Searching for the Cosmion by Scattering in Si Detectors

D. O. Caldwell, B. Magnusson, and M. S. Witherell
Physics Department, University of California, Santa Barbara, California 93106

A. Da Silva and B. Sadoulet
Physics Department, University of California, Berkeley, California 94720

C. Cork, F. S. Goulding, D. A. Landis, N. W. Madden, R. H. Pehl, and A. R. Smith
Lawrence Berkeley Laboratory, Berkeley, California 94720

G. Gerbier, E. Lesquoy, J. Rich, M. Spiro, C. Tao, D. Yvon, and S. Zylberajch
Département de Physique des Particules Elémentaires, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette CEDEX, France
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A new particle, the cosmion, has been proposed to be the dark matter of the Universe and to explain the solar ν deficit by cooling the solar core to reduce ^{8}B ν production. Such cosmions in the galactic halo would scatter from nuclei in terrestrial detectors. Measurements were made in Si ionization detectors in a very-low-background environment down to energies of 1.1 keV. These results exclude nearly all of the mass range possible for cosmions with coherent nuclear interactions.

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Cosmions, weakly interacting massive particles (or WIMPs), have been proposed[1] to solve simultaneously the problem of dark matter, which makes up perhaps 90% of the mass of the Universe, and the deficit of ^{8}B neutrinos from the Sun. If they exist, they would also speed up the evolution of stars in globular clusters[2] and modify the sound speed near the solar center.[3] There is controversy over whether the cosmion hypothesis is compatible with observations, but these potentially important particles can be searched for directly. As the Earth moves through the pervading sea of dark matter, cosmions would scatter[4] from the nuclei of ionization detectors, giving a detectable signal if the energy threshold and backgrounds are sufficiently low. Ge detectors provide some limits[5] on cosmions, but Si detectors should have greater sensitivity.[6] The lighter nucleus gives a larger recoil energy, more of that energy goes into ionization, and Si detectors have lower energy thresholds. These advantages were such that a small quantity of unselected Si with relatively large backgrounds produced the very useful results reported here.

In this experiment an array of four planar Si detectors was mounted on a single-crystal Si cold finger (4 mm thick) to maintain the detectors near liquid-nitrogen temperature. The detectors and cold finger were enclosed in an electroformed Cu (0.25-mm wall thickness) vacuum cryostat evacuated with ion pumps. Each Li-drifted Si detector had a sensitive region with a diameter of 34 and 8-mm thickness, giving an active mass of 17 g. This array was mounted inside the cavity formed by ten blocks of NaI of 15-cm thickness initially used for a search for neutrinoless double-β decay[7] of ^{76}Ge. Two of the original eight germanium detectors remained in place. The NaI anticoincidence shield had a threshold of 30 keV and was in turn inside a very pure Pb shield of 20-cm thickness. The cold finger passed through a narrow slot in the shield, placing only detectors inside the shield in such a way that they had no line of sight to the outside. The whole apparatus was under an overburden of 600 m of water equivalent in the powerhouse of the Oroville, California dam.

The pulse heights and arrival times of signals from all the detectors were recorded and analyzed off-line. Data from only the one Si detector with the lowest threshold and background were used here. Its energy spectrum, calibrated against known photopeaks, is shown in Fig. 1. These data were filtered to eliminate events in the Si detectors coincident with counts in any other detector and events attributed to microphonics because bursts of two or more events occurred within 2 s. Complete records of about 2000 events were rejected whenever more than four burst rejections occurred in that record.

In Fig. 1 the Gaussian electronic noise ($\sigma = 0.22$ keV) gives an effective threshold of ~ 1.1 keV, which is about 3 times lower than obtained with Ge.[5] The background, however, is an order of magnitude higher than in the same mass of Ge, since no effort was made to obtain low-radioactivity Si. The background includes β-decay spectra from ^{3}H (18.6 keV, 12.3 yr), ^{32}Si (225 keV, 104 yr), and ^{210}Pb (63.1 keV, 22.3 yr). The ^{3}H is a spallation product which was produced in the Si when it was above ground and bombarded by cosmic rays. The presence of ^{32}Si at a rate of about 300 counts/kg day indicates that the Si was obtained from surface sand, since ^{32}Si is produced in the atmosphere (by cosmic rays interacting with Ar) and subsequently falls to the surface

