Search for Supermassive Relics with a 2000-m^2 Array of Plastic Track Detectors

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A direct search has been made for supermassive relics (heavier than about 10^{12} GeV/c^2) with a 2000-m^2 array of CR-39 track-etch detectors deployed underground for 2.1 yr. The nonobservation of penetrating tracks places a new upper limit for the velocity-dependent flux at 3.2×10^{-16} cm^{-2}s^{-1}sr^{-1}, for magnetic monopoles carrying various magnetic charges, for electrically charged relics, and for strange matter. This flux limit corresponds to a limit on the relic abundance of order $n_x/n_\gamma = 10^{-29}$ relative to the 3-K photons.

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Recently the existence of various kinds of supermassive stable particles has been conjectured: Supermassive magnetic monopoles are generically predicted[1] by grand unified theories, Kaluza-Klein theories, and superstring theories. A large number of the grand unified theories and superstring theories predict[2] the existence of monopoles with multiple Dirac magnetic charges. Superstring theories[3] and composite theories of leptons and quarks[4] speculate on the existence of fractionally or integrally charged supermassive particles, which might not be totally confined. Higher-dimensional theories contain[5] supermassive (of the order of the Planck mass) stable particles named "pyrgon," which may be charged. If there exists a new conserved quantum number, the lightest particles carrying it must be stable. A quark matter which is absolutely stable (strange matter) has been proposed[6] as the ground state of nuclear matter. If such particles exist, they should have been created in the very early Universe and might have survived to today as the supermassive relics of the big bang. They might have participated in galaxy formation and may be trapped in the clusters of galaxies and in the galaxies with typical virial β ($\equiv v/c$) of 3×10^{-3} and 10^{-3}, respectively. Such supermassive particles might constitute the dark mass of the galaxies and of the Universe. The existence of magnetic field in the galaxies can be used to deduce[7] an upper limit for the flux of magnetic monopoles of order 10^{-15} cm^{-2}s^{-1}sr^{-1} (Parker bound) at $\beta\sim10^{-3}$. However, possibilities of local enhancement have been considered[8] for the flux trapped in the solar system with an expected typical β of 10^{-4}.

With the aim of searching for an extremely low abundance of order $n_x/n_\gamma = 10^{-30}$ relative to the 3-K photons, we are conducting a search for penetrating tracks using a total of 3500 m^2 of CR-39 plastic track detectors. The results from an 80-m^2 array[9] in a mine and from a 160-m^2 array[10] at a mountain altitude have been reported elsewhere. In this paper, we report on an analysis of a 2000-m^2 array placed at underground sites.

The principle[11] of finding tracks in a plastic track-etch detector is as follows. The passing particle leaves a trail of localized damage (latent trail) in the form of broken chemical bonds. This trail is more vulnerable to a chemical attack than the bulk of the plastic. By chemically etching the plastic, visible etch cones are developed along the latent trail on each surface of the sheet with a half cone angle $\phi = \arcsin(V_B/V_T)$, where V_B is the bulk etch rate of the plastic and V_T is the etch rate along the track. The sensitivity $S \equiv V_T/V_B$ is an increasing function of the amount of locally deposited energy and depends also on the characteristics of the plastic and the etching condition. If the sensitivity S is high enough, a heavy etching[12] can make the two etch cones on both surfaces link and form an etch hole, which can be detected by means of a rapid scanning technique described below. The condition necessary to produce the etch hole depends on the S of the track and its zenith angle θ_c and is given by[12]

$$\cos\theta_c \geq S^{-1}D/(D-d)\,, \qquad (1)$$

where D and d are the thickness of the CR-39 before and after etching. To eliminate accidental background holes, coincident holes on multiple layers are required for a track candidate.

The CR-39 was manufactured by Sola Optical Japan Ltd. using the monomer supplied by PPG (Pacific) Industry in Japan. The monomer was cured for 21 h with 3% IPP (di-isopropyl peroxydicarbonate) initiator and 0.01% antioxidant, Naugard 445. The characteristics of this CR-39 have been described elsewhere.[12,13]

The experimental sites were three caverns with a depth of 10^4 g cm^{-2} at the Ohya stone quarries located 100 km north of Tokyo. The detector array was composed of 8000 unit modules. Each module consisted[13] of four layers of CR-39 plastic plates each with an area of 560 mm × 545 mm and 1.59 ± 0.03 mm in thickness.

Each layer was separately brought to the experimental site and firmly fixed to the others by small pieces of double-adhesive tape with 2.0-mm spacing between the layers. The stack was then packed at 1 atm of air in a laminated bag made of polymer sheets and aluminum foil, which is light shielding and airtight. Exposure of the detector modules started between September 1986 and May 1987, and ended between December 1987 and February 1990 with an average exposure time of 2.1 yr. The detector modules were oriented horizontally on the floor. The temperature of the sites was between 2 and 15 °C throughout the year.

