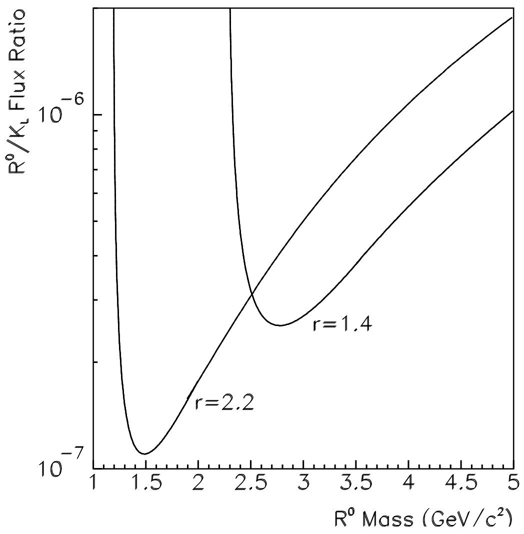


FIG. 4. Upper limits with 90% confidence level on the $R^0/K_L$ flux ratio as a function of $R^0$ mass for two different values of the $R^0$-photino mass ratio $r$. ($R^0$ lifetime $= 10^{-8}$s)

Figure 5 shows the upper limits on $R^0/K_L$ flux ratio as a function of $R^0$ lifetime with different masses for the same $r$(=2.2). Figure 6 shows the 90% confidence level upper limit contours for various $R^0$ masses and lifetimes. These upper limits can also be expressed in terms of limits on the invariant cross section $Ed^3\sigma/dp^3$ times the branching ratio using the conversion factor of $2.1 \times 10^{-36}$cm$^2$/(GeV$^2$/c$^3$) at $x_F = 0.2$ per $1 \times 10^{-7}$ $R^0/K_L$ flux ratio .

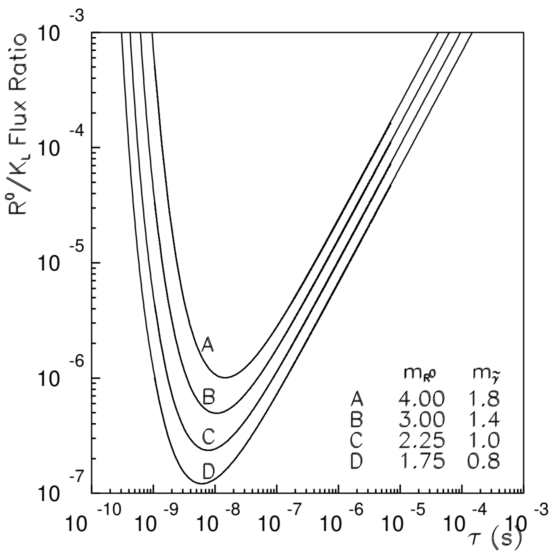


FIG. 5. Upper limits with 90% confidence level on the $R^0/K_L$ flux ratio as a function of $R^0$ lifetime. $m_{R^0}$ and $m_{\tilde{\gamma}}$ are in GeV/c$^2$.($r$=2.2)

Our limits are a significant improvement over the previous (indirect) search by Bernstein *et al.* [11]. Note that this conversion factor and the upper limit on $Ed^3\sigma/dp^3$ reported by Bernstein *et al.* do not take into account the $R^0$ absorption in the target and absorbers. The $R^0N$ cross section is expected [1,12] to be in the range 1/10 to 1 times the $NN$ cross section, which places the $R^0$ absorption factor in the 1.3 to 10.2 range.

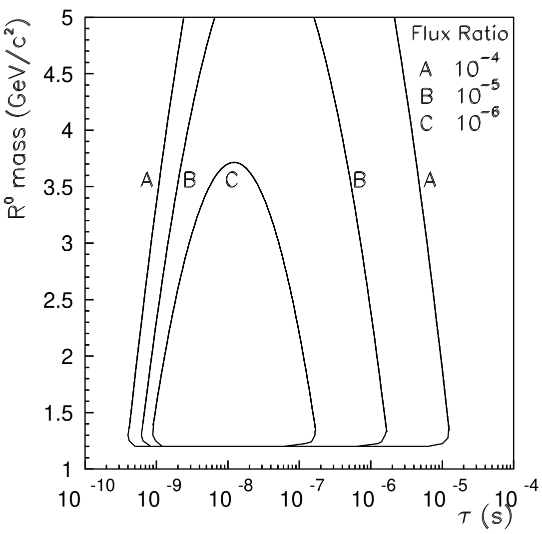


FIG. 6. Upper limits with 90% confidence level on the $R^0/K_L$ flux ratio for various $R^0$ masses and lifetimes.($r$ =2.2)

