Wanted! Nuclear Data for Dark Matter Astrophysics

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Astronomical observations from small galaxies to the largest scales in the universe can be consistently explained by the simple idea of dark matter. The nature of dark matter is however still unknown. Empirically it cannot be any of the known particles, and many theories postulate it as a new elementary particle. Searches for dark matter particles are under way: production at high-energy accelerators, direct detection through dark matter-nucleus scattering, indirect detection through cosmic rays, gamma rays, or effects on stars. Particle dark matter searches rely on observing an excess of events above background, and a lot of controversies have arisen over the origin of observed excesses. With the new high-quality cosmic ray measurements from the AMS-02 experiment, the major uncertainty in modeling cosmic ray fluxes is in the nuclear physics cross sections for spallation and fragmentation of cosmic rays off interstellar hydrogen and helium. The understanding of direct detection backgrounds is limited by poor knowledge of cosmic ray activation in detector materials, with order of magnitude differences between simulation codes. A scarcity of data on nucleon spin densities blurs the connection between dark matter theory and experiments. What is needed, ideally, are more and better measurements of spallation cross sections relevant to cosmic rays and cosmogenic activation, and data on the nucleon spin densities in nuclei.

Cosmological observations agree with a universe made mostly of dark energy and cold dark matter. Their nature is still unknown. In the quest to unveil what dark matter is, there appears to be a need for new or better nuclear physics data.

This short article starts by overviewing the cold dark matter problem: the issue, the simplest idea of a new elementary particle, and some ways to test this idea. This is followed by three uncertain nuclear physics aspects of relevance to the dark matter problem, which are at the same time a request for more information: $A(\mathrm{p},x)B$ and $A(\alpha,x)B$ cross sections up to 100 GeV of beam energy for stable and long-lived ($\gtrsim 1$ Myr) isotopes up to $A\sim 64$ (admittedly a tall order); ${}^{\mathrm{nat}}\mathrm{Ge}(\mathrm{n},x)B$, ${}^{\mathrm{nat}}\mathrm{Xe}(\mathrm{n},x)B$ and ${}^{\mathrm{nat}}\mathrm{Ar}(\mathrm{n},x)B$ cross sections around 1 MeV of beam energy; nucleon spin densities up to ~ 100 MeV/c of momentum transfer (~ 2 fm^{-1}) inside ^{13}C, ^{17}O, ^{19}F, ^{23}Na, ^{43}Ca, ^{73}Ge, ^{127}I, ^{129,131}Xe, ^{133}Cs, ^{183}W, which are nuclei used or soon to be used in dark matter experiments.

I. THE COLD DARK MATTER PROBLEM

Modern cosmology has achieved the measurement in physical units of the energy density of the universe constituents. The most precise method is based on applying the well-known atomic physics of hydrogen and helium ionization and recombination, plus general relativity, to the universe of 13 billions years ago. A recent analysis [1] of several cosmological data shows that the universe is composed mostly of dark energy and cold dark matter: 585 ± 3 pJ/m^3 in dark energy, 194 ± 3 pJ/m^3 in cold dark matter, 37.6 ± 0.5 pJ/m^3 in ordinary matter, 1 to 7 pJ/m^3 in neutrinos, and 0.04175 ± 0.00004 pJ/m^3 in photons. Here "matter" is defined by its equation of state $p\ll\rho$, where p is the pressure and ρ the total energy density including rest mass. "Dark energy" is defined by its equation of state $p=-\rho$ (cosmological constant). Matter is subdivided into "ordinary matter," which in this context is protons, neutrons, and electrons, and "cold dark matter," which does not interact significantly with photons and ordinary matter at hydrogen recombination.

The amount and location of cold dark matter is inferred from a variety of cosmological data ranging from dwarf galaxies to the largest structures in the universe. Galaxies, through rotation curves and velocity dispersion profiles, are observed to spin faster or be hotter than the gravity which the visible mass can support. Clusters of galaxies, through the motion of galaxies, gravitational lensing, and measurements of the gas density and pressure, are observed to be mostly made of invisible mass. The presence of an invisible mass in the universe of ~13 billion years ago is also the simplest way to understand how the inhomogeneities observed in the young universe through the Cosmic Microwave Background (CMB) have evolved into the observed distribution of galaxies.