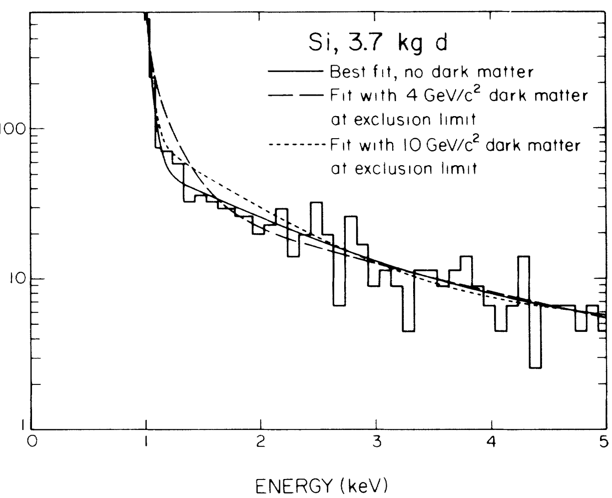

FIG. 1. Low-energy region of the ionization detected in a Si counter for 3.7 kgdays of data. Fits are shown with no dark matter and with addition of signals due to masses of 4 or 10 GeV/c^2 with cross sections on the exclusion contour of Fig. 2.

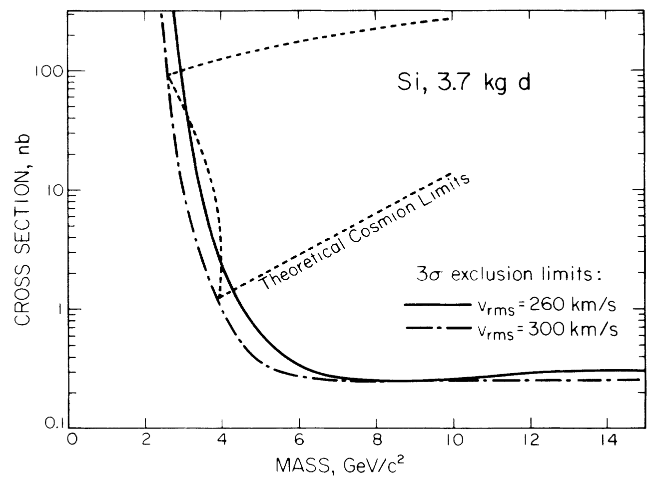

FIG. 2. Exclusion plots for two values of the velocity of dark-matter particles as functions of their mass and elastic cross section on Si. Coherently scattering cosmions are expected to lie within the dashed lines, if they are to solve the solar-neutrino problem.

of the Earth.

The measured energy spectrum has been compared to that expected from a dark-matter particle to set limits on that particle's mass M and cross section $d\sigma/dT$ on silicon. The expected spectrum of recoil energy T is

$$\frac{dN}{dT}=\frac{\rho}{M}\int \mathbf{v} f(\mathbf{v})\frac{d\sigma}{dT}d^3v\,, \qquad (1)$$

where ρ is the local halo density (0.3 GeV/c^2cm^3 or 5×10^{-25} g/cm^3), and $f(\mathbf{v})$ is the distribution of dark-matter velocities in the Earth's frame, assumed to be

$$f(\mathbf{v})=\left(\frac{\sqrt{3/2\pi}}{v_{\rm rms}}\right)^3\exp\left(-\frac{3|\mathbf{v}-\mathbf{v}_E|^2}{2v_{\rm rms}^2}\right), \qquad (2)$$

where the Earth's velocity $|\mathbf{v}_E|=230$ km/s. Assumptions are that the total cross section is independent of the relative Earth-particle velocity $\mathbf{v}$ and $d\sigma/dT$ is isotropic in the center of mass.[8] Values for $v_{\rm rms}$ will be discussed below.

To compare this calculated spectrum with that observed requires converting (1) to the ionization signal spectrum, or equivalent electron energy. Since at low energy Si recoils ionize inefficiently compared to electrons, it is necessary to know how the ionization varies with recoil energy. Because an adequate calibration of this ionization efficiency as a function of energy had not been made, a separate experiment was required. Using those results, which will appear elsewhere,[9] the probability that a given recoil energy would produce a certain ionization signal was convolved with the recoil spectrum from (1).

