Astroparticle Physics 62 (2015) 108–114

Contents lists available at ScienceDirect

Astroparticle Physics

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

Ionization yield from nuclear recoils in liquid-xenon dark matter detection

Wei Mu [a], Xiangdong Ji [a,b,*]

[a] INPAC, Department of Physics, and Shanghai Key Lab for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 18 April 2014
Accepted 31 July 2014
Available online 15 August 2014

Keywords:
Liquid Xenon
Dark Matter
WIMPs
Ionization Yield

ABSTRACT

The ionization yield in a two-phase liquid xenon dark-matter detector has been studied in keV nuclear recoil energy region. The newly obtained nuclear quenching as well as the average energy required to produce an electron–ion pair from the measurement in Seguinot (1992) are used to calculate the total electric charges produced. To estimate the fraction of the electron charges collected, the Thomas-Imel model is generalized to describe the field dependence for nuclear recoils in liquid xenon. With free parameters fitted to experimentally measured 56.5 keV nuclear recoils, the energy dependence of ionization yield for nuclear recoils is predicted, which increases as recoil energy decreases and reaches the maximum value at 2∼3 keV. This prediction agrees well with existing data and may help to lower the energy detection threshold for nuclear recoils to ∼1 keV.

1. Introduction

In recent years, liquid xenon (LXe) has emerged as a leading medium for detecting weakly interacting massive particle (WIMP), which is one of the most promising dark matter (DM) candidates [1–3]. Many advanced LXe detectors [4–8] work in the two-phase mode with measurements of both scintillation (direct scintillation light, denoted as S1) and ionization (proportional scintillation light, denoted as S2) signals at the same time. The scintillation and ionization signals, together with the relative scintillation efficiency ($\mathcal{L}_{eff}$) and the ionization yield ($\mathcal{Q}_y$) respectively, have been used to reconstruct the nuclear recoil energy. Thus $\mathcal{L}_{eff}$ and $\mathcal{Q}_y$ are crucial physical quantities for the energy calibration of WIMP detection.

According to a recent theoretical calculation in Ref. [9], $\mathcal{L}_{eff}$ drops rapidly with decreasing energy in the low energy region, especially below 3 keV important for light DM particle detection (∼10 GeV/c^2). In this case, the uncertainty in $\mathcal{L}_{eff}$ becomes an important factor for reconstruction of the nuclear recoil energy. Because the collection of primary scintillation photons becomes more difficult at low recoiling energy, it is hard to measure scintillation efficiency experimentally. Therefore, the energy threshold of the LXe detectors determined from the primary scintillation efficiency is relatively high. On the other hand, the ionization signal will become more suitable for several reasons: First, the ionization and scintillation signals in LXe are anti-correlated [10,11]. The anti-correlation behavior refers to the phenomenon that the ionization and scintillation signals in liquid xenon are complementary. Therefore, as the decreasing of the scintillation photons in low energy region, the ionization signal can be more prominent. Second, for the two-phase LXe detector, after free electrons reach the gas chamber, the signals are amplified. Then single electrons are measured more easily than single photons [11]. In addition, when a strong external electric field, E_d, is applied across the LXe detector, a larger fraction of ionized electrons may escape from the event site and become ionization signals. Therefore, the ionization signals are a better choice for detection in low recoil energy region and will help lower the energy thresholds of LXe detectors. However, although a series of experimental measurements and theoretical studies have been done for the relative scintillation efficiency ($\mathcal{L}_{eff}$), only few measurements or theoretical studies are available for the ionization yield ($\mathcal{Q}_y$) [11–18].

Serving as a link between the ionization signal and the deposited energy of the WIMPs in LXe, the ionization yield for a two-phase LXe detector is defined as the number of free electrons, which have drifted into the gas chamber, per unit recoil energy (e$^-$/keV):

$$\mathcal{Q}_y(E_{nr}) = \frac{Q(E_{nr})}{E_{nr}}, \quad (1)$$

* Corresponding author at: INPAC, Department of Physics, and Shanghai Key Lab for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, PR China.

