Cosmological Spin-offs †

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Abstract: We review the implications of polarized structure function measurements for experiments to search for cold dark matter particles, such as the the neutralino and the axion.

1 Cold Dark Matter Particles

Many astrophysical observations suggest that the visible baryonic matter is accompanied by larger amounts of invisible dark matter. Mainstream theories of cosmological inflation suggest that the total density of matter in the Universe should be close to the critical density required for its future collapse in a Big Crunch. The upper limits on the baryon density coming from Big Bang Nucleosynthesis calculations suggest in this case that at least 90% of the matter is dark. Models of structure formation based on inflation suggest that most of this dark matter was non-relativistic at the epoch when galaxies and clusters began to form. There are many candidates for this Cold Dark Matter, of which the two particles that are most prominent are the lightest supersymmetric particle, presumably a combination of the supersymmetric partners of the photon, Z and neutral Higgses called a neutralino, and the axion, which is invoked to explain the fact that the strong interactions conserve CP to a very good approximation. Measurements of the quark contributions Δq to the proton spin are relevant to experimental searches for both of these Cold Dark Matter candidates, as we now discuss.

2 Searches for Neutralinos

Several strategies to search for cosmological relic neutralinos have been proposed. One is to look for the products of their annihilations in our galactic halo [2]. Limits on models from the present experimental measurements of the cosmic-ray $\bar{p}$, e^+ and γ fluxes are not yet very constraining.

A second LSP detection strategy is to look for $\chi\chi$ annihilation inside the Sun or Earth. Here the idea is that a relic LSP wandering through the halo may pass through the Sun or Earth [3], collide with some nucleus inside it, and thereby lose recoil energy. This could

†Based on chapter 3 of Ref. [1].

convert it from a hyperbolic orbit into an elliptic one, with a perihelion or perigee below the solar or terrestrial radius. If so, the initial capture would be followed by repeated scattering and energy loss, resulting in a quasi-isothermal distribution within the Sun or Earth. The resulting LSP population would grow indefinitely, à la Malthus, unless it were controlled either by emigration, namely evacuation from the surface, or by civil war, namely annihilation within the Sun or Earth. Evaporation is negligible for χ particles weighing more than a few GeV [4], so the only hope is annihilation. The neutrinos produced by any such annihilation events would escape from the core, leading to a high-energy solar neutrino flux ($E_\nu \gtrsim 1$ GeV). This could be detected either directly in an underground experiment, or indirectly via a flux of upward-going muons produced by neutrino collisions in the rock.

The polarized structure function measurements enter in the estimate of the χ capture rate, which enters in the following general formula [5] for the neutrino flux:

$$R_\nu = 2.7 \times 10^{-2} f\,(m_\chi/m_p) \left(\frac{\sigma(\chi p \to \chi p)}{10^{-40}\,\mathrm{cm}^2}\right) \left(\frac{\rho_\chi}{0.3\,\mathrm{GeV\,cm}^{-3}}\right) \left(\frac{300\ \mathrm{km\,s}^{-1}}{\bar{v}_\chi}\right) \times F_\nu \tag{1}$$

where we have simplified to the case of capture by the Sun, where proton targets predominate. Here f is a kinematic function, ρ_χ and $\bar{v}_\chi$ are the local density and mean velocity of the halo LSPs, and F_ν represents factors associated with the neutrino interaction rate in the apparatus. The factor which interests us here is the elastic LSP-proton scattering cross section $\sigma(\chi\, p \to \chi\, p)$.

