Astroparticle Physics 30 (2008) 12–17

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

A model of nuclear recoil scintillation efficiency in noble liquids

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ARTICLE INFO

Article history:
Received 11 March 2008
Accepted 8 June 2008
Available online 17 June 2008

PACS:
95.35.+d
11.10.Lm
29.40.Mc

Keywords:
Nuclear recoil
Dark matter detection
Relative scintillation efficiency

ABSTRACT

Scintillation efficiency of low-energy nuclear recoils in noble liquids plays a crucial role in interpreting results from some direct searches for weakly interacting massive particle (WIMP) dark matter. However, the cause of a reduced scintillation efficiency relative to electronic recoils in noble liquids remains unclear at the moment. We attribute such a reduction of scintillation efficiency to two major mechanisms: (1) energy loss and (2) scintillation quenching. The former is commonly described by Lindhard's theory and the latter by Birk's saturation law. We propose to combine these two to explain the observed reduction of scintillation yield for nuclear recoils in noble liquids. Birk's constants *kB* for argon, neon and xenon determined from experimental data are used to predict noble liquid scintillator's response to low-energy nuclear recoils and low-energy electrons. We find that energy loss due to nuclear stopping power that contributes little to ionization and excitation is the dominant reduction mechanism in scintillation efficiency for nuclear recoils, but that significant additional quenching results from the nonlinear response of scintillation to the ionization density.

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1. Introduction

Noble liquid scintillators such as liquid xenon [1], argon [2,3], and neon [4] are expected to be excellent targets and detectors for direct dark matter detection experiments searching for weakly interacting massive particles (WIMPs), which may constitute the dark matter in the universe [5–8]. These experiments measure scintillation light induced by low-energy nuclear recoils due to elastic scattering of WIMPs. Absorption of nuclear recoil energy in noble liquid scintillators produces excitons and electron-ion pairs along the track. Free excitons collide with ground states to form excited molecules (excimers) through

$$X^* + X \rightarrow X_2^*, \tag{1}$$

where X stands for any type of noble liquid. Free ions undergo collision, recombination and deexcitation processes,

$$\begin{cases} X^+ + X \rightarrow X_2^+, \\ X_2^+ + e^- \rightarrow X^{**} + X, \\ X^{**} \rightarrow X^* + heat, \\ X^* + X \rightarrow X_2^*, \end{cases} \tag{2}$$

to form excimers. The excimers then decay radiatively from the lowest-excited molecular states ${}^1\Sigma_u^+$ and ${}^3\Sigma_u^+$ to the repulsive ground state ${}^1\Sigma_g^+$.

It is well known that noble liquid scintillators have reduced scintillation yield for low-energy nuclear recoils compared to electronic recoils [9–14]. Only a fraction of the energy loss results in ionization and atomic excitation. Moreover, high ionization density undermines recombination of electron-ion pairs and reduces scintillation light yield. The relative scintillation yield, defined as the ratio of the numbers of photons emitted from pure noble liquids in nuclear and electronic recoil events at the same energy, is a good measurement of the nuclear recoil scintillation efficiency, q_f, determined by the visible deposited energy over the true recoil energy. In the case of electrons and γ-rays, almost all the energy loss by ionization is converted into scintillation light through electron-ion recombination, so the relative scintillation efficiency is assumed approximately equal to 1 in the absence of an electric field. But in the case of nuclear recoils, q_f is much smaller than 1 and can vary as a function of nuclear recoil energy.

The scintillation efficiency plays an important role in the direct detection of WIMPs. In the design of a new experiment, the scintillation efficiency is related to the detection threshold and hence to the background level and ultimate sensitivity. In the interpretation of an experimental result, the scintillation efficiency is crucial to the determination of WIMP mass and WIMP-nucleon cross section. The nuclear recoil scintillation efficiencies for liquid xenon, argon, and neon have been measured [9–14] using neutron sources. The

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0927-6505/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.astropartphys.2008.06.001

detector is usually calibrated with well-known γ-rays, such as 122 keV and 133 keV lines from a ^{57}Co source. The relative scintillation efficiency for γ-rays, ϵ_γ, is defined as the visible energy divided by the incident γ-ray energy, and is assumed to be 1. As discussed later in this paper, this assumption is valid for electronic recoil energy above 20 keV in the noble liquids under investigation. The nuclear recoil scintillation efficiency is determined by the ratio of the nuclear recoil visible energy using the electron-equivalent energy calibration to the true recoil energy $E_{\mathrm{R}}, q_{\mathrm{f}} = E_{\mathrm{R}}^{\mathrm{vis}}/E_{\mathrm{R}}$.

The measurements are usually compared to either Lindhard's theory [15] or Hitachi's treatment [16]. It was found that Lindhard's theory alone can not well explain the observed behavior in the data. The alternative explanation, Hitachi's treatment, states that a biexcitonic quenching mechanism can occur before the free excitons self-trap when the excitation density is very high. This explanation can agree reasonably well with the xenon data [9], but has not been applied to explain low-energy recoil data for neon or argon. Moreover, there are other possible quenching processes that could contribute to the reduction of scintillation efficiency for low-energy nuclear recoils. These include collisions (via the Penning process [17]) between two excited molecular states (excimers) to form one excited state and one ground state [18], and supereleastic collisions that quench the singlet states to triplet states [19].