Comparison of the observed spectrum and that predicted for dark-matter particles resulted in the exclusion plot of Fig. 2, where it was assumed for each value of the mass that only that particle is responsible for the galactic halo density. Masses and cross sections on Si above and to the right of the solid line are excluded. The exclusion contour was obtained by two different maximum-likelihood procedures. One used the region (1.1–1.5 keV) most sensitive to light particles by fitting that small region with a straight line, then adding the dark-matter signal to the fit (allowing the parameters of the "background" line to change but not become negative) until the fit could be rejected at a confidence level of 95%. The second employed a fit to the data up to 225 keV, with shapes of known backgrounds (such as the electronic noise and activities like ^{3}H, ^{32}Si, and ^{210}Pb) plus a quadratic polynomial and an exponential. Changing that background model, which gave a χ^2 compatible with the number of degrees of freedom, to a six-parameter exponential of a polynomial did not change the result. Again, for each assumed mass, a signal was added and the background allowed to vary until the fit over a region sensitive to the dark matter (from 1–6 keV at 4 GeV/c^2 to 1–14 keV for 10 GeV/c^2) could be rejected at the 95% confidence level. If either the energy range of the fit is increased or the known radioactivity background is kept fixed, the limits given below are improved. The final results of the two analyses are in close agreement. Figure 1 shows the results of fits to the background and of including signals from 4 and 10 GeV/c^2 masses with cross sections on the exclusion contour.

The significance of Fig. 2 for cosmions will now be discussed. The original motivation for proposing cosmions was to utilize dark matter to explain the apparent difference[10] of a factor of ~3 between the observations of the ^{8}B neutrinos coming from the Sun and the rate calculated from solar models.[11] The cosmion dark matter could scatter in the Sun, be captured, and fall in toward the core, from which its motion to larger radii could cool the core by the $\sim 10\%$ needed to reduce the flux of ^{8}B neutrinos produced in the core. The cosmion should be more massive than ~ 4 GeV/c^2 so that they do not rapidly evaporate from the Sun, but less massive than ~ 10 GeV/c^2 so that, after thermalizing, they are not confined to such a small region near the solar center that they are inefficient in energy transport. Large-mass cosmions are also too rare in the galactic halo of fixed mass density to be captured in sufficient numbers. The cooling and capture requirements also require the cross section for interactions with protons or helium to be $\sim 10^2$ times the weak cross section. While their scattering region should be high, their annihilation rate must be low and the lifetime very long to maintain an adequate density of cosmions.

These are difficult requirements, and it is not easy to construct in a natural way particle-physics models giving the requisite properties. The models differ principally in the means employed to suppress annihilation and to provide the required extra interaction. Three[12-14] models have been ruled out recently by the results from the CERN e^+e^- collider LEP and the SLAC Linear Collider,[15] but five[16-18] remain. Generally, models survive in which cosmions couple only to light quarks. In all of these models the cosmion cross section on nuclei increases not only by the reduced mass factor, but also roughly as the square of the number of nucleons (A^2). This feature, which is what is meant in this paper by "coherent scattering," makes detectors based on heavy nuclei like Ge or Si sensitive to cosmions. Cosmions more massive than 9 GeV/c^2 have already been excluded by our Ge experiment,[5] and the object of the present experiment was to reduce the mass limit down to 4 GeV/c^2, the lowest value expected at that time.

A recent calculation of the evaporation mass limit by Gould[19] reaches smaller masses than had been found previously, and this result is given by the left-hand dashed line in Fig. 2. These dashed lines indicate the region of mass and cross-section space which could be occupied by coherently scattering cosmions if they are to solve the solar-neutrino problem. All published, presently viable cosmion models would be within this boundary. The cross-section limits are more uncertain than the lower mass limits. A mean cross section $\bar{\sigma}$ of 7×10^{-36} cm^2 per baryon is optimal for cosmion capture and thermal transport, corresponding to a mean free path of the order of the solar radius.[20] However, it is believed[20] that the range of values for $\bar{\sigma}$ which can solve the solar-neutrino problem is roughly 10^{-36}–10^{-34} cm^2. The conservative limit of 10^{-34} cm^2 was used for the upper boundary. The lower boundary is more complicated, since the cosmion undergoes few interactions in each orbit and hence is not in local thermal equilibrium with nuclei. A recent calculation[21] of that limit for cosmions with coherent interactions was used. It corresponds to $\bar{\sigma}\approx 10^{-36}$ cm^2 and yields a solar-neutrino count rate of 3.2 solar-neutrino units,[10] near the upper limit in that experiment. No high-mass boundary is shown,[22] although Press and Spergel[1] argue for a limit near 10 GeV/c^2 for $\bar{\sigma}$ near 10^{-36} cm^2.