After the exposure, the detector modules were collected and twelve small holes were drilled through to provide the position references. The modules were decomposed into four layers at the underground sites and the first two layers were then separately brought out to the etching facilities.[14] The etching was carried out[13] at 90 °C in a sodium hydroxide solution of 10 mol/liter. For 19% of the modules, one or two of the first two layers were overetched or broken in the handling. For such modules, the corresponding third and/or fourth layers were etched. The final thickness (d) for these samples was 0.41 ± 0.08 mm (rms), corresponding to a removed thickness of 1.18 mm. The etch holes in the CR-39 sheets were then searched for using a rapid scanning system.[10,15] With this system, etch holes with a diameter greater than 20 μm can be detected with 100% efficiency. The overall position resolution is 1.0 mm rms. The distance between a pair of holes in the corresponding two layers was then measured for every combination. Figure 1(a) shows the distribution of the distances obtained from an analysis of 7327 pairs of CR-39 sheets. This distribution is consistent with the ones expected for random coincidences and shows no significant accumulation of events at short distances. The distance distribution expected for an isotropic flux of penetrating tracks is shown in the figure for various sensitivities. We note that at least 96% of the detected penetrating tracks should have a distance shorter than 10 mm.

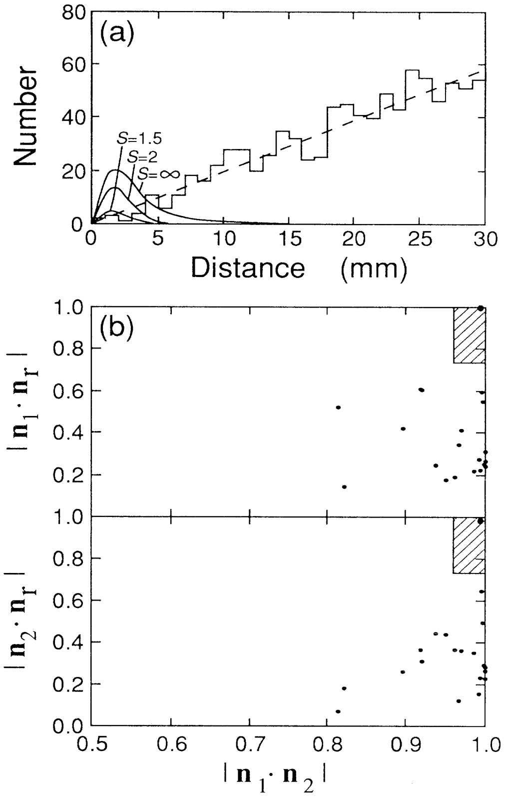

FIG. 1. (a) Distribution of the distances between pairs of holes detected in two corresponding layers. The curves show the distribution (in an arbitrary vertical scale) expected for an isotropic flux of relics for various sensitivities S. The dashed line shows the expected distribution due to random coincidences. (b) Correlations $|\mathbf{n}_1\cdot\mathbf{n}_2|$ vs $|\mathbf{n}_1\cdot\mathbf{n}_r|$ and $|\mathbf{n}_1\cdot\mathbf{n}_2|$ vs $|\mathbf{n}_2\cdot\mathbf{n}_r|$ for the twenty pairs of holes which have a distance shorter than 10 mm after the rejection of background holes having irregular shapes. Shaded areas indicate the regions in which 90% of the true track events should fall.