What is cold dark matter made of? Of course it cannot be photons, but it cannot either be any of the unstable particles in the standard model of particle physics, because they do not live for billions of years. Nor can it be protons, neutrons, or electrons, because they would have coupled to the CMB photons. Finally it cannot be standard model neutrinos either because their mass is too small. No known particle can be cold dark matter: this

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is the dark matter problem.

The simplest and most elegant idea is that cold dark matter is a new massive elementary particle that interacts weakly, a WIMP (for Weakly Interacting Massive Particle). One naturally obtains the right cosmic density of WIMPs, and more importantly one can experimentally test the WIMP hypothesis because the same physical processes that produce the right density of WIMPs make their detection possible.

The WIMP cosmic density is set by WIMP production and annihilation in the primordial universe, e.g., quark-antiquark annihilation into WIMP-antiWIMP, or WIMP-WIMP if an antiWIMP is identical to a WIMP: $q\bar{q} \to \chi\overset{(-)}{\chi}$ and its inverse $\chi\overset{(-)}{\chi} \to q\bar{q}$. WIMP production may also occur at high energy particle accelerators, which may lead to the discovery of dark matter in the laboratory. WIMP annihilation in galactic halos or astrophysical objects like stars may allow the indirect detection of WIMPs through their annihilation signals. The crossed reaction $q\chi \to q\chi$ may allow the direct detection of WIMPs by scattering of galactic WIMPs in laboratory detectors. Scattering also sets the size of the smallest dark halos in the universe.

During the years, claims of WIMP detection have come and gone. Among the current claims are (i) the detection of an excess microwave emission around the Galactic Center (the WMAP/Planck haze), (ii) an annual modulation in the direct detection rate expected from the motion of the Earth around the Sun [2], (iii) a tentative detection of gamma-ray lines at ∼130 GeV photon energy from regions near the Galactic Center [3], and (iv) an excess in the flux of cosmic ray positrons above ∼10 GeV [4, 5].

It is the latter evidence that has brought the author to consider the nuclear physics aspects of dark matter searches. The excess is claimed over an expected background due to positron production by cosmic ray collisions in the galaxy. How well is this background predicted? It turns out that nuclear physics uncertainties are important, as described in the next section.

II. COSMIC RAY BACKGROUNDS

The principle behind indirect detection of particle dark matter is that dark matter particles transform into ordinary particles, which are then detected or inferred. Our galaxy is inside a halo of dark matter particles that wander around randomly and occasionally annihilate producing otherwise rare cosmic rays, like positrons, antiprotons, and photons with special spectra. Many cosmic ray and photon detectors have been searching for these signals from dark matter in cosmic ray and gamma-ray fluxes.

The Alpha Magnetic Spectrometer (AMS), under the direction of Samuel Ting, flew a prototype for 10 days on the Space Shuttle Discovery in June 1998 (AMS-01), and has been collecting data on the International Space Station since May 2011 (AMS-02). The first science results, presented after this conference [5], show the positron flux measured with the unprecedented precision of a few per-

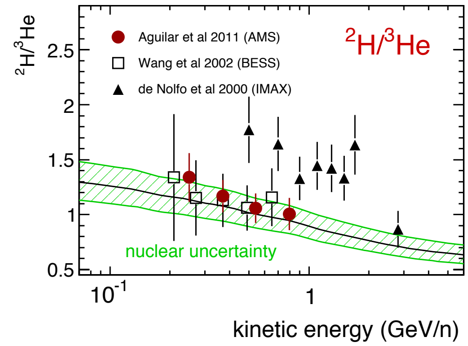

FIG. 1. Cosmic ray abundance ratio as a function of the cosmic ray kinetic energy. The nuclear cross sections entering cosmic ray calculations are much more uncertain than the upcoming AMS-02 measurements of isotopic ratios, which will be an order of magnitude more precise than the AMS-01 data points in this ^{2}H/^{3}He plot from Tomassetti [15].

cent from 500 MeV to 350 GeV. Ten times more data are expected and thus a much better precision.

