Laboratory Limits on Galactic Cold Dark Matter

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Interesting limits are set on candidates for cold-dark-matter particles in the halo of our Galaxy from their interaction with a very-low-background Ge detector used to search for double-β decay. Dirac neutrinos constituting all of dark matter are excluded for masses between 12 GeV/c^2 and 1.4 TeV/c^2. There are slightly better limits on magninos and cosmions, proposed massive particles which also explain the solar-neutrino problem but which interact more strongly with Ge. In addition, millicharged shadow matter is ruled out as the main form of dark matter.

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Clearly one of the most important questions facing basic physics is the nature of the majority of the matter in the Universe. Since perhaps 90% of matter is detected only through its gravitational interactions, knowledge of what constitutes this dark matter would have widespread importance for astrophysics and cosmology. Since it is unlikely[1] that dark matter consists of particles as they are known in the standard model, the discovery of their nature would also point the way to important new particle physics. Useful constraints on candidates for dark matter can already be set by apparatus used to search for neutrinoless double-β decay. In order to approach lifetime limits[2] of 10^{24} yr on this process in ^{76}Ge, it has been necessary to take extreme measures to reduce backgrounds. When the energy threshold for the Ge detectors is made as low as possible, the resulting background rates can be used to set limits on the scattering of the dark-matter candidates from the Ge nuclei.[3] We report here limits on some specific models for dark matter, as well as giving some more general constraints from measurements with the UCSB/LBL double-β-decay detector.[4]

The apparatus has been described elsewhere,[4] but some relevant features will be mentioned here. Although up to eight Ge detectors have been used for double-β decay, the data of concern here comes from just one detector of about 160-cm^3 fiducial volume (0.9 kg). The Ge detectors were surrounded by ten blocks of NaI(Tl) scintillator, which formed a complete anticoincidence shield of 15 cm thickness. Compton scattering, which provides the main source of radioactivity background at low energies, is suppressed not only by the vetoing of the scattered γ in the NaI or another Ge detector, but also because many of the γ's come from cascade decays, and the detection of one of these other γ's would also eliminate the event. The threshold at 30-keV equivalent electron energy for the NaI counters is high enough so that the small energy deposits by the dark-matter candidates do not cause a veto signal, except for the case of large cross section. The NaI detectors are surrounded by borated polyethylene to degrade and capture neutrons and then by a 20-cm shield of 99.999% pure virgin lead.

Much effort has been devoted to the finding of structural materials of low radioactivity and to the development of fabrication procedures to reduce the amount of such materials. In order also to avoid losing γ's before they could be vetoed, it was particularly necessary to keep structural material to a minimum inside the NaI cavity and to have that used of as low an atomic number, Z, as possible. Thus the Ge detectors do not have the usual thermal shield, but instead an overlying metallization 1000 Å thick. They are enclosed in cylindrical cans of electroformed Cu with walls 0.25 mm thick, with each set of two cans attached to a similarly made flat box which passes through a slot in the NaI and serves as the vacuum cryostat, evacuated by ion pumps and containing the cold finger to keep the Ge at liquid-nitrogen temperature. Each 4-mm-thick cold finger is made from single-crystal Si, which has about twice the conductivity of Cu at this temperature, is of very high purity, and has low Z, reducing the absorption of γ rays. Before fabrication, a kilogram or more of material to be used was measured with a low-background Ge spectrometer with picocurie sensitivity, and after fabrication the piece was tested again.