The upper limits on the $R^0/K_L$ flux ratio constrain the light gluino scenario assuming a specific model for the $R^0$ production. The perturbative QCD calculations [6,7] suggest $\sigma(R^0) \simeq 860e^{-2.2m_{R^0}}$ $\mu$b in 800 GeV/c $pN$ collisions, where $m_{R^0}$ is in the units of GeV/c$^2$. This estimate is approximately consistent with the heavy flavor production cross sections. For our experiment, this $\sigma(R^0)$ implies that the $R^0/K_L$ flux ratio for an $R^0$ of mass $m_{R^0}$ is expected to be $9.2 \times 10^{-2}e^{-2.2m_{R^0}}$, assuming a factor of 10.2 for the $R^0$ absorption. The mass-lifetime region for which this $R^0/K_L$ flux ratio expectation exceeds the measured upper limits is taken to be ruled out. For example, the expected $R^0/K_L$ flux ratio for an $R^0$ with 2 GeV/c$^2$ mass is $1.1 \times 10^{-3}$. Since this expectation exceeds our upper limits in the lifetime range of $3.4 \times 10^{-10}$ – $1.3 \times 10^{-4}$ s, we rule out $R^0$'s with 2 GeV/c$^2$ mass in this lifetime range with 90% confidence level. Figure 7 shows the excluded regions obtained in this fashion for two different values of the mass

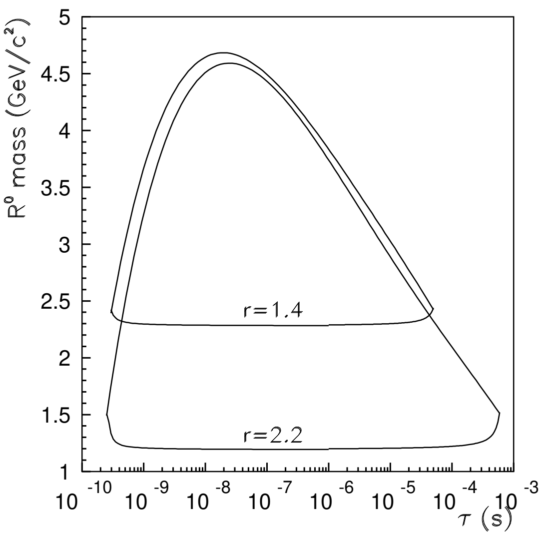


FIG. 7. $R^0$ mass-lifetime regions excluded by this analysis at 90% confidence level for two different values of the $R^0$-photino mass ratio $r$.

ratio $r$. Apart from the low mass cutoff for $m_{R^0} \lesssim 0.648r/(r-1)$ GeV/c$^2$, the contour shapes in figure 7 are fairly insensitive to the value of mass ratio $r$. The contours for the cosmologically interesting region correspond to $r \lesssim 1.8$ [2].

In summary, our search places stringent upper limits on the $R^0/K_L$ flux ratio . For example, the 90% confidence level upper limit on the $R^0/K_L$ flux ratio for an $R^0$ with mass 1.75 GeV/c$^2$, lifetime $6\times10^{-9}$ s, and mass ratio $r$=2.2 is $1.2\times10^{-7}$. As figure 7 shows, these stringent limits rule out the production of $R^0$ particle in a wide range of masses ($\sim$1.2 – 4.6 GeV/c$^2$) and lifetimes ($\sim 3\times10^{-10} - 7\times10^{-4}$ s). A search [13] for light supersymmetric *baryons* ($uud\tilde{g}$ and $uds\tilde{g}$) in the mass range 1.7–2.5 GeV/c$^2$ has also reported null results.

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