For the 94 pairs of holes which have a distance shorter than 10 mm, we closely examined the shape of the holes under the microscope. 74 pairs can be safely rejected as consisting of background hole(s) having irregular shapes. By use of Bevalac beams we checked that the penetrating tracks always produced holes with clear circular or elliptical shape. These irregular holes can be explained[12] as due to the intrinsic defects of CR-39 plates. For each of the remaining twenty pairs, which consist of circular or elliptical holes, we checked if the shapes and hole positions were consistent with being due to a single penetrating track. For this purpose, the unit vectors of the track directions were calculated for each pair of holes by three independent methods: Two unit vectors $\mathbf{n}_1$ and $\mathbf{n}_2$ are calculated from the shapes (major and minor axes of the apparent ellipse) of the holes of the first and the second layers, respectively. A unit vector $\mathbf{n}_r$ is derived from the relative position of the two holes. A single penetrating track should satisfy the condition $|\mathbf{n}_1\cdot\mathbf{n}_2| \sim |\mathbf{n}_1\cdot\mathbf{n}_r| \sim |\mathbf{n}_2\cdot\mathbf{n}_r| \sim 1$. Figure 1(b) shows the correlations $|\mathbf{n}_1\cdot\mathbf{n}_2|$ vs $|\mathbf{n}_1\cdot\mathbf{n}_r|$ and $|\mathbf{n}_1\cdot\mathbf{n}_2|$ vs $|\mathbf{n}_2\cdot\mathbf{n}_r|$ for the twenty pairs. Taking account of the accuracy of calculating $\mathbf{n}_1$, $\mathbf{n}_2$, and $\mathbf{n}_r$, we expect that 90% of the true track events should fall inside the shaded area shown in the figure. In fact, one event falls in the shaded regions. This event has an incident zenith angle of 7°. The final thicknesses of the first and the second layers of this event were 240 and 320 μm, respectively, both much thinner than the average final thickness. For this event, we searched for the corresponding etch holes of the track by etching the third and the fourth layers to final thicknesses of 320 and 400 μm, respectively. With close examination under the microscope, no hole was found in the third or fourth layer within a distance of 10 mm of the expected track position, which was determined by extrapolating the trajectory defined by the hole positions in the first two layers. From the shape of the tracks found in the first two layers, this event appears to be produced by a light nucleus stopped in the stack. The origin of this event is now under examination. The other 19 events observed at large $|\mathbf{n}_1\cdot\mathbf{n}_2|$ and small $|\mathbf{n}_1\cdot\mathbf{n}_r|$ and $|\mathbf{n}_2\cdot\mathbf{n}_r|$ are consistent with accidental coincidences of random short tracks, mostly normal-incident light nuclei such as helium. These light nuclei are likely to be fragments of air or CR-39 material produced[16] by cosmic-ray-induced neutrons incident when the CR-39 was at the surface before and after the exposure.

For the sake of redundancy, we performed an independent analysis which did not rely on the shape observation of the holes. For 84 out of the 94 pairs of holes mentioned above, at least one of the third or the fourth layer, on which we searched for etch holes at the expected track positions, remained intact after the etching. With close examination under the microscope, no hole was found within 5 mm of the expected track position.

Thus we have no candidate for a penetrating track in the four layers of CR-39. To obtain an upper limit on the flux, the sensitivity of CR-39 has to be evaluated as a function of velocity for each type of relic. The response of CR-39 to highly ionizing charged particles has been measured in the velocity region $\beta \geq 10^{-2}$, where the energy loss is dominated by that due to recoiling electrons and the sensitivity can be well described as a function of the restricted energy loss (REL),[17] which is defined as the localized part of the energy loss deposited close to the particle path. For the lower velocity region, $10^{-4} < \beta < 10^{-2}$, it has been shown by Price[18] that the elastic recoil of atoms significantly contributes to the track formation and that the sensitivity for heavily ionizing particles can be expressed by the same function of REL as at higher β. We assume that the sensitivities for magnetic monopoles and strange matter are also expressed by the same function of REL. The RELs were calculated at $\beta \gg 10^{-2}$ according to Refs. 19 and 20 for magnetic monopoles and for electrically charged relics, respectively. For $\beta < 10^{-2}$, we calculated the REL of electrically charged relics following Refs. 21 and 22 for the contribution from recoiling electrons and from recoiling atoms, respectively. For the REL of magnetic monopoles at $\beta < 10^{-2}$, we follow Ahlen and Kinoshita[23] for the energy loss as a conservative lower limit. At $\beta \sim 10^{-3}$, where the effect of the energy gap becomes significant, we took this effect into account following Ritson,[24] choosing 4 eV (Ref. 25) as an effective energy gap of the chemical bonds of the plastic. For magnetic monopoles at $\beta \sim 10^{-4}$, the energy loss via elastically recoiling atoms was calculated[25] following Price[18] adopting the classical approximation. For strange matter, REL was calculated according to Ref. 26. The RELs of the magnetic monopoles and electrically charged relics are summarized in Fig. 2 as a function of velocity.