The theoretical models of cosmic ray propagation (GALPROP [6] and DRAGON [7]) are more uncertain than the AMS-02 data (see e.g. note 17 in Ref. [5]). In these models, cosmic rays diffuse in a $\sim 10 \times 40$ kpc region of random magnetic fields surrounding the Galactic disk. Primary cosmic rays (p, ^{4}He, C, N, O, . . ., Fe, ^{64}Ni) are produced in supernova remnants, as first evidenced in Ref. [8]. Secondary cosmic rays (^{2}H, ^{3}He, ^{7,9,10}Be, ^{10,11}B, . . ., ^{26}Al, ^{35}Cl, ^{54}Mn, . . .) are produced in cosmic ray collisions with the interstellar medium, which is 90% H and 10% He in mass. The ratio of secondary to primary fluxes carries information on the astrophysical model. AMS-02 is expected to measure many of the important isotopic ratios to $\sim 1\%$ precision up to Fe and ~ 100 GeV/nucleon, and much higher precision at lower energies [9].

The nuclear physics implemented in GALPROP is impressive: a nuclear reaction network from ^{64}Ni downward; nuclear decays, mostly β, from the Nuclear Data Sheets; total p(p, x) and A(p, x) inelastic cross sections adapted from Ref. [10]; total $A(^4\mathrm{He}, x)$ inelastic cross sections from fits to data; $A(\mathrm{p}, x)B$ spallation cross sections from LANL-T16, CEM2k and LAQGSM [11], Silberberg-Tsao's YIELDX2000 [12] and/or Webber *et al.* [13], with special fits to data for production of ^{2,3}H, ^{3}He, Li, Be, B, Al, Cl, Sc, Ti, V, Mn; $A(^4\mathrm{He}, x)B$ spallation cross sections from Ref. [14].

Despite this admirable nuclear physics collection, the $A(\mathrm{p}, x)B$ and $A(\alpha, x)B$ spallation cross sections are much more uncertain than the upcoming AMS-02 measurements. Tomassetti [15] has provided an example of this, using a compilation of nuclear cross sections for ^{2}H and ^{3}He production in interstellar space – ^{4}He(p, d)^{3}He, ^{4}He(p, pn)^{3}He, ^{4}He(p, 2p)^{3}H, ^{4}He(p, pd)^{2}H, ^{4}He(p, ppn)^{2}H, ^{4}He(p, ppnn)^{1}H, p(p, π)^{2}H – and modified parametrizations from Ref. [16] (see Fig. 1).

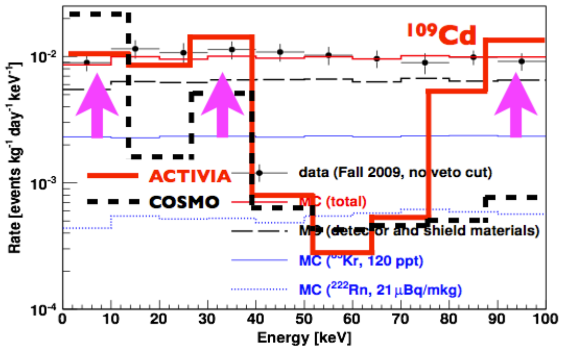

FIG. 2. Measured electromagnetic background in XENON100 (black crosses) compared with Monte-Carlo simulations for the cryostat radioactivity (thin black and red lines) and the liquid xenon radioactivity (thick red and black lines). The arrows point to energy bins in which the Monte-Carlo background exceeds the measured background. (Figure obtained from zooming and overlapping figures in [17, 22].)

Thus the author wishes for better measurements of as many $A(\mathrm{p},x)B$ and $A(\alpha,x)B$ cross sections as possible up to 100 GeV for long-lived ($\lesssim$ 1 Myr) isotopes with $A \lesssim 64$, which are the progenitors of the H, He, Li, Be, B, etc. cosmic ray fluxes that will soon be measured to $\sim 1\%$ precision by AMS-02.