To convert these solar cross-section limits to cross sections of cosmions of mass M interacting with Si, we scale with A^2 and the square of the reduced mass:

$$\sigma_{\rm Si}=\sigma_{\rm He}\left(\frac{m_{\rm He}+M}{m_{\rm Si}+M}\right)^2\left(\frac{m_{\rm Si}}{m_{\rm He}}\right)^4 . \qquad (3)$$

This implies that the cosmion interacts primarily with He, not H, and $\sigma_{\rm He}=8\bar{\sigma}$. Since the capture and thermal transport are mainly from He scattering, dependence on the square of the number of protons or neutrons, instead of A^2, would change the cross section on Si by $\sim 10\%$. Equation (3) would not be correct if the cosmion had spin-dependent couplings.[23]

In Fig. 2 the mass–cross-section region for dark-matter particles excluded by the present experiment is shown by either a solid line for $v_{\rm rms}=260$ km/s or a dash-dotted line for $v_{\rm rms}=300$ km/s. The result is quite dependent on this rather uncertain root-mean-square cosmion velocity. Since $v_{\rm rms}$ can be between 1.2 and 1.8 times the solar circular speed, which itself could be between 215 and 260 km/s,[24] extreme values of $v_{\rm rms}$ are 260 and 470 km/s. Figure 2 displays the effect of using the minimum possible value of 260 km/s and also a more typical value of 300 km/s. For $v_{\rm rms}$ below 300 km/s small regions remain for cosmions near the evaporation masses at the extreme cross sections. The effects of varying $v_{\rm rms}$, the halo density ρ, or the ionization-efficiency calibration are shown in Table I. The value of ρ is likely[25] to be in the range of 0.30–0.43 GeV/c^2cm^3, but changing ρ shifts both the exclusion boundary and the cosmion zone, so there is little dependence on this parameter. The effects of the ionization-efficiency calibration, known to about 10%, are negligible compared to other uncertainties. Also negligible is the effect of any reasonable value (>600 km/s) of an escape-velocity

TABLE I. Variation of the cosmion mass limits (for low mass) and cross-section limits (for high mass) with the parameters $v_{\rm rms}$ of the Maxwellian distribution of cosmion velocities, local halo density of dark matter ρ, and ratio of ionization to recoil energy R for Si nuclei.

	$\sigma=1$ nb	$\sigma=10$ nb
$dM/d\ln v_{\rm rms}$	5 GeV/c^2	2.5 GeV/c^2
$dM/d\ln\rho$	2 GeV/c^2	0.5 GeV/c^2
$dM/d\ln R$	3 GeV/c^2	2 GeV/c^2
	$M=10$ GeV	
$d\sigma/d\ln v_{\rm rms}$	0.45 nb	
$d\sigma/d\ln\rho$	0.54 nb	
$d\sigma/d\ln R$	0.3 nb	

cutoff in the velocity distribution. At present we are making new detectors to lower the noise threshold so as to have sensitivity below the remaining mass region allowed even for the extremes of the astrophysical parameters.

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[1]J. Faulkner and R. L. Gilliland, Astrophys. J. **299**, 994 (1985); L. M. Krauss, Harvard University Report No. HUTP-85/A008a, 1985 (unpublished); W. H. Press and D. N. Spergel, Astrophys. J. **296**, 679 (1985); R. L. Gilliland, J. Faulkner, W. H. Press, and D. N. Spergel, Astrophys. J. **306**, 703 (1986).

[2]J. Faulkner and F. J. Swanson, Astrophys. J. **329**, L47 (1988).

[3]J. Faulkner, D. O. Gough, and M. N. Vahia, Nature (London) **321**, 226 (1986); W. Däppen, R. L. Gilliland, and J. Christensen-Dalsgaard, Nature (London) **321**, 229 (1986); A. N. Cox, J. A. Guznik, and S. Raby, Astrophys. J. **353**, 698 (1990).

[4]M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985).

