Direct Dark Matter Detection: Overview and Update

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A series of modern experimental efforts aim for direct detection of particle dark matter in the Galactic halo. In this contribution, principles of direct detection are discussed in the context of modern experiments. Recent theoretical analysis on the extraction of particle properties and Galactic halo properties are reviewed, as well as astrophysical limits to direct dark matter detection.

1 Introduction

It is well-established that our Galaxy, as well as external galaxies, contains a substantial amount of dark matter that is deduced primarily via gravitational effects. Null results from searches for gravitational microlensing along the line-of-sight towards the Magellanic clouds imply that no more than $\sim 10\%$ of the Galactic dark matter halo is comprised of compact objects such as planets or low-mass stars [1, 2]. The dominant component of the dark matter must be smooth enough as to not cause an excess of microlensing events, and nearly cold and collisionless so as to satisfy constraints from the large scale distribution of galaxies and the Cosmic Microwave Background [3].

Cold, collisionless Weakly-Interacting Massive Particles (WIMP) in thermal equilibrium in the early Universe may freeze-out with a relic abundance of order the observed dark matter density, $\Omega_{\rm DM} = 0.227^{+0.015}_{-0.016}$. Elastic scattering processes between WIMPs and quarks may lead to observable signals in low background underground detectors [4]. It is therefore prudent to search for particles with these properties to determine whether they constitute a significant fraction of the mass of the Galactic halo.

This contribution reviews principles, results, and future prospects for direct searches of WIMP dark matter particles. It is intended to provide a theoretical overview and framework for the various experimental results discussed at this meeting. For details on each of the experiments, please see the respective presentations [1] and proceeding contributions.

2 Principles

WIMP-nucleus scattering in direct detection experiments is non-relativistic, described by incoming WIMP velocities of order $(v/c) \sim 10^{-3}$. The energy deposited to the nucleus in the

[1]`http://axion-wimp.desy.de/e80839/`

interaction is $\sim 1-10$ keV, much less than the typical nuclear binding energy scale of MeV per nucleon. Even though the energy deposited to the nucleus is small, experiments are primarily sensitive to the high velocity tail of the distribution of WIMPs in the halo.

In terms of fundamental interactions, it is most standard to assume that WIMP-nuclei elastic scattering is described by a momentum-independent contact interaction. For standard scalar, fermionic, and vector dark matter construction of non-relativistic operators then leads to the WIMP-nucleus cross section (See e.g. [5] for a recent analysis and review). More general dark matter models can be considered, e.g. inelastic dark matter [6] or dark matter with momentum-dependent interactions.

The lightest neutralino of supersymmetry has been extensively studied as a dark matter candidate. See Refs. [7] for general reviews of supersymmetric dark matter candidates. Though a wide range of cross sections are predicted in neutralino models, experimental limits and theoretical considerations point to the "zeptobarn" scale as characteristic for spin-independent cross sections [8]. Modern experimental limits are quickly approaching this regime of sensitivity.

The observed recoil spectrum due to WIMP interactions is given by the integral $dR/dE_R = N_T \rho_\chi / m_\chi \int_{v_{\rm min}}^{v_E} d^3v v f(v) d\sigma/dE_R$, where N_T is the number of targets, ρ_χ is the local WIMP density, and m_χ is the WIMP mass. The minimum velocity for scattering is $v_{\rm min}$ and the escape velocity is v_E. The differential cross section scales as $d\sigma/dE_R \propto v^{-2}$, so that the rate is simply parameterized as proportional to the integral over the WIMP velocity distribution as $\int dv f(v)/v$.

3 Recent Results

The final results from the CDMS experiment, and also first results from ZEPLIN III [9] and EDELWEISS II [10], are beginning to exclude WIMP cross sections predicted in the canonical Constrained Minimal Supersymmetric Standard Model (CMSSM) [13, 14]. The first results from the XENON100 experiment achieve a cross section sensitivity of $\sim 3 \times 10^{-44}$ cm^2 at a WIMP mass of ~ 40 GeV [12].

Due to the results of the CoGent [16] and DAMA [15] experiments, there has been recent interest in WIMPs in the relatively low-mass range ~ 10 GeV [18]. A new low threshold analysis from CDMS with a trigger threshold of 2 keV excludes parameter space associated with possible low mass WIMP signal interpretations by DAMA/LIBRA and CoGeNT [11]. The CDMS analysis reduces their energy thresholds by identifying the relevant electron recoil backgrounds. The first results from XENON100 may be sensitive to this low mass regime depending on the energy resolution of the scintillation efficiency at low nuclear recoils [19].

4 Future Prospects

A direct detection of particle dark matter would represent a scientific achievement of profound importance. Though at the present stage direct dark matter detection experiments operate as "discovery" experiments, it is worthwhile to consider the scientific gain a positive signal would entail. A new laboratory would be opened up that allows to probe the fundamental interactions of particle physics, and also a new field of "dark matter astronomy" will be born.

The limits discussed above assume a canonical dark matter halo model described by a smooth maxwellian distribution function with a local dark matter density of 0.3 GeV cm^{-3} and a Galactic escape velocity of 544 km/s. A series of recent papers has explored how these limits and future signals will change depending on the properties of the Galactic dark matter distribution [20]. Several authors have also revisited the constraints on the local dark matter density given astrophysical data [21]. Though our knowledge of the distribution of local dark matter from astrophysical observations is impressive, it is unlikely it in of itself constitute a strong enough prior when attempting to determine the WIMP mass.

Ultra-high resolution simulations of Galaxy-mass dark matter halos have determined, at their resolution limits of $\sim 10^3$ $M_\odot$, the smooth versus clumpy mass and velocity distribution in the Galactic halo [22]. Numerical simulations that include baryonic effects have particle resolutions over two orders of magnitude larger [24]. Though the smooth component of the velocity distribution is most significant, these simulations show deviations from standard Maxwellian models, particularly at high velocity tail close to the escape velocity. Deviations of the smooth distribution from maxwellian behavior can be analytically understood starting from cosmologically-motiaved density profiles, under simplifying assumptions [25].

Current direct detection experiments operate under the principle of zero astrophysical backgrounds. However, this will be possible only up to a certain sensitivity level. Irreducible signals from coherent scattering of solar neutrinos [26] limit the extraction of dark matter-nucleon cross sections below 10^{-46} cm^2 at energies below ~ 7 keV for Ge and below ~ 5 keV for Xe [27]. At lower cross sections of $\sim 10^{-48}$ cm^2 neutrino signals from atmospheric and diffuse supernova become significant over the entire energy recoil range where a WIMP signal is expected.

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