A Search for Strongly Interacting Dark Matter

(presented by M. SPIRO)

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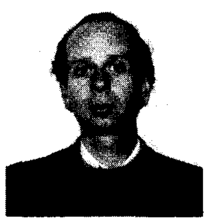

ABSTRACT

A silicon semiconductor detector near the top of the atmosphere is used to search for strongly-interacting particles in our galactic halo. The data exclude, as the dominant component of the halo, such particles with masses between 2 GeV/c^2 and 10^5 GeV/c^2. Comparisons are made with previously reported data taken at the Earth's surface and underground.

The idea that our galaxy is surrounded and pervaded by a halo of gravitationally-trapped weakly-interacting elementary particles has been discussed extensively in the literature [1]. Most attention has been centered on candidate particles in supersymmetric theories, where the lightest new particle is required to be stable. If this particle is a neutral photino, scalar neutrino, or higgsino, it would be weakly interacting and, thus, lead naturally to a dissipationless halo as implied by galactic velocity curves [2]. In addition, cosmological densities near the closure density can be generated with reasonable choices of parameters [3].

While the aforementioned particles are truly weakly interacting (low energy cross sections on protons near 10^{-38} cm^2) it was noted by Goldberg and Hall [4] that even for particles with cross sections in the barn range, the low density of interstellar space makes them effectively weakly interacting ($\tau_{scatter} > 10^{10}$ yr). For such strongly interacting particles, cosmologically important densities can be generated by assuming a particle-antiparticle asymmetry, as is done with baryons. Possible candidate particles have been discussed by Goodman and Witten [5] and Goldberg and Hall [4].

It is the purpose of this paper to report on a search for such particles using a silicon semiconductor detector near the top of the atmosphere. We will also compare our results with those from a search for weakly-interacting halo particles with a subterranean germanium semiconductor detector [6].

The basic principle of halo particle detection, due to Goodman and Witten [5], is to detect the energy deposited by nuclei recoiling from elastic collisions with halo particles. For a halo particle of mass m_h and velocity $v=\beta c$, a nucleus of mass m_t will receive a kinetic energy, T, given by:

$$T = m_t c^2 \beta^2 \ (1 - \cos\theta) \ \frac{m_h^2}{(m_t + m_h)^2} \qquad (1)$$

where θ the center-of-mass scattering angle. For halo particles, β is near 10^{-3} (the galactic virial velocity), so nuclear recoil energies are in the keV range. For $m_h >> m_t$, the maximum recoil energy (at fixed β) approaches an asymtotic value, equal to 52 keV for silicon (at $\beta=10^{-3}$). For $m_h << m_t$, the maximum recoil energy rises quadratically with m_h. For a given detector, this results in a minimum detectable mass determined by the maximum halo velocity, β_{max}, and the minimum detectable recoil energy, T_{min}:

$$(m_h c^2)_{min} = \frac{\sqrt{T_{min} \ m_t c^2/2}}{\beta_{max}} \qquad (2)$$

where we have assumed $m_h << m_t$.

The actual spectrum of nuclear recoil energy is determined by the differential scattering cross section, $d\sigma/dT$, the local halo mass density, ρ, and the halo velocity distribution, $f(\vec{v})$:

$$\frac{dN}{dTdt} = \frac{\rho}{m_h} \int \frac{d\sigma}{dT}(v,T)\, f(\vec{v})\, v\, d^3v \qquad (3)$$

For nonrelativistic halo particles, $d\sigma/dT$ is expected to be nearly independent of T (isotropic scattering in the center of mass) and proportional to v^{-2} (yielding an energy-independent total cross section). Under these assumptions, dN/dTdt is determined by the integral of $f(\vec{v})/v$ above the minimum velocity needed to give a recoil energy T. For purposes of illustration, we will assume that the halo velocity distribution is a truncated Boltzmann distribution with an r.m.s. velocity of 250 km/s and a maximum velocity of 550 km/s [7]. The Earth then moves through the halo at a velocity of 250 km/sec, giving a maximum for v of 800 km/sec. The resulting recoil energy spectra for a silicon target and for m_h = 10 and 10^5 GeV/c^2 are shown as the solid lines in figure 1. (The recoil energy has been corrected for detector response; see below.) The form of the spectrum is independent of m_h, though the average T depends on m_h as in equation (1).

Integrating over T, the total scattering rate in an unshielded silicon detector is determined by the low energy cross section, σ_{sil}, and by m_h:

$$\frac{dN}{dt} = 1.4\; 10^5\; g^{-1} s^{-1}\; \frac{\sigma_{sil}}{0.5\ \text{barn}}\; \frac{1\ \text{GeV}/c^2}{m_h}\; \frac{\rho}{0.4\ \text{GeV}/c^2\ \text{cm}^{-3}} \qquad (4)$$

The nominal values appearing in the above equation refer to the geometrical cross section of silicon and to an estimate [8] of the total halo mass density. The halo particle mass is, of course, unknown.

