Dark matter search by exclusive studies of X-rays following WIMPs nuclear interactions

H. Ejiri [a,b], Ch.C. Moustakidis [c], J.D. Vergados [d,*]

[a] INT, University of Washington, Seattle, WA 98195, USA
[b] JASRI-SPring-8, Mikazuki-cho, Hyogo 679-5198, Japan
[c] Department of Theoretical Physics, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece
[d] University of Ioannina, Ioannina, GR-45110, Greece

Abstract

It is shown that weakly interacting massive particles (WIMPs), which are possible cold dark matter candidates, can be studied by exclusive measurements of X-rays following WIMPs nuclear interactions. Inner-shell atomic electrons are ionized through WIMP-nuclear interaction, and then mono-energetic X-rays are emitted when they are filled by outer-shell electrons. The number of inner-shell holes amounts to as large as one per five nuclear recoils for K-shell and several per recoil for L-shell in the case of medium heavy target nuclei interacting with 100–300 GeV WIMPs. Then the K and L X-ray peaks show up in the 5–50 keV region. Consequently exclusive studies of the X-rays in coincidence with the nuclear recoils and the ionization electrons are found to provide excellent opportunities to detect WIMPs such as the lightest super-symmetric particles (LSP).
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PACS: 95.35.+d; 12.60.Jv

1. Introduction

Exotic dark matter is one of the major components of the dark matter in the universe. Experimental studies of the dark matter [1–3], together with the recent WMAP observations [4, 5], indicate that the universe consists of the dark matter with $\Omega_{CDM} \approx 30\%$, the dark energy with $\Omega_\Lambda \approx 65\%$ and the baryonic matter with $\Omega_b \approx 5\%$, with Ω_{XY} being the fraction of the mass of the type XY. The dark matter is considered to be mainly of the cold variety made of weakly interaction massive particles (WIMPs) such as the lightest super-symmetric particles (LSP). The nature of WIMPs can only be unveiled by their direct detection in the laboratory. It is, thus, of great interest to directly search for WIMPs from the view point of both particle physics

and cosmology. Such experimental studies of WIMPs, however, require high sensitivity detectors and/or novel methods, since the WIMP signals are expected to be extremely rare and occur at very low energy.

The purpose of the present Letter is to show for the first time that:

(i) inner-shell electrons are well excited through WIMPs nuclear interactions,
(ii) hard X-rays are emitted when inner-shell holes thus created are filled by outer-shell electrons and
(iii) exclusive measurements of such X-rays provide new excellent opportunities for high-sensitivity studies of WIMPs.

Many experimental searches for WIMPs have been made in the last decade. As a result the DAMA experiment has claimed the detection of cold dark matter particles with a mass of $\approx$ 30–100 GeV, by the observation of a seasonal modulation of the low-energy spectra [6]. On the other hand subsequent ex-

* Corresponding author.
E-mail addresses: ejiri@rcnp.osaka-u.ac.jp (H. Ejiri), moustaki@auth.gr (Ch.C. Moustakidis), vergados@cc.uoi.gr, vergados@artemis1.physics.uoi.gr (J.D. Vergados).

periments, such as the EDELWEISS [7] and CDMS [8] data, almost exclude cold dark matter events in the region claimed by DAMA. At least, if the WIMP-nuclear interaction is of the scalar type. In order to settle such issues several groups are currently planning suitable experiments using high-sensitivity detectors.

All searches for WIMPs have so far been made by attempting to observe the recoiling nuclei, following their elastic scattering with the WIMPs. This seemed to be the only possibility, since the average energy of the dark matter constituents is too low to excite the nucleus with appreciable rates. In fact most experiments have employed targets with a large mass number A, expecting the coherent mode to dominate, since the cross-section is proportional to A^2. In any event the recoil energy spectrum of the elastic scattering is of a continuum shape, decreasing rapidly as the energy increases. It thus exhibits almost identical behavior with that of the background. It is thus very hard to separate and identify the interesting recoil signal from those due to the background.