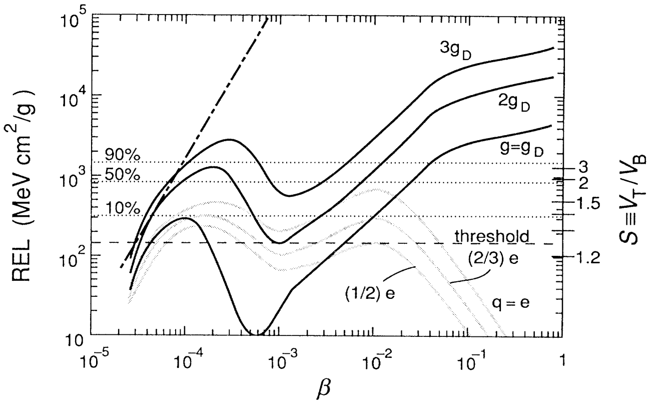

FIG. 2. The expected REL (restricted energy loss) and the sensitivity S of various supermassive relics as a function of β. The solid and the gray curves represent the REL of magnetic monopoles and of electrically charged relics, respectively. The dash-dotted line represents the minimum REL of strange matter. The horizontal dotted lines indicate the REL values corresponding to 10%, 50%, and 90% detection efficiency for isotropic flux. The horizontal dashed line indicates the minimum REL required to produce etch holes.

The sensitivity S of our CR-39 was determined as a function of REL by irradiating the samples with Bevalac ion beams and then etching simultaneously with the actual exposed sheets. The degradation of CR-39 sensitivi-

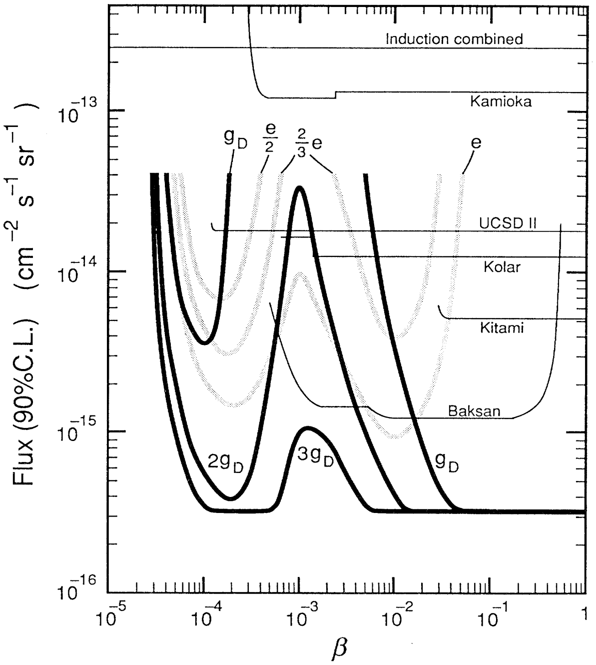

FIG. 3. Flux limits (90%-confidence level) on magnetic monopoles (solid curves) and on electrically charged relics (gray curves) as a function of β. The best limits by previous direct searches using different techniques are also shown for comparison (see Ref. 27).

ty (aging) and the fading of the latent tracks during the exposure were also measured by using the CR-39 samples irradiated by test beams and stored in the actual site.[12] The corrections to the sensitivity from these effects were -2% and -5% per year for aging and fading, respectively. To obtain the acceptance of the CR-39 array for an isotropic flux of supermassive relics, the effective solid angle was calculated using Eq. (1) for each value of REL.

Flux limits on the magnetic monopoles and on the electrically charged relics at the 90%-confidence level are shown in Fig. 3 assuming an isotropic flux. Also shown in Fig. 3 are the most stringent existing flux limits for magnetic monopoles from direct searches with different techniques.[27,28] For the magnetic monopoles with single Dirac charge, the present experiment places the most stringent limits for the flux at 3.7×10^{-15} and $3.2\times10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in the velocity range $4\times10^{-5}<\beta<2\times10^{-4}$ and $10^{-2}<\beta<1$, respectively. For the magnetic monopole carrying double and triple Dirac charge, we place the best limits for the flux at $3.2\times10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ in the velocity range $4\times10^{-5}<\beta<1$. It should be noted that the present search places a unique flux limit at $\beta\sim10^{-4}$, which is typical of that expected for the relics trapped in the solar system. For strange matter, the present experiment places an upper limit for the flux at $6.4\times10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ at the 90%-confidence level considering only the downward flux. We note that a flux of $3\times10^{-16}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ at $\beta=10^{-3}$ corresponds to a relic abundance n_X/n_γ of order 10^{-29} relative to the 3-K photons, assuming a galactic concentration factor of 4×10^4.[29]

For both magnetic monopoles and electrically charged relics, the minimum detectable mass is calculated to be 10^{10} GeV/c^2 for $\beta\sim10^{-3}$ and 10^{12} GeV/c^2 for $\beta\sim10^{-4}$, respectively. For strange matter, the calculated minimum mass is 10^{12} GeV/c^2 for β of 10^{-3}-10^{-4}. Our limit for the strange matter represents a 16-times improvement over the best limit of the previous direct search[28] in the mass range of 10^{12}-10^{15} GeV/c^2.

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