Nuclear proton and neutron distributions in the detection of weak interacting massive particles

G. Co' [1 2] , V. De Donno [1 2] , M. Anguiano [3] , A. M. Lallena [3]

[1]Dipartimento di Matematica e Fisica "E. De Giorgi", Università del Salento, Italy

[2]Istituto Nazionale di Fisica Nucleare sez. di Lecce, Italy

[3]Departamento de Física Atómica, Molecular y Nuclear, Universidad de Granada, Granada, Spain

The elastic collision with a nucleus is the main mechanism used by modern detectors to identify neutralinos, or more in general weakly interacting massive particles (WIMPs).

The cross section describing this collision with spin zero nuclei is usually described as

$$\sigma \, = \, \sigma_{\chi p} \, F^2_{ch}(q) \, |Z \, + \, g_{np} \, N|^2 \quad , \tag{1}$$

where $\sigma_{\chi p}$ is the, unknown, WIMP-proton cross section, $F_{ch}(q)$ is the charge form factor extracted from the electron-nucleus elastic cross section data, and Z and N the proton and neutron numbers, respectively. The factor g_{np} takes care of the different interaction of the WIMP with protons and neutrons.

In specific applications, the Helm factorization of the charge form factor $F_{ch}(q)$ [1] is usually adopted. This factorization has a simple analytic expression and the values of its parameters have been chosen to provide a good description of the empirical charge distributions overall the nuclear chart, with the exclusion of very light nuclei.

From the nuclear structure point of view, there are two relevant approximations contained in the expression (1). The first one is related to the use of the charge form factor. Since the WIMPs are insensitive to the electromagnetic interaction, the pointlike proton distributions should be used instead of the charge distributions. The second approximation consists in the fact that in Eq. (1) proton and neutron distributions are not separately identified. This could be a good approximation for $Z = N$, nuclei but not for neutron excess nuclei which, on the other hand, are the major components of the WIMP detectors.

We have studied the relevance of these approximations for a set of spin zero nuclei which are interesting in WIMP detectors [2]. We can summarize our work by saying that we substituted the expression (1) with

$$\sigma^{\rm SI}_{\chi A} \, = \, \sigma_{\chi p} \, |Z \, F_p(q) \, + \, g_{np} \, N \, F_n(q)|^2 \quad , \tag{2}$$

where the proton, $F_p(q)$, and neutron, $F_n(q)$, form factors have been calculated by using the pointlike proton and neutron distribution obtained by Hartree-Fock (HF) [3] and Hartree-Fock plus Bardeen, Cooper and Schrieffer (HF+BCS) calculations [4].

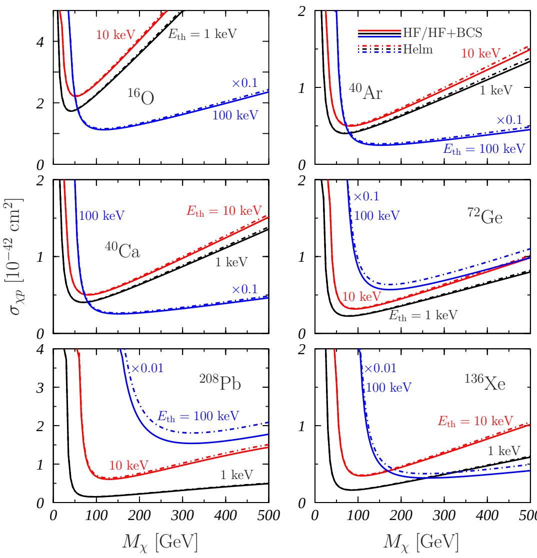

Figure 1. Upper limits of the WIMP-proton cross section $\sigma_{\chi p}$ as a function of the WIMP mass M_χ. The various curves have been obtained for different values of the detection energy threshold E_{th}. The dashed-dotted lines indicate the results obtained by using the Helm form factors, the full lines with our model.