In order to identify WIMPs signals, one needs to use detectors which are almost free of backgrounds or to identify and measure additional quantities with signatures, which are characteristic of WIMPs. Thus many groups measure the ratio of ionization to phonon, the ratio of ionization to scintillation and/or the pulse-shape to differentiate the electron backgrounds. The seasonal modulation of the event rates, due to motion of the earth motion is another good way to identify the cold dark matter, provided that origin of the backgrounds is fully understood and one is convinced that it does not show any seasonal variation. Directional experiments correlated with the sun's direction of motion are also good signatures. Especially if they are combined with measurements of the annual modulation [9]. Admittedly, however, such experiments are hard [10].

It has been shown back in 1993 by one of the present authors (H.E.) and his colleagues [11] and recently by another (J.D.V.) and his colleague [12] that γ-rays, following inelastic scattering off nuclei, provide a unique way to study WIMPs, in particular spin-coupled dark matter since the γ energy can be as large as 10–100 keV and is monochromatic. Furthermore, unlike the nuclear recoil measurements, no quenching effect appears in the case of the γ detection. For these reasons it appears quite feasible to measure such γ-rays.

In the previous paper [13,14], we have shown that the measurement of ionized electrons via WIMPs nucleus interactions can be a good and realistic way for the direct detection of the LSP.

The present proposal, i.e. X-ray measurements for the identification of the dark matter constituents, is based on the above mentioned previous studies of the γ-ray and the ionization electron detection. More specifically in the present Letter we suggest that the X-rays, following the elastic scattering of WIMPs off medium heavy nuclei, have several unique features making them suitable for WIMP studies. We show, in particular, that the production rate of K and L X-rays is large and, accordingly, the direct detection of WIMPs by exclusive studies of the X-rays is realistic. The study of the X-rays following the scattering of WIMPs off nuclei offers some unique advantages such as:

(1) The K and L X-rays show discrete peaks in the 5–50 keV energy region for medium-heavy nuclei, in contrast to the nuclear recoil detection, which exhibits a continuous spectrum falling rapidly with energy beyond a few keV. The observed energy spectrum of the nuclear recoil is further shifted to the lower energy region in a solid detector due to the quenching effect. The X-rays are thus free from detector threshold effects, since the threshold is below a few keV in most detectors.

(2) The nuclear recoil is followed by hard X-rays. Then exclusive measurement of the nuclear recoil in coincidence with such hard X-rays reduce most BG signals by orders of magnitudes. Thus it is realistic with the exclusive measurement to study WIMPs in the region of around 10^{-7} pb proton cross-section. Detectors for such high-sensitivity experiments are going to be discussed later.

(3) The X-ray production rate relative to the standard nuclear recoil rate is determined by kinematical conditions. It thus depends on the dark matter particle mass, but it is independent of any other properties of WIMPs or the nuclear structure. This is not the case of the γ-rays arising from inelastic scattering, since the inelastic cross-sections depend on the nuclear structure and are not well known.

(4) X-ray detection will aid the standard experiments in two ways:
   - by inclusive measurements of the energy sum of the nuclear recoil, the ionization electrons and the X-rays,
   - by exclusive studies of the X-rays in coincidence with the nuclear recoil and/or the ionization electrons. Experimentally, identification of the X-ray, the ionization electron and the nuclear recoil are feasible by spatial and time correlation analyzes of their energy deposits.

The X-ray production rate is simply evaluated as in case of the ionization electron rate discussed in the previous papers [13, 14]. Using the same notations there, the ratio of the $n\ell$-shell electron ionization rate to the nuclear recoil rate, normalized to one electron per atom, is given as [14]

$$\frac{\sigma_{n\ell}}{\sigma_r} = p_{n\ell} \int \left| \phi_{n\ell}\left(\sqrt{2m_e T}\right) \right|^2 f(T, \epsilon_{n\ell}) m_e \sqrt{(2m_e T)} \, dT, \quad (1)$$

with

$$f(T, \epsilon_{n\ell}) = \frac{\int N v^2 e^{-v^2/v_0^2} \sinh(2v/v_0) \, dv}{\int D v^2 e^{-v^2/v_0^2} \sinh(2v/v_0) \, dv}, \quad (2)$$

where $p_{n\ell}$ is the probability of one electron in the $n\ell$ shell.