[5]D. O. Caldwell, R. M. Eisberg, D. M. Grumm, M. S. Witherell, B. Sadoulet, F. S. Goulding, and A. R. Smith, Phys. Rev. Lett. **61**, 510 (1988); an earlier experiment of the same type, S. P. Ahlen, F. T. Avignone, III, R. L. Brodzinski, A. K. Drukier, G. Gelmini, and D. N. Spergel, Phys. Lett. B **195**, 603 (1987), did not reach quite such low masses.

[6]B. Sadoulet, J. Rich, M. Spiro, and D. O. Caldwell, Astrophys. J. **324**, L75 (1988).

[7]D. O. Caldwell, R. M. Eisberg, D. M. Grumm, M. S. Witherell, F. S. Goulding, and A. R. Smith, Phys. Rev. Lett. **59**, 419 (1987), and earlier publications quoted therein.

[8]Anisotropy resulting from an exchanged particle has almost no effect on the results, unless the mass of that particle is $\lesssim 25$ MeV/c^2, and no existing cosmion model utilizes a particle of such a low mass.

[9]G. Gerbier, E. Lesquoy, J. Rich, M. Spiro, C. Tao, D. Yvon, S. Zylberajch, P. Delbourgo, G. Haouat, D. Humeau, F. S. Goulding, D. A. Landis, N. W. Madden, A. R. Smith, D. O. Caldwell, B. Magnusson, M. S. Witherell, B. Sadoulet, and A. Da Silva, Phys. Rev. D (to be published).

[10]J. W. Rowley, B. T. Cleveland, and R. Davis, Jr., in *Solar Neutrinos and Neutrino Astronomy,* edited by M. L. Cherry *et al.*, AIP Conference Proceedings No. 126 (American Institute of Physics, New York, 1985), p. 1; K. H. Hirata *et al.*, Phys. Rev. Lett. **63**, 16 (1989).

[11]J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988); S. Turck-Chièze, S. Cahen, M. Cassé, and C. Doom, Astrophys. J. **335**, 415 (1988).

[12]G. F. Giudice and E. Roulet, Phys. Lett. B **219**, 309 (1989).

[13]S. Raby and G. B. West, Nucl. Phys. **B292**, 793 (1987); Phys. Lett. B **194**, 557 (1987); **200**, 547 (1988).

[14]S. Raby and G. B. West, Phys. Lett. B **202**, 47 (1988).

[15]K. Griest and J. Silk, Nature (London) **343**, 261 (1990); L. M. Krauss, Phys. Rev. Lett. **64**, 999 (1990), and experimental papers cited in these references.

[16]G. B. Gelmini, L. J. Hall, and M. J. Lin, Nucl. Phys. **B281**, 726 (1987). This paper has three cosmion models differing in annihilation-suppression mechanism.

[17]G. B. Ross and G. C. Segrè, Phys. Lett. B **197**, 45 (1987).

[18]J. G. Bartlett, M. Gleiser, and J. Silk, Institute of Theoretical Physics Report No. NSF-ITP-89-132, 1989 (unpublished).

[19]A. Gould, Astrophys. J **356**, 302 (1990).

[20]A. Gould and G. Raffelt, Astrophys. J. **352**, 654 (1990).

[21]Y. Giraud-Héraud, J. Kaplan, F. Martin de Volnay, C. Tao, and S. Turck-Chièze, in Proceedings of the International Conference, "Inside the Sun," Versailles, France, 1989 (to be published).

[22]Since this paper was initially submitted, a paper by D. Dearborn, K. Griest, and G. Raffelt [Center for Particle Astrophysics, University of California, Berkeley, Report No. CfPA-TH-90-012, 1990 (unpublished)] has appeared with more complete calculations, including an upper mass limit which is cross-section dependent. This uses the result of Ref. 19 and agrees with the calculation of Ref. 21, so in the crucial low-mass region there is confirmation of the limits presented here.

[23]G. F. Giudice and S. Raby [Fermilab Report No. FERMILAB-PUB-90/105-T, 1990 (unpublished)] have recently succeeded in devising a cosmion with spin-dependent interactions to evade our bounds, but the new physics they have to introduce to avoid existing experimental limitations shows how difficult it is to construct such a model.

[24]D. N. Spergel and D. O. Richstone, in *Dark Matter,* edited by J. Audouze and J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1988), p. 419; D. N. Spergel (private communication).

[25]R. A. Flores, Phys. Lett. B **215**, 73 (1988).