E-mail address: xdji@sjtu.edu.cn (X. Ji).

http://dx.doi.org/10.1016/j.astropartphys.2014.07.013
0927-6505/

where $Q(E_{\rm nr})$ is the number of the free electrons produced from nuclear recoil with initial energy $E_{\rm nr}$. This value is expected to depend on the external electric field but be independent of two-phase LXe detector design.

In this paper, we present a theoretical study of the energy dependence of ionization yield for nuclear recoils. To obtain $\mathcal{Q}_y$ theoretically, one has to calculate the actual collectable charges, Q. The latter in turn depends on the following two quantities: 1) the total charges produced from nuclear recoils, Q_0, and 2) the ionization efficiency, $r = Q/Q_0$. In the present study, we use the nuclear quenching factor, also called Lindhard factor $q_{\rm nc}(E_{\rm nr}) = \eta(E_{\rm nr})/E_{\rm nr}$, calculated in Ref. [9] and the experimentally measured average energy to produce an electron–ion pair, also called W-value, in Ref. [19] to calculate the number of total charges produced by the nuclear recoils, $Q_0 = E_{\rm nr}q_{\rm nc}(E_{\rm nr})/W$. We use the generalized Thomas-Imel model to predict the field and energy dependence of the ionization efficiency, $r = Q/Q_0$, taking into account the effects of the ionization density and the track structure of nuclear recoils. Consequently we find the ionization yield,

$$\mathcal{Q}_y(E_{\rm nr}) = \frac{E_{\rm nr}q_{\rm nc}(E_{\rm nr})}{W} \times \frac{Q}{Q_0}(E_{\rm nr}) \times \frac{1}{E_{\rm nr}} = \frac{q_{\rm nc}(E_{\rm nr})}{W} \times \frac{Q}{Q_0}(E_{\rm nr}), \quad (2)$$

which will be compared with available experimental data.

This paper is organized as follows. In Section 2, we review the ionization process of nuclear recoils and the measured W-value in different experiments. Combining theoretically calculated Lindhard factor with experimentally measured W-value, we calculate the number of total charges generated by nuclear recoils. In Section 3, we review the electron–ion recombination process and existing theoretical models for recombination rate. Then we generalize the Thomas-Imel [20] box model to parameterize the field dependence of ionization yield for nuclear recoils by considering the specific track structure of nuclear recoils. In Section 4, we present the model prediction for energy dependence of the ionization yield from nuclear recoils. Finally, we summarize and discuss our results in Section 5.

2. Electronic energy dissipation and total charge yield

In this section, we review the recent theoretical results on the total electronic energy dissipation (Lindhard factor) and the experimentally measured average energy required to produce one electron–ion pair, hence calculate the total charge yield from nuclear recoils.

2.1. Electronic energy dissipation and nuclear quenching

When a xenon nucleus is elastically scattered by a DM particle, it becomes a recoiling xenon atom (or nucleus) with kinetic energy up to a few tens of keV [21]. During the slowing down process, the recoiling xenon atom will excite and ionize other atoms inside the LXe medium, and at the same time produce secondary recoils, which subsequently lead to a collision cascade together with secondary trajectories surrounding the principle trajectory of the initial recoiling atom. After all the recoiling xenon atoms in the collision cascade are thermalized, the initial kinetic energy of the recoiling xenon atom dissipates into the kinetic energy of xenon atoms, excitation and ionization energies of atomic electrons. The electronic excitations will give rise to photons (scintillation signals) and free electrons (ionization signals), respectively.