Since a real atom has Z electrons per atom, the cross-section ratio to be observed is obtained by multiplying the ratio given in Eq. (1) by the factor Z. In the last equation, both the numerator and the denominator (nuclear recoil) have been convoluted with the WIMP velocity distribution, which is taken to be Gaussian with respect to the galactic center [14].

The kinematical ranges have been discussed in our earlier work [14]. For the reader's convenience we only mention here that the upper limits of integration in both the numerator and the denominator of Eq. (2) correspond to the maximum LSP velocity, which is given by the escape velocity, $v_{esc} = 2.84 v_0$

with $\upsilon_0 = 220$ km/s the Sun's rotational velocity. The lower limit in the denominator is set to zero, a conservative estimate assuming that the nuclear recoil detection can go down to zero energy threshold. The lower limit in the numerator is given by:

$$\upsilon_{\min} = \sqrt{\frac{2(T - \epsilon_{n\ell})}{\mu_r}}. \tag{3}$$

In other words the whole expression is a function of T and $\epsilon_{n\ell}$. The range of integration in Eq. (1) over the electron energy is between $T = 0$ and $T = \frac{1}{2}m_\chi \upsilon_{\mathrm{esc}}^2 + \epsilon_{n\ell}$. The precise value of the maximum energy is not very relevant, since the rate peaks at much lower electron energies. If one attempts to detect electrons one encounters a threshold energy [14], E_{th}, but in the experiment proposed here X-rays will be detected, not electrons. For completeness, however, we mention that the total rates for electron detection are sensitive to the value of E_{th} [14], but the rates associated with the inner-shell electrons are not. This is true in particular for the 1s rates, regardless of the WIMP mass. For a WIMP mass of 100 GeV the 1s rates change less than 3% in going from $E_{\mathrm{th}} = 0$ to $E_{\mathrm{th}} = 0.2$ keV.

The inner-shell production rates have been evaluated in the case of the ^{131}Xe isotope, as a typical isotope of medium heavy nuclei. It is noted that inner-shell excitation rates depend on the atomic number, as it has previously been shown [14], but not on the mass number. In fact natural Xe isotopes will be used for experiments with Xe. The ratios of the inner-shell ionization to the nuclear recoils, together with the binding energies, are shown for light, medium and heavy WIMPs with the mass of 30, 100 and 300 GeV in Table 1.

The number of the K-shell (1s shell) holes per recoil increases as the WIMP mass increases. It is quite sizable and remains almost constant for mass ⩾ 100 GeV. This is due to the fact that the average nuclear recoil velocity increases with the WIMP mass. The number of the L-shell (2s and 2p) holes per recoil can be as large as 5–7 for WIMP mass in the range 30–300 GeV. Since K X-ray emission necessarily requires larger energy transfer from WIMPs than L X-ray one, ratios of K X-ray to L X-rays depend on the WIMP mass. Accordingly, the K to L ratio can be used to get the WIMP mass, if both can be clearly observed.

The $n\ell$ X-ray production rate is simply obtained by using the X-ray branching ratio as

$$\frac{\sigma_{n\ell}(\mathrm{X})}{\sigma_r} = b_{n\ell} \frac{\sigma_{n\ell}}{\sigma_r}, \tag{4}$$

where $\sigma_{n\ell}(\mathrm{X})$ is the sum of the X-ray rates for X-rays filling the $n\ell$ shell and $b_{n\ell}$ is the fluorescence ratio. The Auger electron branching ratio is simply given by $1 - b_{n\ell}$. Here we assumed that the inner-shell electron holes are filled by outer-shell electrons in the same atom via X-ray emission or the Auger effect. Non-radiative electron transfer to the inner-shell from neighboring atoms is considered to be small, since the nuclear recoil velocity is much smaller than the K-shell electron velocity. The K-shell fluorescence ratio for Xe is 0.89 in case of one K-hole in the atom. X-ray cross-sections relative to the nuclear cross-sections, given by $[Z\sigma_{n\ell}(\mathrm{X})/\sigma_r]$ are 0.03, 0.20, and 0.23 for WIMPs with 30, 100 and 300 GeV, respectively. The X-ray rate increases as the WIMP mass increases as can be seen from the data of Table 1.