We have considered six nuclei of interest in the WIMP detectors. Three of these nuclei, ^{16}O, ^{40}Ca and ^{208}Pb, are doubly magic. For these nuclei we have calculated the nucleon distributions by using a non relativistic HF approach with a finite-range nucleon-nucleon interaction. This approach has been well tested against other mean-field approaches, non relativistic HF with zero-range interactions and relativistic Hartree approaches [3]. The comparison with the empirical charge distributions and the experimental elastic electron scattering cross sections is highly satisfactory. In the other three nuclei we have considered, ^{40}Ar, ^{52}Ge and ^{136}Xe, the single particle levels are not completely filled. In these cases, we have carried BCS calculations on top

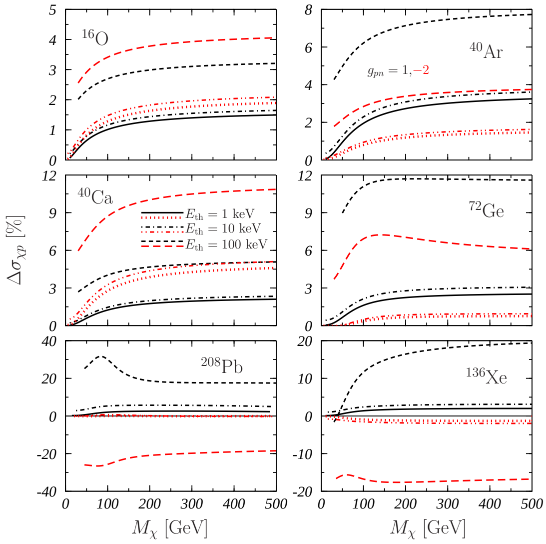

Figure 2. Relative differences between the limit values of $\sigma_{\chi p}$ as a function of M_χ calculated with our model and those obtained with the Helm model.

to the HF solutions to evaluate the partial occupation probability of the various single particle levels [5].

The cross sections obtained by inserting the HF and HF+BCS nucleon distributions in Eq. (2) have been used to evaluate the probability of detecting a WIMP. In Fig. 1 we show the upper limits of $\sigma_{\chi p}$, as a function of M_χ, needed to detect at least a single event per day in an ideal detector of 100 tons, for threshold energies of 1, 10 and 100 keV. The full lines show the results obtained by using our matter distributions, while the dashed-dotted lines indicate the results obtained by using the Helm form factors. The results relative to the threshold energy E_{th}, of 100 keV have been multiplied by 0.1 in case of ^{16}O, ^{40}Ca, ^{40}Ar, ^{72}Ge nuclei, and by 0.01 for ^{136}Xe and ^{208}Pb nuclei.

As expected the line of the exclusion plot is lower for lower values of E_{th}, i.e. for a larger sensitivity of the detector. The differences between our results and those obtained with the Helm form factors become larger with increasing target mass, with increasing M_χ values, and with increasing E_{th}. These results show a minimum difference of 1.4% in the case of ^{16}O for $E_{th} = 1$ keV, and a maximum one of 15% for ^{208}Pb with $E_{th} = 100$ keV.

The results we have so far presented have been obtained by assuming the same coupling strength of the WIMP with protons and neutrons, i. e. $g_{np} = 1$ in Eq. (2). We expect that, by releasing this assumption, as suggested, for example, in Ref. [6], the requirement of a correct description of proton and neutron distributions becomes more important. For this reason, we have carried on calculations for different values of g_{np}. We have chosen values of g_{np} producing extreme situations.

We have evaluated the consequences of these differences by calculating limits as those shown in Fig. 1 with different values of g_{np}. We show in Fig. 2 the relative differences $\Delta\sigma_{\chi p}$ between the limits of the WIMP-proton cross section calculated with our matter distributions and those obtained with the Helm form factors. The results for $E_{\rm th} = 1, 10, 100$ keV are shown. The black (full, dashed-dotted and short-dashed) lines show the relative differences of our reference calculations done with $g_{np} = 1$, i.e. those obtained from the results of Fig. 1. The red (dotted, dashed-doubly-dotted and long-dashed) lines indicate the differences obtained with $g_{np} = -2$, a value comparable with that suggested in Ref. [6]. In all the cases the largest differences have been obtained for a threshold energy of 100 keV. As it has been previously discussed, the differences are enhanced with increasing E_{th}. We do not identify common trends in this figure. Sometime the $g_{np} = -2$ results show the largest differences, in other cases the largest differences are produced by $g_{np} = 1$. We observe that in ^{40}Ar, ^{72}Ge and ^{136}Xe these values can reach the 20%.

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