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A New Approach to Nuclear Form Factors for Direct Dark Matter Searches

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Abstract

We present a new approach to determine the nuclear form factors which are important for the direct dark matter experiments. We perform a systematic global determination of the form factors covering a wide range of nuclei, from ^{9}Be to ^{209}Bi. The commonly-used Lewin-Smith approach is improved by fitting both parameters of the Fermi proton-density distributions directly to the experimental data. Our procedure allows to extract the widely-used Helm form factor, providing for the first time realistic (conservative) uncertainties for the parameters. In addition, we rely on recent measurements of antiprotonic atoms to constrain the neutron-density distributions. Systematics errors are estimated and possible correlations are explored.

Keywords: Dark matter, dark matter direct detection, nuclear form factor.

1. Introduction

The goal of several ongoing and future direct detection experiments is to discover the dark matter present in our galactic halo in the form of Weakly Interacting Massive Particles (WIMPs). These experiments attempt to isolate from various backgrounds the signal of nuclear recoils from the elastic scattering of WIMPs with the target nuclei inside the detector [1–16]. The expected differential rate of nuclear recoils in a detector is given by (see for instance Ref. [17]):

$$\frac{dR}{dE_{nr}} = \frac{\rho_\chi}{2m_\chi\mu^2}\,\sigma^{SI}\,F^2(q)\int_{v_{min}}^{v_{escape}}\frac{f(\vec{v},t)}{v}\,d^3v \quad (1)$$

where E_{nr} is the energy of the recoiling nucleus, ρ_χ is the local halo WIMP density, m_χ is the WIMP mass and $\mu = m_\chi M/(m_\chi + M)$ the WIMP-nucleus reduced mass; $f(\vec{v},t)$ is the WIMP velocity distribution in the reference frame of the detector and σ^{SI} the spin-independent WIMP-nucleus elastic scattering cross section off a point-like nucleus; $F(q)$ is the nuclear form factor which depends on the recoil momentum $q = \sqrt{2ME_{nr}}$.

The nuclear form factor critically determines the spectrum of the recoil nuclei. Therefore its precise determination and error estimation is crucial to establish the bounds on the WIMP-nucleon cross section from running experiments and to plan future ones.

In direct dark matter searches and related studies, it has been customary to describe the nuclear form factors using the Helm ansatz [18], which leads to an analytic expression for the form factor. On the other hand, the charge density distributions have been extracted from muon spectroscopy [19] using two-parameter Fermi (2PF) distributions. The widespread strategy to deal with this dichotomy is to convert the 2PF parameters into Helm ones adopting an *ad − hoc* value for the nuclear thickness [20].

The present approach improves the one of Ref. [20] (Lewin-Smith), taking also into account the information about neutron-density distributions recently extracted in measurements of antiprotonic atoms [21, 22]. We provide realistic (conservative) uncertainties for the parameters, estimating the systematic errors and exploring possible correlations. At the same time, we keep the simple and analytic expressions intrinsic of the Helm parameterization.

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2. The Nuclear Form Factor

The spatial extension of a nucleus is described by the nuclear form factor. The role of the form factor is easily understood by looking, for example, at the elastic scattering of electrons off nuclei [23]. The scattering of electrons from a point-like target is simply described by the Rutherford/Mott formula (Coulomb scattering). However, the nucleus is not point-like, but has a structure. It is observed that the Rutherford formula agrees with the experimental cross sections only for small momentum transfers q, i.e., for scattering angles very close to $0°$. At larger q the experimental cross sections are systematically smaller and show typical diffraction patterns, which reflect the internal structure of the nucleus. The location of the minima is related to the size of the target nucleus. For light nuclei the form factor falls off slowly with q^2, while for heavier ones the more extended density distributions cause a stronger fall-off of the form factor. In the limit of a point-like target nucleus $F(q) \rightarrow 1$.

The form factor is the Fourier transform of the nuclear density:

$$F(\vec{q}) = \frac{1}{A} \int \rho_{nucl}(\vec{r})\, e^{i\vec{q}\cdot\vec{r}}\, d^3\vec{r} \tag{2}$$

normalized so that $F(0) = 1$. Dark-matter studies have traditionally assumed that

$$\frac{\rho_{nucl}}{A} = \frac{\rho_{charge}}{Z}\,, \tag{3}$$

relying on the well measured nuclear charge density distributions to determine the form factor and bypassing the fact that neutron distributions are, in general, different.

The charge distribution of protons in nuclei can be extracted precisely and, to a large extent, model independently. It has been extensively determined by elastic scattering of electrons [24] and, more recently, also by muonic atom spectroscopy [19]. The present knowledge of the neutron distributions is far more uncertain. Therefore, realistic error estimates should take their larger errors into account. This is particularly important in scenarios where the cross sections on protons and neutrons are different.

3. The Form Factor in the Lewin-Smith Approach

The approach commonly used to determine the from factor for direct dark matter searches for the spin-independent case is reported in Ref. [20]. The nuclear density distribution is assumed to be the same as the charge distribution of protons. This is available for a large set of nuclei [19] in the form of 2PF distributions:

$$\rho(r) = \rho_0 \left[1 + exp\left(\frac{r-c}{a}\right)\right]^{-1}\,, \tag{4}$$

where c is the nuclear radius at half of the central density ρ_0, and a is the diffuseness of the nuclear surface. The latter is related to the surface thickness $t = 4\ ln3\ a$, defined as the distance over which the density decreases from 90% to 10% of ρ_0.

As there is no analytical expression for the Fourier transform of the 2PF distribution, most dark matter studies adopt the Helm expression [18] for the spin-independent form factor

$$F(qR) = 3\frac{J_1(qR)}{qR} e^{-(qs)^2/2}\,, \tag{5}$$

where R is the effective nuclear radius, s is the nuclear skin thickness and $J_1(qR)$ is the spherical Bessel function.

The strategy of Lewin and Smith is to convert the 2PF parameters into Helm ones. This is achieved by equating the root mean square radii

$$r^2_{rms}(\text{2PF}) = \frac{3}{5}c^2 + \frac{7}{5}\pi^2 a^2\,, \tag{6}$$

$$r^2_{rms}(\text{Helm}) = \frac{3}{5}R^2 + 3s^2\,. \tag{7}$$

The diffuseness is fixed at $a \simeq 0.52$ fm [19], while c is derived from a not-weighted fit to the muon spectroscopy data of Ref. [19]: $c \simeq \left(1.23\,A^{1/3} - 0.60\right)$ fm. Finally, an $ad-hoc$ value is taken for $s \simeq 0.9$ fm. According to Ref. [20], this value is chosen to improve the matching between the form factors obtained with the Helm ansatz and from numerically-integrated 2PF distributions.

This approach is qualitative, with only the radius parameter c fitted to the data, while both a and s are fixed. Moreover, it only accounts for the proton distribution and the errors are not estimated.

4. A New Approach to the Nuclear Form Factor

We have performed a systematic global determination of nuclear form factors for nuclei ranging from ^{9}Be to ^{209}Bi. Concerning the proton distributions, we improve the Lewin-Smith approach [20] by fitting directly the measured nuclear radii [19] and diffuseness [24]. We also add the information on the neutron distributions, obtained from antiprotonic atoms [21, 22].