The above results were obtained [14] using realistic wave functions [15]. It should be mentioned, however, that these wave functions do not include relativistic effects, which may somewhat affect the inner-shell electrons and, in particular, 1s bound electron wave functions. In the present case, however, the outgoing electrons have very low energy. So the event rates are not affected by the lower component of the corresponding spinors. We find that, in the case of the Coulombic interaction, the modification of the upper component due to relativistic effects reduces the 1s hole production by less than 30%. Anyway more detailed such calculations are under study and will appear elsewhere.

K X-rays are followed by L X-rays, and L X-rays are by M X-rays and so on. The energy sum of these X-rays is just the K-shell binding energy. These X-rays are converted to electrons via the photo-electric effect in detectors. Then, in the case of one $n\ell$-shell hole, the sum of the photo-electron energies and the sum of the Auger electron energies are given by the binding energy ($-\epsilon_{n\ell} \geqslant 0$). Therefore, one expects to find a $n\ell$ excitation signal with a relative rate (ratio) of $Z\sigma_{n\ell}/\sigma_r$ and electron energy of $-\epsilon_{n\ell}$.

It is indeed impressive to find that the average number of inner-shell electron holes, per nuclear recoil, are about 0.2 in the K-shell and about 5 in the L-shell in the case of ^{131}Xe for a WIMP mass of 100 GeV. In other words, one recoil nucleus is followed approximately one K X-ray per 5 recoils and by five L X-rays per recoil. This effect, however, is less dramatic in the case of a lighter WIMP (see Table 1).

The implications and the impact of the X-ray signal for high sensitivity studies of WIMPs are great because of its unique features. Let us, first, discuss effects of the X-rays on the energy spectrum in inclusive experiments. The total energy signal for

Table 1
The binding energies and the inner-shell ionization ratios in WIMP nuclear interactions for ^{131}Xe. The inner-shell ionization rates, normalized to one electron per atom, relative to the nuclear recoil rates are given in the 3–5 columns, and the inner-shell cross-sections relative to the nuclear recoil cross-sections are in the 6–8 columns

$n\ell$	$-\epsilon_{n\ell}$ keV	$\left[\frac{\sigma_{n\ell}}{\sigma_r}\right]_L$	$\left[\frac{\sigma_{n\ell}}{\sigma_r}\right]_M$	$\left[\frac{\sigma_{n\ell}}{\sigma_r}\right]_H$	$\left[\frac{Z\sigma_{n\ell}}{\sigma_r}\right]_L$	$\left[\frac{Z\sigma_{n\ell}}{\sigma_r}\right]_M$	$\left[\frac{Z\sigma_{n\ell}}{\sigma_r}\right]_H$
1s	34.56	0.0006	0.0041	0.0047	0.034	0.221	0.255
2s	5.45	0.0224	0.0271	0.0271	1.211	1.461	1.463
2p	4.89	0.0703	0.0834	0.0836	3.796	4.506	4.513
3p	0.96	0.1017	0.1050	0.1050	5.492	5.670	5.670
3d	0.68	0.1734	0.1775	0.1775	9.364	9.585	9.585

one event of an elastic scattering of WIMP is given by the sum,

$$E = QE_r + E_X + E_e, \qquad (5)$$

where E_r is the recoil energy with the quenching factor Q and E_X and E_e are, respectively, the total energy of the X-rays and that of the ionization and Auger electrons. In inclusive experiments, where X-ray signals are not separated from Auger electron signals, the energy sum of the X-rays and Auger-electrons is measured. A large fraction of the recoil events are followed by one K X-ray and/or several lower-energy X-rays, and thus the total energy is shifted by the sum of the X-ray energies.

In case of the 1s electron ionization followed by K X-rays, the energy spectrum is given approximately as

$$E_{1s} = QE_r^0 + E_{X_{1s}}(1 - Q), \qquad (6)$$

where $E_{X_{1s}} = -\epsilon_{1s}$ is the sum of the X-ray energies and $E_r^0 = E_r + E_{X_{1s}}$ is the recoil energy without 1s inner-shell excitation. Note that the recoil energy is used partly to excite the 1s electron to the continuum. Then the energy spectrum is shifted to higher energy side by $E_{X_{1s}}(1 - Q)$. This shift shows up as a bump at the energy around $E_{X_{1s}}(1 - Q)$ in medium-heavy mass detectors with $Q \ll 1$. These features of the energy spectrum may be used to identify the WIMP events to improve the detection sensitivity.