A more universal description of the reduced scintillation efficiency for nuclear recoils is preferred for all noble liquid scintillators. Since the proposed quenching mechanisms are all dependent on the density of the ionization and excitation track left by the recoiling nucleus, it is possible to form a combined model of these mechanisms without incorporating details of the relative contributions of the different mechanisms. Birk's saturation law for organic scintillators [20] provides a convenient description of the dependence of scintillation quenching on ionization density. In this study, we apply Birk's law to noble liquids, offering a conventional way to determine the total scintillation efficiency of nuclear recoils by measuring Birk's constant (*kB*). It has been shown that the luminescence intensity in the noble gas scintillator depends solely on the energy density and is independent of the kind of the particle [21,22]. This is to say that a measurement of *kB* for noble liquids will allow understanding of the relative scintillation efficiency for nuclear recoils induced by neutrons, alphas, and other heavy isotopes. This is a very valuable way to determine the scintillation efficiency for nuclear recoils induced by all types of particles in noble liquid scintillators. Furthermore, this method allows determination of the relative scintillation efficiency for nuclear recoils in noble liquids by measuring the constant *kB* with γ-rays. This is a much easier measurement compared to the nuclear recoil measurements with neutron and alpha sources.

In this paper, we propose a model to combine Lindhard's theory and Birk's saturation law to describe the reduction in scintillation efficiency observed in noble liquid scintillators. We describe these two reduction mechanisms in Section 2 and 3, respectively. The model combining these two reduction mechanisms is presented in Section 4 and its predictions are compared to experimental data in Section 5. The scintillation efficiency (ϵ_γ as a function of recoil energy) for very low-energy electrons and γ-rays is discussed briefly in Section 6. Finally, we summarize our conclusions in Section 7.

2. Reduced ionization energy by nuclear collisions

When a neutron or WIMP scatters elastically off a noble liquid atomic nucleus, the recoiling nucleus then loses its energy by colliding with electrons and nuclei within the detector. This nuclear recoil process involves the competition between, on the one hand, energy transfer to atomic electrons and, on the other hand, energy transfer to translational motion of atoms. The total rate at which the recoiling nucleus loses energy with respect to distance ($\mathrm{d}E/\mathrm{d}x$) is dependent on the medium through which it travels, and is also called the stopping power. At low energies, the total stopping power of the noble liquid atom consists of electronic and nuclear stopping power. The electronic stopping power is the amount of energy per unit distance that the recoiling nucleus loses due to electronic excitation and ionization of the surrounding noble liquid atoms. The nuclear stopping power is the energy loss per unit length due to atomic collisions that contribute to the kinetic energy (thermal motion) of the noble liquid atoms, but that do not result in internal excitation of atoms. The proportion of electronic to nuclear stopping power depends on the recoil energy of the nucleus. If the recoil energy were very large, the nuclear stopping power would be very small compared to the electronic stopping power. However, in the energy range of WIMP-nucleus elastic scatterings, the nuclear stopping power plays a significant role in the energy loss of the recoiling noble liquid nucleus Lindhard et al. [15] discussed in detail the theory of energy loss of low-energy nuclei.

Supposing that the recoiling nucleus loses all of its energy in the detector, the total energy loss can be expressed in terms of the losses due to the electronic stopping power η and nuclear stopping power v as [15]

$$E_{\mathrm{R}} = \eta(E_{\mathrm{R}}) + v(E_{\mathrm{R}}), \tag{3}$$

where η and v are both functions of recoil energy E_{R}. As only the portion of the energy lost in electronic excitation or ionization will result in the creation of excitons and electron-ion pairs in the noble liquids, the fraction defines an ionization energy reduction factor (f_{n}) due to losses to the nuclear stopping power

$$f_{\mathrm{n}}(E_{\mathrm{R}}) \equiv \frac{\eta(E_{\mathrm{R}})}{E_{\mathrm{R}}} = \frac{\eta(E_{\mathrm{R}})}{\eta(E_{\mathrm{R}}) + v(E_{\mathrm{R}})}. \tag{4}$$

As the total stopping power is

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{tot}} = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{elec}} + \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{nucl}}, \tag{5}$$

$f_{\mathrm{n}}(E_{\mathrm{R}})$ can then be determined by the ratio of two integrals

$$f_{\mathrm{n}}(E_{\mathrm{R}}) = \frac{\int_0^{E_{\mathrm{R}}} (\mathrm{d}E/\mathrm{d}x)_{\mathrm{elec}}\mathrm{d}E}{\int_0^{E_{\mathrm{R}}} ((\mathrm{d}E/\mathrm{d}x)_{\mathrm{elec}} + (\mathrm{d}E/\mathrm{d}x)_{\mathrm{nucl}})\mathrm{d}E}. \tag{6}$$

To present f_{n} as a function of recoil energy, the integrals above should be evaluated for each possible recoil energy. Lindhard et al. [15] represents f_{n} as

$$f_{\mathrm{n}} = \frac{kg(\varepsilon)}{1 + kg(\varepsilon)}, \tag{7}$$

where, for a nucleus of atomic number $Z, \varepsilon = 11.5E_{\mathrm{R}}(\mathrm{keV})Z^{-7/3}$, $k = 0.133Z^{2/3}A^{-1/2}$, and $g(\varepsilon)$ is well fitted by: $g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon$. Fig. 1 shows this ionization energy reduction factor for noble liquids from Lindhard's theory.

3. Reduced scintillation yield due to high ionization density

3.1. Birk's saturation law

The passage of a particle in a noble liquid produces a structured track along its path that is conveniently described in terms of a core and a penumbra [23]. The penumbra that surrounds the core is a low ionization density zone. The core is expected to be a high ionization density zone, so ionization density dependent quenching caused by biexcitonic collisions or the Penning process is likely to occur there. On the one hand, the free excitons can be self-trapped to form excimers, for example, Ar_2^*, that then fluoresce to