When the apparatus was constructed, the emphasis was on achievement of low background and good Ge resolution near 2.041 MeV, the region to be searched for a peak from neutrinoless double-β decay in ^{76}Ge. However, when it was decided to look for dark matter, we found that there was a rapidly rising background below about 400 keV. This was due to the presence of about half a gram of In, which undergoes a 486-keV β^- decay with a half-life of 4×10^{14} yr! When the In was removed from one detector, the background for that detector became flat down to about 14 keV at a level of $\frac{1}{2}$ count/(keV kg day), except for some x-ray peaks. A part of that spectrum is shown in Fig. 1, and it will be noticed that at lower energies there is a rise in the counting rate due mainly to Ga (10.4 keV), and a little to Zn (9.7 keV) x-ray peaks which result from the ^{68}Ge-^{68}Ga decay chains.[2] The counting-rate drop at the low end of the x-ray peaks begins to be offset by the rapidly rising noise rate which currently limits measurements to about 3 keV. The noise has three sources: inadequate infrared shielding (since we avoided using a thermal shield on the Ge), electronic noise, and microphonics. Although further improvements in background will occur, certainly because of decay of the ^{68}Ge-^{68}Ga activity and probably also because of detector improvements, we already have lower backgrounds in the low-energy region than have heretofore been available. Hence, we have utilized those data to set useful limits on several dark-matter candidates.

An interesting speculation[5] which has motivation from string theory is that another world may occupy the space in which we live and that this shadow universe interacts with us only gravitationally. However, Holdom[6] has pointed out that if any connector particle exists, no matter how heavy, then the shadow world has a massless

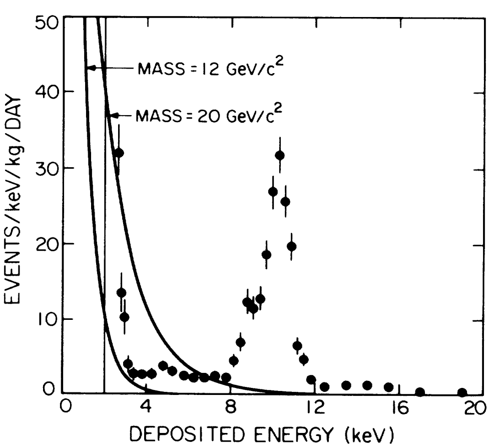

FIG. 1. Ionization energy detected at the low end of the operating range of one Ge counter in a four-week run. Below the Ga and Zn x-ray peaks the noise is almost flat until 3 keV. The threshold was set at 2.0 keV. The two curves show the contributions expected for particles of mass 12 and 20 GeV/c^2, which interact via Z^0 exchange. If we take into account the almost flat background in the 3–8-keV region, the 12-GeV/c^2 curve is ruled out at the 95% confidence level.

photon which mixes with our photon, providing a way in which shadow photons can interact with us through a very weak electric charge. Thus shadow matter would emit mainly shadow photons, which we could not detect, but also our photons with strength $\propto\epsilon^2$, where perhaps $\epsilon\sim10^{-3}$. Goldberg and Hall [7] have investigated whether such millicharged shadow matter could be a candidate for the dark matter. Although their model is constrained by big-bang cosmology, galactic astrophysics, and searches for fluxes of dark-matter particles, including limits set by another Ge detector,[8] there appeared to be a range of allowable masses of the shadow proton versus the shadow electron. The Ge limits[8] came from observations both at the surface and at a depth of 4000 m of water equivalent (mwe) where the count rates were $\simeq 100$ kg^{-1} day^{-1} for Ge nucleus recoil energies which give ionization energies of 20–150 keV. Over this same energy range our count rates were about $\frac{1}{3}$ of that, but what is really significant in this case is that our apparatus is at a depth of only about 600 mwe. The 4000-mwe result[8] was being satisfied[7] by the requirement that the interaction cross section, and hence the mass, of the shadow proton be sufficiently large so that too few such particles survived to that depth to be counted. Scaling the Goldberg-Hall calculations to 600 mwe gives a result that requires a further increase in cross section by about an order of magnitude. This, then, effectively wipes out the allowable region in shadow proton versus shadow electron mass. The only faint possibility remaining is if the shadow electron's mass is less than the value of $\frac{1}{3}$ GeV/c^2 at which the calculations break down, there being no predictions in that region with which to make comparisons.