Exclusive studies of the X-rays are very powerful for high sensitivity experiments. K X-rays from Xe fly through Xe detectors for about 100 mg/cm^2, while L X-rays for about 4 mg/cm^2, before depositing their energies via photoelectric effects. Thus separation of the X-ray signals from those of the nuclear recoil and the ionization electrons can be made by using good position-resolution detectors of the order of 1 mg/cm^2 (i.e. 1.5 mm in 1 atm Xe gas) for exclusive measurements. The K X-rays from the I isotopes have a range of about 200 μm in NaI.

The K_{ij} X-ray ratio is evaluated as

$$\frac{\sigma_K(K_{ij})}{\sigma_r} = \frac{\sigma_{1s}}{\sigma_r} b_{1s} B(K_{ij}), \qquad (7)$$

where $B(K_{ij})$ is the K_{ij} X-ray branch [16]. The K X-ray rates are evaluated for the K-shell holes given in the Table 1 by using the K_{ij} X-ray branch for one K-hole in the atom.

The cross-sections for K X-rays relative to the nuclear recoil are obtained from the ratio in Eq. (7) by multiplying the total electron number Z. They are shown for ^{131}Xe isotopes in Table 2.

K$_\alpha$ and K$_\beta$ lines can be separated experimentally by using good energy-resolution detectors, but the sum of all K lines can be measured in modest energy-resolution experiments.

One option of detectors for exclusive studies of the X-rays following WIMPs scattering off nuclei is a TPC with Xe gas. The trajectory analysis makes it possible to identify the WIMP nuclear interaction point with the recoil and ionization electrons and the X-ray interaction point with the photo-electron track. A super-module of Xe gas ionization chambers for nuclear recoils and plastic scintillation-fibers for K X-rays is an alternative way for exclusive studies of X-rays and nuclear recoils.

Recently highly-segmented NaI scintillator array has been developed at Tokushima group [17]. It consists of 16 layers of thin NaI plates, each with 50 mm long 50 mm wide and 500 μm thick. Since the thickness of the NaI plate is of the order of the range of K X-rays from I isotopes, nuclear recoils are measured in one layer of NaI in coincidence with the K X-rays in an adjacent layer. One may expect the similar K X-ray rate from ^{127}I with $Z = 53$ as the rate from ^{131}Xe with $Z = 54$ given above.

The exclusive experiments are free of most backgrounds from natural and cosmogenic radioactive impurities in detector components, detector shields and experimental walls. Cosmogenic muons are well rejected by veto counters against charged particles. Then remaining backgrounds in the exclusive experiments are due to cosmogenic neutrons scattered off target nuclei, resulting in inner-shell electron excitations and X-ray emissions.

The event rate for ionization electrons relative to that for elastic neutron–nucleus scattering has already been estimated in our previous work [11]. Fig. 8 of this reference gives less than 0.05 per kg per y for all produced electrons. Thus the background K X-rays is expected to be less than that and even less than 0.01 by means of active shields such as plastic or liquid scintillators, since, in contrast to the weakly interacting WIMPs, the neutrons are strongly interacting particles. BG rates from fast neutrons at 4000 m w.e underground laboratories are less than 10^{-3} counts per kg per day, which are negligible in comparison with the WIMP signal rate resulting from a 10^{-7} pb p-cross-section. So this sort of background is not worrisome.

In any case K and L X-rays as well nuclear recoils resulting from WIMP interactions exhibit a similar pattern with those produced with neutrons capable of causing the same momentum transfer as WIMPs in the mass range of 100–300 GeV, i.e. neutrons with energy in the 10–20 MeV range. Thus one can exploit this fact to study experimentally the signals of interest by using neutrons as a probe.