Thus, to calculate the charge yield, one has to know the total electronic energy dissipation of the recoiling atom. The whole collision cascade process is in principle quantum mechanical and involves complicated many-body physics. One normally uses the Lindhard factor, also called nuclear quenching factor, to estimate the fraction of the energy given to electrons. This quantity was originally derived from Lindhard's basic integral equation in Ref. [22], which is an approximation for the collision cascade,

$$q_{\rm nc}(E_{\rm nr}) = \frac{\eta(E_{\rm nr})}{E_{\rm nr}} = \frac{kg(\epsilon)}{1 + kg(\epsilon)}, \quad (3)$$

where $\eta(E_{\rm nr})$ is the energy transferred to electrons, the so-called electron equivalent energy, when the initial nuclear recoil energy is $E_{\rm nr}$. $g(\epsilon)$ is an empirical expression which can be found in Ref. [21] and k is the proportionality constant between the electronic stopping power $(dE/dx)_{\rm el}$ and the velocity of the projectile (recoil atom) [23]. For xenon, Lindhard proposed a value $k = 0.166$ [22]. Considering the collision cascade, Hitachi re-calculated the electronic stopping power of recoiling xenon atoms in a LXe target and derives a smaller value $k = 0.110$ [12]. One can also calculate the nuclear quenching factor $q_{\rm nc}$ from computer simulations. We use TRIM from the SRIM-2013 package [24] to simulate the slowing down process of an energetic xenon atom in xenon medium. From this result, we electron equivalent energy $\eta(E_{\rm nr})$ and obtain the nuclear quenching factor $q_{\rm nc}$. However, all the theoretical treatments overestimate the total electronic energy dissipation due to ignoring the faster fall-off behavior of the electronic stopping power (ESP) in low energy region. We extrapolated the ESP to lower energy region using the power-law based on the ESP measured in the energy region 40∼200 keV [25]. And we have performed a calculation of Lindhard factor in Ref. [9] in which the result is much lower than that given by Lindhard, Hitachi, or TRIM. In Fig. 1, we show the results. From experimental data, the nuclear recoils produce more scintillation light than the electronic ones, and hence the Lindhard quenching factor $q_{\rm nc}$ shall be smaller than relative scintillation efficiency $\mathcal{L}_{\rm eff}$. Clearly our result satisfy this requirement. Thus we adopt our new result for the Lindhard quenching.

2.2. Average energy required to produce one electron–ion pair

To describe the average energy required to produce one electron–ion pair, Platzman's phenomenological theory, which is originally proposed for high-energy radiation in rare gases in Ref. [26], is widely referenced as a theoretical explanation. Platzman assumes the total dissipated electronic energy can be divided into three parts: ionization, excitation and sub-excitation electrons:

$$E^{ee} = N_iE_i + N_{ex}E_{ex} + N_i\epsilon, \quad (4)$$

where E^{ee} is the electronic energy dissipation, or the electron equivalent energy, N_i is the number of electron–ion pairs produced at an

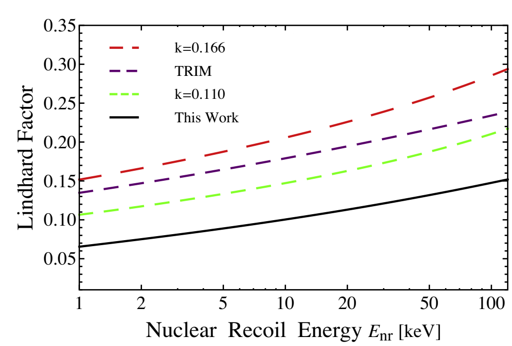

Fig. 1. The Lindhard factor, $q_{\rm nc}(E_{\rm nr}) = \eta(E_{\rm nr})/E_{\rm nr}$, of LXe shows the fraction of energy given to electrons. The red dashed curve is the empirical result from Eq. (3) setting k = 0.166, which is widely quoted by different authors while the green dashed curve is the result when setting k = 0.110, which is calculated by Hitachi. The purple dashed curve is calculated using TRIM. The black solid curve is used in this work and obtained by using the ESP fitted to the available experimental data [9]. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)