To see how the polarized structure functions enter into the estimation of the elastic scattering cross section [5], first note that the LSP interacts with hadrons via an effective four-fermion interaction of the general form $\chi\chi\bar{q}q$, which is mediated by the exchanges of massive particles such as the Z^0, Higgs bosons and squarks $\tilde{q}$, as seen in Fig. 1. This four-fermion interaction

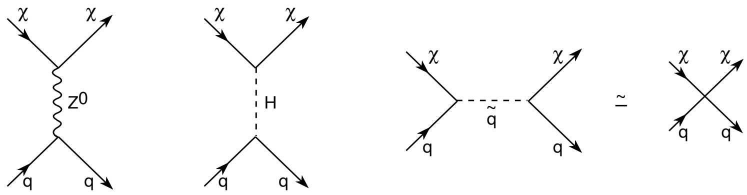

Figure 1: *The exchanges of massive particle such as the Z^0, Higgs boson and squarks give rise to an effective four-fermion interaction between the neutralinos χ and quarks inside a proton target.*

is similar in many ways to the original Fermi four-fermion weak interaction mediated by $W^\pm$ exchange. The matrix elements of the latter interaction between nucleon states are governed by the familiar β-decay constant g_A, which may be written in the form

$$|g_A| = \Delta u - \Delta d \tag{2}$$

Analogous expressions in terms of the Δq exist for the spin-dependent part of the χ-nucleon scattering matrix element. For example, if the χ were to be a pure photino state, we would have

$$a_p = \frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s \tag{3}$$

It is amusing to note that this is exactly the same combination of the Δq that appears in charged-lepton scattering off a proton target [5]. In a sense, the EMC and its successors have been measuring $\tilde{\gamma}$-nucleon scattering!

The EMC and subsequent measurements indicate values of the Δq that are rather different from those predicted by the naïve quark model, which means that the dark matter scattering matrix elements are also rather different, and hence also the upper limits on the halo dark matter density that can be deduced from a given search for high-energy neutrinos from the core of the Sun or the Earth. By now, as discussed in the first lecture, the determination of the Δq is quite precise, and, as discussed earlier in this lecture, we no longer believe that the LSP χ can be a pure $\tilde{\gamma}$. Consider, for example, the plausible case of an essentially pure $U(1)$ gaugino LSP $\tilde{B}$: its scattering matrix elements on protons and neutrons are given by [6]

$$a_p \simeq \frac{17}{36}\Delta u + \frac{5}{36}(\Delta d + \Delta s) \qquad\qquad a_n \simeq \qquad (\Delta u \leftrightarrow \Delta d) \tag{4}$$

We see that, in this case, the uncertainties [6] from polarized structure measurements are likely to be much smaller than those from other components in equation (1). In the long run, it seems that a search for upward-going neutrino-induced muons with a 1 km^2 detector could almost certainly detect LSP annihilation [7], if most of the cold dark matter is indeed composed of LSPs.

The third LSP search strategy is to look directly for LSP scattering off nuclei in the laboratory [8]. It is easy to see that the typical recoil energy

$$\Delta E < m_\chi v^2 \simeq 10 \left(\frac{m_\chi}{10\,\mathrm{GeV}}\right) \mathrm{keV} \tag{5}$$

deposited by elastic χ-nucleus scattering would probably lie in the range of 10 to 100 keV. The type of spin-dependent interaction, mediated by Z^0 or $\tilde{q}$ exchange, that we discussed in previous paragraphs is likely to dominate for light nuclei [9], whereas coherent spin-dependent interactions mediated by H and $\tilde{q}$ exchange are likely to dominate scattering off heavy nuclei [10]. As we have already discussed, the spin-dependent interactions on individual nucleons are controlled by the Δq: translating these into matrix elements for interactions on nuclei depends on the decomposition of the nuclear spin, which must be studied using the shell model [9] or some other theory of nuclear structure [11]. The spin-independent interactions on individual nucleons are related to the different quark and gluon contributions to the nucleon mass, which is also an interesting phenomenological issue related to the π-nucleon σ-term. Again, the issue of nuclear structure arises when one goes from the nucleon level to coherent scattering off a nuclear target.

We will not discuss here the details of such nuclear calculations, but we see in Fig. 2 that the spin-independent contribution tends to dominate over the spin-dependent one in the case of Germanium, though this would not be the case for scattering off Fluorine [9].

