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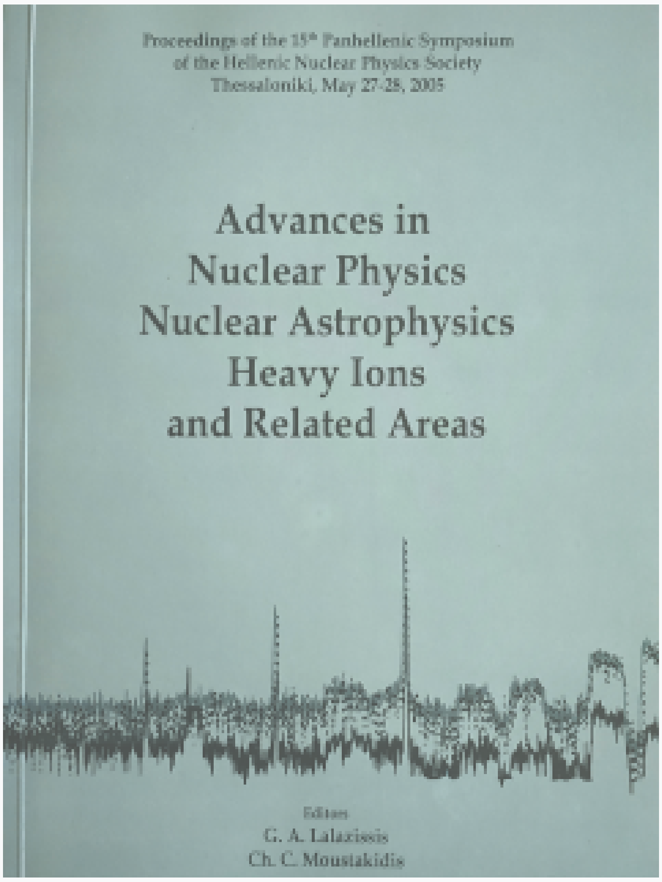

Direct dark matter research by observing electrons produced in neutralino-nucleus collisions

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Direct dark matter research by observing electrons produced in neutralino-nucleus collisions

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Abstract

The most important process for directly detecting dark matter is the LSP-nucleus elastic scattering by measuring the energy of the recoiling nucleus. In the present work we explore a novel process that is the detection of the dark matter constituents by observing the low energy ionization electrons. We develop the formalism and apply it in calculating the ratio of the ionization rate to the nuclear recoil rate in a variety of atoms. The obtained ratios are essentially independent of all parameters of supersymmetry except the neutralino mass, but they crucially depend on the electron energy cut off. Based on our results it is both interesting and realistic to detect the LSP by measuring the ionization electrons following the-LSP nuclear collisions.

1 Introduction

Supersymmetry naturally provides candidates for the dark matter constituents where the most favored is the lightest supersymmetric particle (LSP).

However the event rates, of LSP-nucleus elastic scattering, are expected to be quite low and the nuclear recoil energies are extremely small. Thus one has to try to reduce the background to the lowest possible level and to understand possible origins of backgrounds to be corrected for [1,2]. Anyway one has to search for characteristic signatures associated with the LSP. Such are:

- The time dependence of the event rates, which is due to the motion of the Earth (modulation effect).
- The correlation of the observed rates of directionally sensitive experiments with the motion of the sun.
- Inelastic excitations to low lying excited nuclear states have also been considered [3].
- Detecting the dark matter constituents by observing the low energy electrons, which follow the ionization of the atom during the LSP-nucleus collision [1,2].

The last possibility may be realized with the technology of gaseous TPC detectors [4]. We propose that the produced electrons in atomic excitation should be studied by exclusive measurements and we consider a number of experimentally interesting targets.

2 The essential ingredients of our calculation

The differential cross section for the LSP nucleus scattering leading to the emission of electrons in the case of non-relativistic neutralino takes the form [1,2]

$$d\sigma(\mathbf{k}) = \frac{1}{v}\frac{m_e}{E_e}|M|^2 \frac{d\mathbf{q}}{(2\pi)^3}\frac{d\mathbf{k}}{(2\pi)^3}(2\pi)^3 \frac{1}{2(2l+1)} \sum_{n\ell m} p_{n\ell} \times \quad (1)$$
$$\left[\tilde{\phi}_{n\ell m}(\mathbf{k})\right]^2 2\pi\delta\left(T_\chi + \epsilon_{nl} - T - \frac{q^2}{2m_A} - \frac{(\mathbf{p}_\chi - \mathbf{k} - \mathbf{q})^2}{2m_\chi}\right).$$