Whereas equation (2) limits the sensitivity of a given experiment to values of m_h above a minimum value, equations (3) or (4) limits the sensitivity to values of σ/m_h above the value where the scatter rate becomes less than the background rate due, for example, to the ambiant radioactivity or cosmic rays. In addition, Earth-bound experiments are limited at high cross sections and low masses by the energy loss (due to elastic collisions) of halo particles as they pass through the atmosphere. For example, for a cross section on nitrogen of 0.4 barn, the atmosphere represents about 16 scattering lengths, limiting surface experiments to masses greater than ~200 GeV/c^2. Deep underground experiments are sensitive to strongly-interacting particles with masses greater than ~10^5 GeV/c^2.

Following the suggestion of Goodman and Witten, we have circumvented this problem by using an energy spectrum (figure 1) of a 0.5 g silicon semiconductor detector taken during a balloon flight on October 7, 1977. The detector had a resolution (FWHM) of ~150 eV at 1 keV and viewed the zenith (solid angle ~ π) though a 5 mm quartz window. At the maximum altitude, the detector was also shielded by ~4.5 g/cm^2 of atmosphere which, combined with the quartz, makes about 0.1 of an interaction length for a cross section of 0.5 barn. The detector was shielded from below by the Earth which effectively ranged out strongly interacting particles of masses less than ~ 10^7 GeV/c^2. During the flight, the zenith was within 10° of the direction of the solar system's movement through the galaxy, nearly ideal for dark matter searches.

The data shown in figure 1 are for the detector at its maximum altitude and are consistent with the spectrum expected from passing cosmic rays. The form of the spectrum

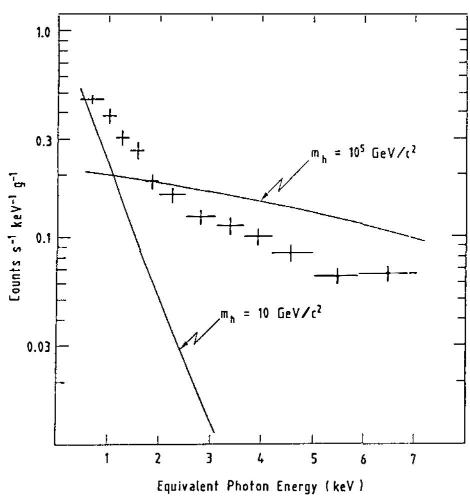

Figure 1 : The energy spectrum of the silicon detector at the maximum altitude during the balloon flight. The solid curve shows the spectrum of nuclear recoils expected in a silicon detector (no shielding) due to halo particles of mass 10 GeV/c^2 (σ_{sil} = 2 10^{-5} barn) and of mass 10^5 GeV/c^2 (σ_{sil} = 1 barn). The theoretical curve has been corrected for detector response using the theory of reference [9].

was roughly invariant during the flight. The minimum rate occured at an altitude of ~100 m where it was about 1/5 the rate shown in figure 1.

Before comparing the spectrum of figure 1 with that predicted for nuclei recoiling from collisions with halo particles, the energy scale must be corrected for the difference between the electron-hole pair yield of recoiling nuclei and the yield of X-ray photoelectrons used to calibrate the detector. This was done using the theory of Linhard et al. [9] (their equation 5.2 and figure 9) which has been verified for silicon at the 30% level by the experiments of Sattler [10]. The correction factor is about 4, so the data running from 0.4 to 7.0 keV correspond to nuclear recoils between 2.0 and 20. keV.

Predicted spectra were then generated as a function of m_h and σ_{sil} using the halo model described above. In generating the spectra, halo particles were degraded in their passage through the residual atmosphere assuming elastic scattering with a cross section equal to $.67\sigma_{sil}$.

Figure 2 shows the zone in parameter space that is excluded by our data by requiring the generated dN/dtdT be less than the measured differential rates at 100 m altitude and at maximum altitude. No attempt was made to subtract the cosmic-ray background. The zone's boundary at low m_h ($m_h \sim 2.1$ GeV/c^2) is determined by equation (2) for T_{min}=2 keV

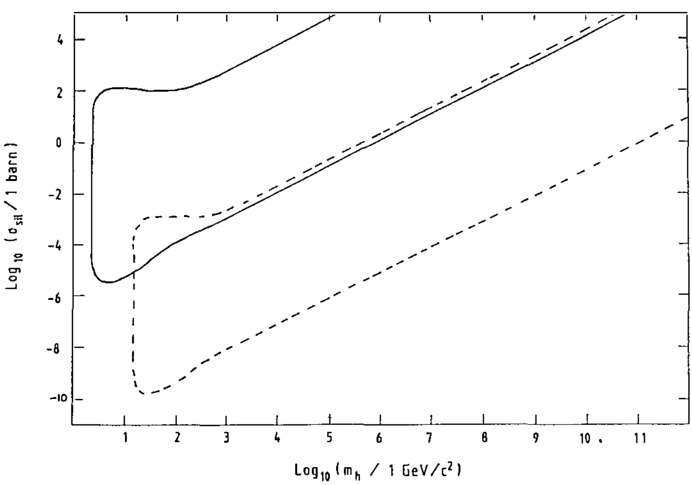

Figure 2 : The solid line shows the region in m_h-σ_{sil} space that is excluded by the balloon data. The dashed line shows the regions excluded by the detector of reference [6] at 4000 m.w.e.