Another candidate for dark matter is the class of weakly interacting massive particles (WIMP's) which interact via Z^0 exchange. This vectorial, spin-independent interaction is coherent in a nucleus and so depends on the square of the number of neutrons, N^2. If the coupling of these particles is similar to that of Dirac neutrinos and their mass is greater than a few GeV/c^2, the resulting large annihilation cross section necessitates, at masses above a few GeV/c^2 particle-antiparticle asymmetry for them to be responsible for all of dark matter.[9] An asymmetry similar to that of baryons would require a mass of the order of 10 GeV/c^2.

For such a particle of mass m scattering from a Ge nucleus of mass M, the average energy deposition at low energy is $\langle E_d\rangle = m^2M\langle v^2\rangle/(m+M)^2$, where $\langle v^2\rangle$ is the mean square speed of m. For these low values of E_d, the recoiling nucleus ionizes very inefficiently and gives an ionization signal much smaller $(\sim\frac{1}{4})$ than that of an electron of the same kinetic energy. Fortunately, accurate measurements[10] of this ionization efficiency have been made by neutron scattering in Ge down to an equivalent electron energy of 2 keV ($E_d \approx 10$ keV), and the results agree very well with the theory of Lindhard *et* *al.*[11] It is the equivalent electron energy which is plotted in Fig. 1.

To compare the measured rates in Fig. 1 with the spectrum expected for a given mass of Dirac neutrino from the halo of our Galaxy, we took a halo density of 0.3 GeV/cm^3, which is 5.3×10^{-25} g/cm^3, and a Maxwellian velocity distribution with a root mean square average of 270 km/s without any truncation (which could exist if the Galaxy escape velocity were relatively low). For the relevant period (March) we assumed the velocity of the Earth with respect to the halo to be 230 km/s. With use of the known[3] interaction cross section and the parametrization of Lindhard's model[11] by Robinson,[12] the solid curves of Fig. 1 were generated for several values of m. If we assume a flat background in the region 3–8 keV, masses above 12 GeV/c^2 are excluded. The mass value is actually double valued for a fixed halo density, so that there is an upper bound of 1.4 TeV for the region of excluded masses. If we decrease the halo density by 30%, the lower mass limit increases from 12.0 to 12.5 GeV/c^2. Changing the rms velocity to 240 km/s increases the limit to 12.2 GeV/c^2.

There is an interesting variant on the standard Dirac neutrino which Raby and West have proposed[13] in order to have the same particle not only be the main component of dark matter but also explain the solar-neutrino problem. This apparent deficit of ^{8}B neutrinos coming from the sun[14] could be explained[15] by WIMP's being trapped in the Sun and transporting energy from the core to larger solar radii, thereby slightly cooling the central region from which most of the neutrinos originate. This mechanism requires cross sections with protons of about 10^{-36} cm^2, a low enough annihilation rate, and masses roughly in the range of 4 to 15 GeV/c^2. Below 4 GeV/c^2 the particles evaporate too rapidly from the surface and above about 15 GeV/c^2 they do not travel far enough from the core to cool it efficiently. Such particles could also explain[15] the discrepancy between observations of solar oscillations and the standard solar model, but the required properties are not possessed by conventional or even previously proposed particles.[16] The Raby-West[13] solution is to postulate a fourth-generation Dirac neutrino, called a magnino, since it would have a large magnetic moment arising from the existence nearby in mass of its charged partner and associated Higgs particle. The resulting electromagnetic interaction with protons has an appropriate cross section $\simeq 10^{-36}$ cm^2, much higher than the weak-interaction cross section. For a heavy nucleus like Ge, however, the electromagnetic interaction becomes only comparable to the weak interaction. In addition, the interference term becomes model dependent, since it involves the charge radius r and magnetic moment μ of the magnino. The complete cross section has been calculated for us by Raby and West. With parameters ($\mu=1/8\pi^2$, $r^2=\mu^2/8m^2$, where m is the magnino mass) suggested by the authors, the resulting mass limit is 11 GeV/c^2, which is not very different from that for a particle with only weak interactions. Although the statement is often made that WIMP's with cross sections large enough to account for the solar-neutrino problem should be easy to detect in laboratory experiments, this model at least shows that that is not necessarily so. However, as the mass of either the incident particle or the target nucleus is diminished, the relative effect of the electromagnetic interaction becomes more important.