In order to avoid any complications arising from questions regarding the allowed SUSY parameter space, we will present our results normalized to the standard neutralino-nucleus cross section. The obtained branching ratios are essentially independent of all parameters of supersymmetry except the neutralino mass and take the form [1,2]

$$\frac{d\sigma(T)}{\sigma_{nrec}} = \frac{1}{4}\sum_{n\ell} p_{n\ell}|\tilde{\phi}_{n\ell}(\sqrt{2m_e T})|^2 m_e\sqrt{2m_e T}$$
$$\times \frac{\int_{-1}^{1} d\xi_1 \int_{\xi_L}^{1} d\xi K^{\frac{(\xi+\Lambda)^2}{\Lambda}}[F(\mu_r v(\xi+\Lambda))]^2}{\int_0^1 2\xi d\xi [F(2m_r v\xi)]^2} dT \qquad (2)$$

where $F(q)$ is the nuclear form factor. The nuclear form factor $F(u)$ entering in Eq. (2) has the general form

$$F(u) = \frac{Z}{A}F_Z(u) + \frac{N}{A}F_N(u)\ . \qquad (3)$$

The proton and neutron form factors ($F_Z(u)$ and $F_N(u)$ respectively) are calculated by the Fourier transform of the proton density distribution $\rho_Z(\mathbf{r})$ and neutron density distribution $\rho_N(\mathbf{r})$ respectively. In the present work $\rho_Z(\mathbf{r})$ and $\rho_N(\mathbf{r})$ are constructed using harmonic oscillator wave functions.

In the present work we consider also very accurate spin-independent atomic wave functions obtained by Bunge *et al* [5], by applying the Roothaan-Hartree-Fock method (RHF) to calculate analytical self-consistent-field atomic wave function.

The LSP obeys a velocity distribution. In our vicinity it is commonly assumed that LSP obeys a simple Maxwell-Boltzmann velocity distribution with respect to the galactic center, namely

$$f(v) = \frac{1}{(v_0\sqrt{\pi})^3} e^{-(v^2/v_0^2)} \qquad (4)$$

with $v_0 = 220$Km/s. One has to imposes by hand an upper velocity bound (escape velocity), $v_{esc} = 2.84 v_0$.

Folding both the numerator and denominator of Eq. (2) with the LSP velocity distribution, after multiplying each with the LSP flux $\frac{\rho(0)}{m_\chi}\frac{m}{Am_p}v$ we obtain the differential ratio $\frac{1}{R}\frac{dR_e}{dT}$, with R_e the

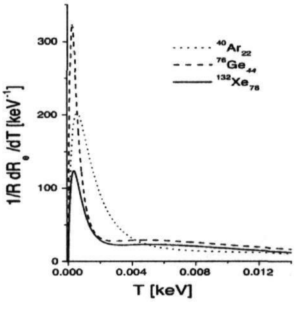

Fig. 1. The differential rate for ionization electrons, divided by the total rate associated with the nuclear recoils, as a function of the electron energy T (in keV) for various atoms. The results exhibited were obtained for a typical LSP mass $m_\chi = 100$ GeV by including a nuclear form factor, but without recoil threshold effects.

rate for the ionization. The resulting expression takes the form:

$$\frac{1}{R}\frac{dR_e}{dT} = \frac{d\sigma(T)}{\sigma_{nrec}} = \sum_{n\ell} p_{n\ell} |\tilde{\phi}_{n\ell}(\sqrt{2m_e T})|^2 m_e \sqrt{2m_e T}$$

$$\times \frac{\int_{\upsilon_{min}}^{\upsilon_{max}} N\upsilon^2 e^{-\upsilon^2/\upsilon_0^2} \sinh(2\upsilon/\upsilon_0) d\upsilon}{\int_{\upsilon'_{min}}^{\upsilon_{max}} D\upsilon^2 e^{-\upsilon^2/\upsilon_0^2} \sinh(2\upsilon/\upsilon_0) d\upsilon} dT. \tag{5}$$

In Eq. (5) υ_{max} is the escape velocity, while $\upsilon_{min} = \sqrt{\frac{2(T-\epsilon_{n\ell})}{\mu_r}}$ and $\upsilon'_{min} = \frac{\sqrt{2Am_pQ_{th}}}{2\mu_r}$.