and $\beta_{max} \sim 2.5\ 10^{-3}$. (Equation (2) also shows the sensitivity of this lower limit to the assumed halo model (β_{max}) and to the efficiency of recoiling nuclei to produce electron-hole pairs.) The zone's boundary at low σ_{sil}/m_h is determined by the background rate (at 100 m altitude) and on the assumed halo density and mean velocity. More generally, the boundary corresponds to $\rho<v>\sigma_{sil}/m_h = 1.6\ 10^{-23}\ s^{-1}$. The boundary at high σ_{sil} is determined by the shielding of the residual 4.5 g/cm^2 of atmosphere, and is, thus, dependent on the assumed relationship between σ_{sil} and σ_{air}.

Also shown in figure 2 is the exclusion zone obtained using a 135 cm^3 germanium detector [6] at 4000 m.w.e. The underground curve was calculated by us using the spectrum of reference [6] corresponding to ~100 counts/kg-day for nuclear-recoil energies between 20 and 150 keV. For simplicity, we have assumed a germanium cross section equal to $2\sigma_{sil}$. The part of the curve corresponding to low σ was shown in reference [6], where the authors were concerned only with weakly-interacting particles.

As seen in figure 2, the two experiments are quite complementary and rule out a continuous region. However, the slight overlap between them is misleading since it depends on the assumed halo density, which is uncertain by at least a factor of two, and may have a baryonic component. Fortunately, several surface experiments rule out the region of overlap. For instance, silicon counters in our laboratory have background rates of ~3 $10^{-3} s^{-1} keV^{-1} g^{-1}$. This is about a factor 10 below the background in the balloon flight (altitude = 100 m) and yields a limit on σ/m a corresponding factor of 10 lower than that shown by the solid line in figure 2. Proportional counters used in low level counting of Auger electrons have reached similar levels of background [11]. Caldwell et al. [12] have obtained a background level in their germanium-crystal spectrometer that is similar to that of reference [6] but at a depth of only 500 m.w.e. Their exclusion zone would extend to values of σ/m about a factor 10 higher than that shown by the dashed line in figure 2.

For a 1 barn cross section, the totality of the data exclude m_h between 2 GeV/c^2 and 10^{11} GeV/c^2. Extension of this limit to higher masses would require further reduction of background by, for example, using coincidences between two germanium detectors underground. It should be possible to reach ~10^{17} GeV/c^2 with this technique.

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References

[1] For reviews of the dark matter problem see
K.A.Olive and D.N.Schramm, Comments Nucl. Part. Phys. 15 (1985) 69
H.R. Pagels, Comments Nucl. Part. Phys. 14 (1985) 289.

[2] S.M. Faber and J.S. Gallagher, Ann. Rev. Ast. Astrophys. 17, (1979) 135;
D. Burstein and V.C.Rubin, Astrophys J. 297, (1985) 423.

[3] J.Silk and M.Srednicki, Phys.Rev.Lett. 53 (1984) 624.
J.Ellis et al., Nucl. Phys. B238 (1984) 453.
J.S. Hagelin et al., Nucl. Phys. B241 (1984) 638.
L.E. Ibanez, Phys. Lett. 137B (1984) 160.
B.A. Campbell et al., Phys. Lett. B 173 (1986) 270.
G.L. Kane and I.Kani, Nucl. Phys. B277 (1986) 525.

[4] H. Goldberg and L.J. Hall, Phys. Lett. B 174 (1986) 151.

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

[6] S.P.Ahlen et al. Harvard-Smithsonian Observatory preprint 2292 (1986).

[7] For a discussion of halo models see A.K.Drukier, K. Freese and
D.N.Spergel, Phys. Rev. D 33 (1986) 3495.

[8] J.A.R. Caldwell and J.P. Ostriker, Ap. J. 251 (1981) 61.

[9] J. Linhard, V.Nielsen, M.Scharff, and P.V.Thomsen,
Kgl. Danske Videnskab Selskab, Mat.-Fys. Medd. 33, No. 10 (1963).

[10] A.R. Sattler, Phys. Rev. 138 (1965) A1815;
A.R. Sattler and F.L. Vook, Phys. Rev. 155 (1967) 211.

[11] T. Kirsten in '86 Massive Neutrinos in Astrophysics and
and in Particle Physics, ed. O.Fackler and J.Tran Thanh Van,
(Editions Frontieres,1986).

[12] B.A. Caldwell in these proceedings.