In contrast, there are models for WIMP's to solve the solar-neutrino problem in which the large cross section on protons is reflected in a large cross section on Ge as well. These include the cosmion of Gelmini, Hall, and Lin,[17] which interacts with light quarks via a heavy colored scalar, another fourth-generation neutrino of Raby and West,[18] which has a stronger interaction because of a light neutral Higgs boson, and the neutrino from broken E_6 of Ross and Segrè,[19] which gets its needed interaction from an additional Z'. A single mass limit of <9 GeV/c^2 is determined from the data for all of these models because the cross sections are large enough so that the limit is set by the kinematic threshold.

Since such models may be ephemeral, it is important to display the results of this experiment in a way which may have wider eventual application. Such information is shown in Fig. 2, which is an exclusion plot in dark-particle mass versus interaction cross section, primarily of that particle with Ge, although the upper limit is for the cross section on material above the detector. In the region of large masses, the upper limit on cross section corresponds to the case in which the energy deposition in

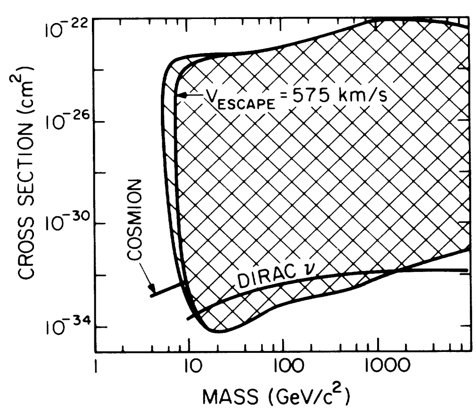

FIG. 2. Mass exclusion plot for particular cross sections for the interaction with Ge (or, for the upper boundary, with the Earth) using data from the present experiment. The larger shaded region is excluded if the escape velocity is infinite; the smaller region, if the escape velocity is 575 km/s. All limits are 2σ. The curve near the bottom of the plot shows the cross section as a function of mass for a Dirac neutrino. The short line with the label cosmion shows the expected cross section for cosmions with mass between 4 and 9 GeV/c^2.

the NaI is sufficient to veto the event. At lower masses, particles with large enough cross section with the Earth are slowed before they reach the apparatus so that they produce insufficient recoil energy to be observed. The left edge of the exclusion region is determined by the data near threshold. Note the small difference in this region which occurs if a 575-km/s escape velocity is assumed to truncate the Maxwellian velocity distribution. The rise with mass of the lower edge comes from a combination of the decreasing number density of the incident particles (since the mass density of the halo is fixed) and of an increasing contribution of the background due to the widening of the expected energy distribution. We have taken into account the loss of coherence at high masses, assuming a radius of 4×10^{-13} cm for the Ge nucleus. Above about 50-GeV mass the background at energies above the Ga x ray is setting the limit. At high masses, the lower limit is proportional to mass. All mass limits given here are at the 2-standard-deviation level. In all cases the usual assumption has been made that the considered particles constitute all of dark matter.

Figure 2 shows that existing Ge detectors set useful limits on dark-matter candidates. We have shown here that one class of proposed dark matter, millicharged shadow matter, is effectively eliminated and that the masses of particles with an initial asymmetry in the universe, such as Dirac neutrinos, magninos, and cosmions, are being constrained. While the present apparatus will give improved results after some time, more promising is the development of Si detectors which can cover the full range (down to 4 GeV) of interest for WIMP's which could also solve the solar-neutrino problem.[20]

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