Table 2
K X-ray cross-sections relative to the nuclear recoil, rates and energies in WIMPs nuclear interactions with ^{131}Xe. $[Z\sigma_K/\sigma_r]_L$, $[Z\sigma_K/\sigma_r]_M$ and $[Z\sigma_K/\sigma_r]_H$ are the ratios for light (30 GeV), medium (100 GeV) and heavy (300 GeV) WIMPs

K X-ray	$E_K(K_{ij})$ keV	$B_K(K_{ij})$	$\left[\frac{Z\sigma_K(K_{ij})}{\sigma_r}\right]_L$	$\left[\frac{Z\sigma_K(K_{ij})}{\sigma_r}\right]_M$	$\left[\frac{Z\sigma_K(K_{ij})}{\sigma_r}\right]_H$
K$_{\alpha2}$	29.5	0.284	0.0086	0.0560	0.0645
K$_{\alpha1}$	29.8	0.527	0.0160	0.1036	0.1196
K$_{\beta1}$	33.6	0.154	0.0047	0.0303	0.0350
K$_{\beta2}$	34.4	0.034	0.0010	0.0067	0.0077

Background events due to Compton and photoelectric scattering of low-energy photons may give the same topology of energy deposition as WIMP events followed by K or L X-rays if the Compton-scattered electrons are in the nuclear recoil energy-window of 2–20 keV and the Compton-scattered photons are in the X-rays energy window. Such low-energy photons, however, are unlikely to be Compton scattered. Simulation of typical U–Th impurities of the orders of 0.1 mBq per kg give 10^{-3} per kg per day, which is negligible. We should also mention that low-energy photons less than 100 keV in medium-heavy atoms are predominantly due to the photoelectric effect, while Compton scattering is unlikely. On the other hand, medium and higher energy photons may double-Compton scattered to give two electron signals quite like the recoils and the X-rays do. Scattered photons, however, are finally captured in other parts of the detector or by veto-counters around the detector, and, thus, they can be rejected.

Acutely, simulation analyzes for thin NaI modules give BG rates of the order of 2×10^{-2} per day per kg in the low-energy region in case of the exclusive measurements. This is similar to the upper limit of high-sensitivity CDMS experiment [8] and 2 orders of magnitude lower than the DAMA BG rate. Accordingly the sensitivity of the order of 10^{-7} pb proton cross-section can be expected in exclusive measurements for the medium and heavy WIMPs.

In short, the X-rays following WIMP nuclear interactions are of great interest to improve the sensitivity of the dark matter studies. WIMPs interacting with nuclei in medium and heavy mass region are likely followed by energetic K and L X-rays in the 10 keV region far above threshold energy of most detectors. In case of 100 GeV WIMPs interacting with ^{131}Xe, the K X-ray probability is more than 20%, and the energy sum is as large as 34 keV. Thus inclusive study of the recoil energy spectrum by means of solid detectors with a large quenching factor can be used to measure effectively the hard X-rays without the quenching reduction.

Exclusive studies of the hard X-rays in coincidence with the nuclear recoil and ionizing electrons are very powerful for WIMP search. The X-ray shows up as an isolated peak in the energy spectrum, and the coincidence measurement makes it possible to be almost free of BG's. K X-rays are quite promising to search for medium and heavy WIMPs, and L X-rays are used for light WIMPs as well as medium and heavy WIMPs. Thus it is quite realistic to study WIMPs/LSP in the 10^{-7} pb p-cross-section.

It should be noted that the fluorescence ratio and the K X-ray branching ratio used in the above discussions are those for one K hole in the atom. Actually, the outer-shell electron configuration in the recoil nucleus is not simple, but is rather complex. In fact the K X-rays are mainly the $K_{\alpha1}$ from the L_3 shell and the $K_{\alpha2}$ from the L_2 shell, and their branches de-

pend on the electron occupation-probabilities in the L_3 and L_2 shells. Actually, the $K_{\alpha1}$ and $K_{\alpha2}$ energies are so close to each other that they are not separated in most experiments. Then the sum of the K X-ray intensities is proportional to the K shell vacancy-probability, and is insensitive to the L_3 and L_2 shell occupation-probabilities. In practice, the K X-ray ratio can be calibrated experimentally by using nuclear recoils from low-energy neutron scattering off the target nuclei to be used for WIMPs experiments. Measuring angles of the scattered neutrons, one gets the nuclear recoils corresponding to WIMPs in the 30–300 GeV range.

Acknowledgements

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