3 Couplings of Axions

The axion [13] is another favoured candidate for the cold dark matter, whose mass and couplings to matter are scaled inversely by the axion decay constant f_a:

$$m_a \sim \frac{\Lambda_{QCD}\, m_q}{f_a}, \quad g_{a\bar{f}f} \sim \frac{m_f}{f_a}, \qquad g_{a\gamma\gamma} \sim \frac{1}{f_a} \tag{6}$$

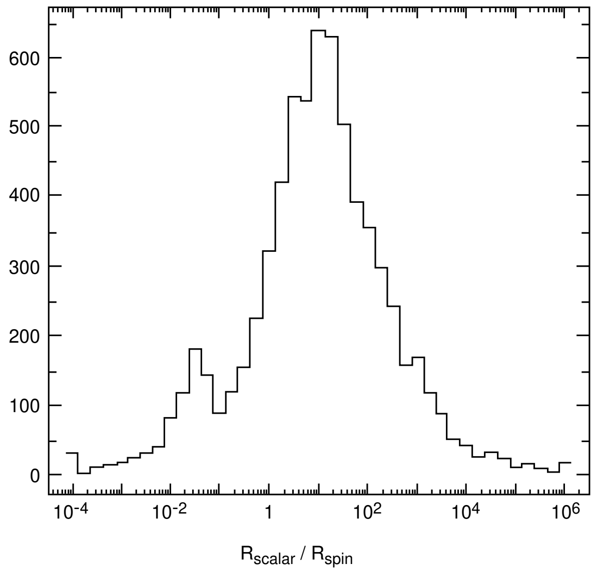

Figure 2: *A comparison of the spin-dependent and spin-independent interaction rates of relic neutralinos χ with Germanium in a sampling of supersymmetric models [12].*

The fact that no axion has been seen in any accelerator experiment tells us that

$$f_a \gtrsim 1\,\mathrm{TeV} \tag{7}$$

and hence that any axion must be associated with physics beyond the scale of the Standard Model.

Axions would have been produced in the early Universe in the form of slow-moving coherent waves that could constitute cold dark matter. The relic density of these waves has been estimated as [14]

$$\Omega_a \simeq \left(\frac{0.6\times10^{-5}\,\mathrm{eV}}{m_a}\right)^{7/6}\left(\frac{200\,\mathrm{MeV}}{\Lambda_{QCD}}\right)^{3/4}\left(\frac{75}{H_0}\right)^2 \tag{8}$$

which is less than unity if

$$f_a \lesssim 10^{12}\,\mathrm{GeV} \tag{9}$$

In addition to these coherent waves, there may also be axions radiated from cosmic strings [15], which would also be non-relativistic by now, and hence contribute to the relic axion density and strengthen the limit in equation (9).

The fact that the Sun shines photons rather than axions, or, more accurately but less picturesquely, that the standard solar model describes most data, implies the lower limit [16]

$$f_a \gtrsim 10^7\,\mathrm{GeV} \tag{10}$$

This has been strengthened somewhat by unsuccessful searches for the axio-electric effect, in which an axion ionizes an atom. More stringent lower bounds on f_a are provided by the agreements between theories of Red Giant and White Dwarf stars with the observations [17] :

$$f_a \gtrsim 10^9\,\mathrm{GeV} \tag{11}$$

Between equations (9) and (11) there is an open window in which the axion could provide a relic density of interest to astrophysicists and cosmologists.

Part of this window may be closed by the observations of the supernova SN1987a, which is where the polarized structure function measurements come into play. According to the standard theory of supernova collapse to form a neutron star, 99% of the binding energy released in the collapse to the neutron star escapes as neutrinos. This theory agrees [18] with the observations of SN1987a made by the Kamiokande [19] and IMB experiments [20], which means that most of the energy could not have been carried off by other invisible particles such as axions.