III. RADIOACTIVE BACKGROUNDS IN DIRECT WIMP SEARCHES

In direct dark matter detection one searches for dark matter particles that arrive on Earth and scatter off nuclei in a detector. The only expected signal is some energy deposition, and since almost anything may deposit energy in a detector, the name of the game is to operate in low background environments with highly efficient background discrimination. This is a very active field and dozens of detectors scattered around the world are taking data or will become operational within a year or so.

Because of the intrinsic difficulty of distinguishing a neutron background from a dark matter signal, understanding the radioactive background in direct detection experiments is very important. The XENON100 study of their background [17] is instructive in regard to the nuclear physics involved. Almost all of the XENON100 radioactivity in the cryostat steel can be accounted for from isotopic measurements of ^{85}Kr, ^{222}Rn, and highly sensitive germanium spectroscopy of similar material [18], adjusted for exposure time and extra ^{54}Mn (only a small excess remains unaccounted for around 1 MeV).

However, radioactivity from the liquid xenon target itself, which arises from neutron activation of xenon, is poorly estimated by existing codes (ACTIVIA [19], COSMO [20], TALYS [21]), which give results differing by orders of magnitude [17, 22]. In particular, in the region of relevance for dark matter searches ($\lesssim$ 100 keV), the simulated background rate exceeds the measured rate

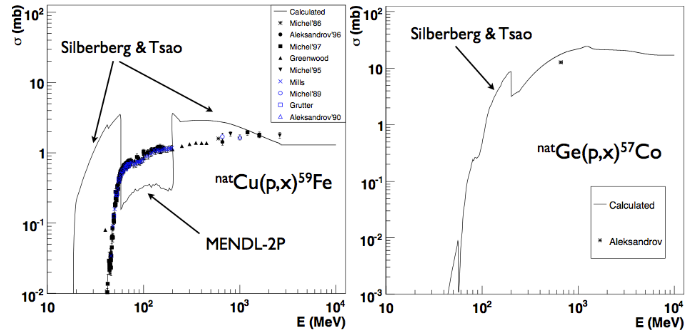

FIG. 3. Examples of activation cross sections used in ACTIVIA (solid line) compared to data (see [19] for larger versions). Can we rely on the cross section in the right panel, which contributes to the background in the dark matter region?

(Fig. 2). A look at some cross sections used in ACTIVIA (Fig. 3) suggests a possible explanation: the activation cross sections are too uncertain.

Therefore the author wishes for more data, or better evaluated data, or better models for (n,x) in Ge, Xe, Ar, which are the target nuclei in large upcoming dark matter experiments such as SuperCDMS, LUX, DarkSide, XENON-1T, EURECA, and DARWIN.

IV. SPIN STRUCTURE FUNCTIONS

Dark matter scattering off nuclei enters both direct and indirect detection strategies, an example of the latter being scattering and capture of dark matter particles into stars. WIMP-nucleus scattering can be either spin-dependent or spin-independent, and indeed in many particle physics models, the dark matter particles have non-zero spin and interact with the spin of the individual nucleons inside the nucleus. The spin-independent form factor (the Fourier transform of the nucleon number density) is relatively well understood theoretically and experimentally, using for example the electric charge form factor measured in muon scattering as a proxy. The analogous quantities for the spin-dependent part (the spin structure functions) are instead the main uncertainty in the calculation of the spin-dependent cross section.

The spin structure functions quantify the distribution of the nucleon spins inside the nucleus. The spin-dependent cross section for the elastic scattering of a spin-$\frac{1}{2}$ WIMP χ of mass m_χ off a spin-J nucleus of mass M with momentum transfer q can be put into the form [23]

$$\sigma_{\mathrm{SD}}(q) = \frac{32\mu^2 G_F^2}{2J+1}\left[a_{\mathrm{p}}^2 S_{\mathrm{pp}}(q) + a_{\mathrm{p}} a_{\mathrm{n}} S_{\mathrm{pn}}(q) + a_{\mathrm{n}}^2 S_{\mathrm{nn}}(q)\right],$$

where $\mu = m_\chi M/(m_\chi + M)$ is the reduced WIMP-nucleus mass, G_F is Fermi's constant, the a_N ($N = \mathrm{p},\mathrm{n}$) are effective coupling constants defined so that the four-particle WIMP-nucleon vertex is $2\sqrt{2}G_F a_N \boldsymbol{\sigma}_N \cdot \boldsymbol{\sigma}_\chi$ (the $\boldsymbol{\sigma}$'s are the Pauli matrices), and the $S_{NN'}(q)$ are the spin structure functions.