3 Results and Discussion

The results for the differential ratio $\frac{1}{R}\frac{dR_e}{dT}$ are exhibited by considering three different atoms (^{40}Ar, ^{76}Ge and ^{132}Xe) for the typical LSP mass $m_\chi = 100$ GeV (see Fig. 1). If we then integrate the differential rate $\frac{1}{R}\frac{dR_e}{dT}$ with respect to the electron kinetic energy T, we obtain the relevant event rate ratio $\frac{R_e}{R}$. The thus obtained results for a number of nuclei are shown in Fig. 2a. They are presented as a function of the threshold energy for electron detection E_{th} for LSP mass $m_\chi = 100$ GeV. We also present them as functions of the LSP mass m_χ, for $E_{th} = 0.2$ keV (Fig. 2b).

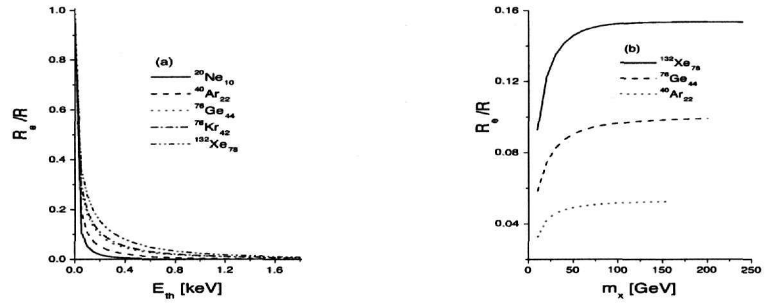

Fig. 2. (a) The total ionization rate per electron divided by the standard nuclear recoil rate as a function of the electron threshold energy. The results exhibited were obtained for a typical LSP mass $m_\chi = 100$ GeV by including a nuclear form factor, but no threshold effects on recoils. (b) The same quantity plotted as a function of the mass m_χ of the LSP. The results were obtained for a threshold energy $E_{th} = 0.2\ keV$

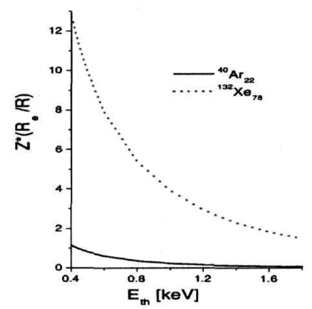

Fig. 3. The same as in Fig. 2a except that now the ionization rate R_e per electron is multiplied by the atomic number Z to obtain the rate per atom. A quenching factor of about 1/3 has also been included in the denominator.

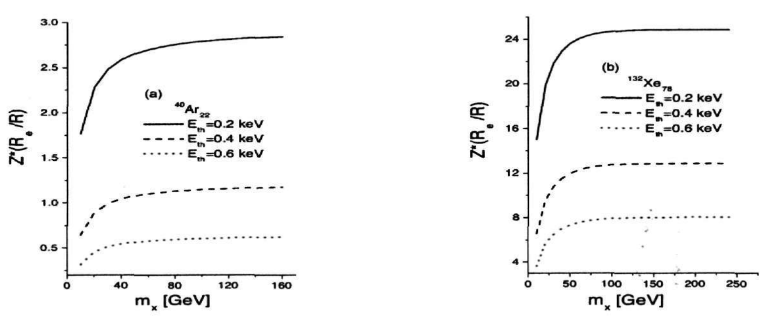

Fig. 4. The same as in Fig. 2b except that now the electron ionization rate per electron has been multiplied by the atomic number Z (the relative event rate per atom is $r = Z\frac{R_e}{R}$). A quenching factor of about 1/3 has also been included in the denominator (standard nuclear recoil).

We clearly see that the results are very sensitive to the threshold energy. It is also clear that the heavier targets are favored. It is encouraging that branching ratios per electron of 10% are possible, if one can reach threshold energies as low as 200 eV, which is feasible for gas targets [1]. It should be mentioned that in obtaining these results we assumed threshold effects for the ionization electrons, but not for the nuclear recoils. So far, the ratio of the electron rate to the recoil rate is normalized to one electron per atom. In practice, the total electron rate for given detector mass is obtained by multiplying the above rate per electron by the atomic number Z. Therefore the ratio of the total electron rate per atom to the nuclear recoil rate is plotted as a function of the threshold energy in Fig. 3 and as a function of the LSP mass in Fig. 4. Here a quenching factor of ≈ 0.3 has in addition been used for the nuclear recoil. The thus obtained ratio is very impressive, even at an electron threshold higher than 0.5 keV.

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