Since the axion is a light pseudoscalar boson, its couplings to nuclear matter are related by a generalized Goldberger-Treiman relation to the corresponding axial-current matrix elements, and these are in turn determined by the corresponding Δq [21]. Specifically, we find for the axion couplings to individual nucleons that

$$\begin{aligned} C_{ap} &= 2[-2.76\,\Delta u - 1.13\,\Delta d + 0.89\,\Delta s - \cos 2\beta\,(\Delta u - \Delta d - \Delta s)]\,, \\ C_{an} &= 2[-2.76\,\Delta d - 1.13\,\Delta u + 0.89\,\Delta s - \cos 2\beta\,(\Delta d - \Delta u - \Delta s)] \end{aligned} \tag{12}$$

Evaluating the Δq at a momentum scale around 1 GeV, as is appropriate in the core of a neutron star, we estimate [6] that

$$\begin{aligned} C_{ap} &= (-3.9 \pm 0.4) - (2.68 \pm 0.06)\cos 2\beta \\ C_{an} &= (0.19 \pm 0.4) + (2.35 \pm 0.06)\cos 2\beta \end{aligned} \tag{13}$$

which are plotted in Fig. 3(a). As in the case of LSP scattering, the uncertainties associated with polarized structure function measurements are by now considerably smaller than other uncertainties, in this case particularly those associated with the nuclear equation of state. The total axion emission rate from the core of a neutron star is approximately proportional to the combination

$${C_{an}}^2 + 0.8\,(C_{an} + C_{ap})^2 + 0.5\,{C_{ap}}^2 \tag{14}$$

which is plotted in Fig. 3(b), together with the associated with the errors in the Δq. Estimating axion emission rates in this way [22], it seems that part of the previous axion window is still open, and an experiment [23] is underway which should be able to detect halo axions if they occupy part of this window.

4 Polarized Scattering and Cosmology

The above examples show how measurements of the spin decomposition may not only deepen our understanding of nucleon structure, but may also help resolve important issues in cosmology. They are essential if one is to make reliable calculations of the nuclear interaction and detection rates for cold dark matter particles, which would be needed to confirm directly the emerging picture of structure formation in the Universe.

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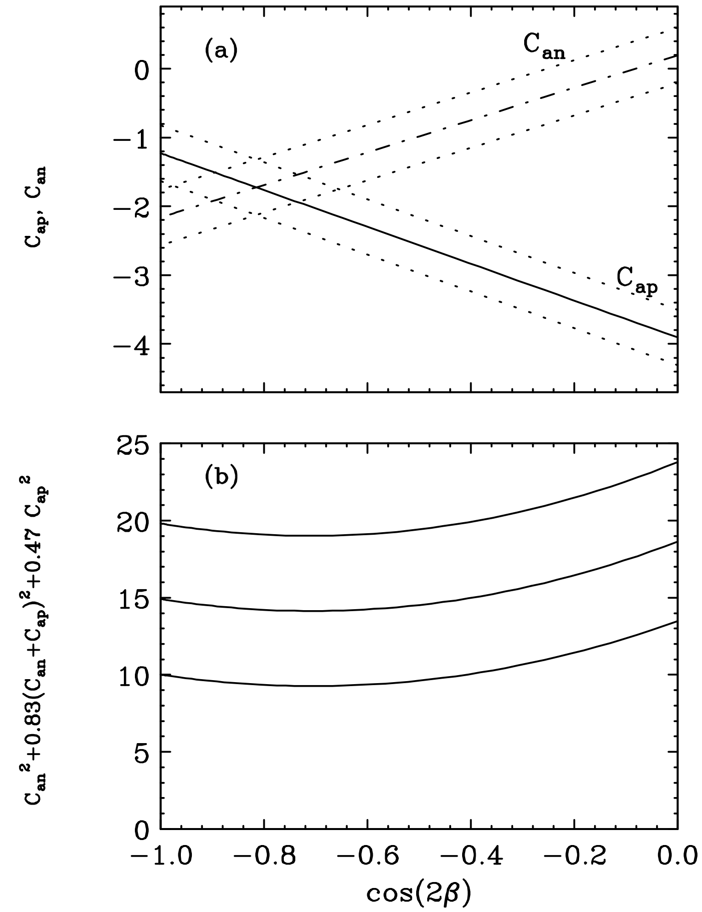

Figure 3: *(a) Axion couplings to the nucleon, as determined in Ref. [6] using polarized structure function data. (b) The total axion emission rate from the core of a neutron star, proportional to the combination* ${C_{an}}^2 + 0.8\,(C_{an} + C_{ap})^2 + 0.5\,{C_{ap}}^2$*, as determined in Ref. [6].*

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