In detail, the WIMP-nucleus spin-spin interaction Hamiltonian is

$$H_{\rm spin-spin} = -\int \mathbf{s}_{\rm DM}(\mathbf{r}) \cdot \Big[a_0 \mathbf{s}_0(\mathbf{r}) + a_1 \mathbf{s}_1(\mathbf{r}) \Big] \, d\mathbf{r},$$

where $\mathbf{s}_{\rm DM}(\mathbf{r})$ is the WIMP spin density, and the $\mathbf{s}_T(\mathbf{r})$ ($T = 0, 1$) are the proton and neutron spin densities in the isospin basis

$$\mathbf{s}_T(\mathbf{r}) = \sum_{i=1}^{A} \frac{\boldsymbol{\sigma}(i)}{2} \, \omega_T(i) \, \delta(\mathbf{r} - \mathbf{r}_i).$$

Here $\omega_0 = 1$, $\omega_1 = \tau_3$ (the third isospin matrix), $a_0 = a_{\rm p} + a_{\rm n}$, and $a_1 = a_{\rm p} - a_{\rm n}$. For WIMP-nucleus scattering, the matrix elements of the WIMP spin current with initial (final) momentum and spin projection $\mathbf{p} m_s$ ($\mathbf{p}' m_s'$) are $\langle \mathbf{p}' m_s' | \mathbf{s}_{\rm DM}(\mathbf{r}) | \mathbf{p} m_s \rangle = \langle m_s' | \mathbf{S}_{\rm DM} | m_s \rangle e^{i\mathbf{q}\cdot\mathbf{r}}$, where $\mathbf{S}_{\rm DM}$ is the WIMP spin operator and $\mathbf{q} = \mathbf{p} - \mathbf{p}'$ is the momentum transfer. The $e^{i\mathbf{q}\cdot\mathbf{r}}$ term gives rise to the spin form factors (Fourier transforms) $\int \mathbf{s}_T(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d\mathbf{r}$, which are expanded in multipoles

$$\int \mathbf{s}_T(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d\mathbf{r} = 4\pi \sum_{\lambda l m} i^{l+\lambda} \, \mathbf{Y}^{(\lambda)}_{lm}(\widehat{\mathbf{q}}) \, s^{(T,\lambda)}_{lm}(q).$$

Here the $\mathbf{Y}^{(\lambda)}_{lm}(\widehat{\mathbf{q}})$ ($\lambda = 0, \pm 1$) are transverse-electric, transverse-magnetic, and longitudinal vector harmonics. The spin structure functions then follow as

$$S_{TT'}(q) = \sum_{\lambda l} \langle J || s^{(T,\lambda)}_l(q) || J \rangle^* \, \langle J || s^{(T',\lambda)}_l(q) || J \rangle.$$

Theoretical calculations of spin structure functions are available, assessed by comparison with magnetic moments and magnetic dipole transitions [24]. However the author is not aware of any data on the spin structure functions. Notice in this regard that the typical momentum transfer in WIMP direct searches is $q = \sqrt{2ME_{\rm recoil}} \sim 50$ to 150 MeV/c in I and Xe, $\sim$ 40 to 120 MeV/c in Ge, and $\sim$ 15 to 45 MeV/c in F. Notice also that the nucleon spin density is similar but not identical to the axial current density appearing in nuclear weak interactions.

Therefore the author wishes for experimental data on the nucleon spin densities (spin structure functions) at $\sim$ 10 to $\sim$ 100 MeV/c in nuclei of relevance to direct WIMP searches, such as ^{13}C, ^{17}O, ^{19}F, ^{23}Na, ^{43}Ca, ^{73}Ge, ^{127}I, ^{129,131}Xe, ^{133}Cs, ^{183}W. The author is unsure about which experimental methods are appropriate to measure the spatial distribution of spin (not magnetization, which also contains a contribution from orbital motions) inside these nuclei.

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