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Properties of liquid xenon scintillation for dark matter searches

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The scintillation yields and decay shapes for recoil Xe ions produced by WIMPs in liquid xenon have been examined. A quenching model based on a biexcitonic diffusion-reaction mechanism is proposed for electronic quenching. The total predicted quenching, nuclear and electronic, is compared with experimental results reported for nuclear recoils from neutrons. Model calculations give the average energy to produce a vuv photon, W_{ph} , to be ~75 eV for 60 keV recoil Xe ions. Some aspects of ionization relating to liquid xenon WIMP detectors are also discussed.

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1. Introduction

Liquid xenon is a promising material for use as a detector in the search for dark matter. Both ionization and scintillation signals may be observed simultaneously. Liquid xenon has a high radioactive purity, a high density (2.94 g/cm^3 at b.p. [1]) and it is not chemically or structurally disruptive. It has a broad scintillation spectrum of about 10nm width in the vuv region and centered at λ=178 nm [2]. The scintillation efficiency is comparable to NaI(Tl) and less quenching effect is expected compared to other solid and liquid scintillators.

Weakly interacting massive particles (WIMPs) are candidates for galactic dark matter [3,4]. Elastic scattering of WIMPs by the nuclei of liquid Xe will produce nuclear recoils with energy up to a few tens of keV [5]. The recoil ion produces excitation and ionization in the medium. Electron–ion pairs recombine to give the excited Xe**, Xe* (free excitons) states that rapidly combine with neighbor atoms, relaxed and self trapped, forming the Xe_2* excited states (self-trapped excitons), which emit vuv photons. Some of the electrons can be collected with an applied electric field. Detection and selection of signals by WIMP, i.e. recoil Xe ions in a liquid xenon dark matter detector, exploit the differences in scintillation efficiency, scintillation decay shape and charge collection for different ions. Scintillation efficiency, which is the scintillation yield per unit energy deposited, is reported to range from 0.15 to 0.5 for nuclear recoils in liquid Xe [6-10]. The scintillation efficiency is also called the quenching factor q.

When an energetic charged particle passes through a medium, it loses its energy in inelastic Coulombic interactions with medium electrons (electronic stopping) and by elastic atomic recoils (nuclear stopping). Electronic stopping is dominant for incident electrons, γ-rays and fast ions. The δ-ray electrons produced in elastic collisions undergo slowing down processes producing ionization and excitation. Part of the total energy, E, of the particle is converted to ionization and excitation of the medium and can be observed. The energy loss in nuclear stopping is converted to atomic motion. The recoil or scattered atom loses some of its energy in electronic stopping. A part, T, of the total energy loss, E, is ultimately given to electrons and the rest, E-T, is spent in atomic motion. The nuclear recoils suffer considerable "nuclear" quenching $q_{nc} = T/E$.

The recoil ion to γ-ray signal ratio, RC/γ, in semiconductors [11-14] shows good agreement with nuclear quenching based on the theory of Lindhard et al. [15]. Semiconductors show good linearity of ionization signals from electrons to fission fragments except for small defects. All the energy given to electronic stopping can be observed. However, this outcome is not the case for liquid and solid scintillators. Most measurements reported for liquid xenon, in fact, show considerably smaller values [6,8-10] than the Lindhard prediction because of "electronic" quenching (q_{el}) for high LET (Linear Energy Transfer = -dE/dx) particles. The total quenching factor q_{TTL} is given by $q_{nc} \times q_{el}$ (q=1 for no quenching).

Another important factor, which is often neglected, is that q_{TTL} is not always equal to the RC/γ ratio. Electrons and γ-rays show no high-excitation-density quenching, but a reduced efficiency for electron–ion recombination in liquid xenon [16], and in inorganic crystals [17]. This process, produces fewer photons, which is equivalent to q_{el} <1. The thermalization distance r_{th} is comparable to or much longer than the Onsager radius r_c (the radius where an electron with thermal energy has an equal probability to recombine with or escape recombination with the geminate ion) in those media. The long thermalization distances prevent many electron-ion pairs from recombining within the experimental observation time or allow electrons to escape to the detector walls. These escape electrons do not contribute to scintillation. To obtain the RC/γ ratio, "nuclear" quenching, "electronic" quenching and escaping electrons have to be considered in scintillators.

The “electronic” quenching has been studied and discussed for many years in radiation physics and chemistry [17-19]. Birk’s equation [17] relates the specific photon production rate dL/dx to the stopping power dE/dx;

$$\frac{dL}{dx} = \frac{C_1(-dE/dx)}{1 + C_2(-dE/dx)} \qquad (1)$$

where C_1 and C_2 are fitted parameters. This equation has shown considerable success in explaining the LET dependence of scintillation yields for organic scintillators, where the scintillation and quenching mechanisms are presumably complicated. Paradoxically, this phenomenological equation fails in explaining the scintillation efficiency in simple condensed rare gases. The quenching factor q is not simply a function of LET. The quality of ionizing particles has to be considered. Information regarding the track structure and energy migration becomes indispensable.

No satisfactory theories exist for explaining quenching for recoil ions in WIMP detectors composed of liquid or solid scintillators. Researchers have compared the experimental values with the Lindhard model (nuclear quenching); however, many do not include electronic quenching. Pécour et al. [20] fitted their data in CsI(Tl) with the Birks-Lindhard model, which does not apply for condensed rare gases as mentioned above. This paper proposes an “electronic” quenching mechanism based on a diffusion-reaction model of free excitons with a specific reaction rate. The model was originally applied to the quenching due to high excitation density in liquid Ar with success [21]. Although it is the self-trapped excitons (dimers) that the scintillate, the “free” excitons play an important role in “electronic” quenching.

2. Nuclear quenching and electronic LET

The nuclear and electronic quenching are considered separately. Stopping powers, nuclear and electronic, were found in HMI tables [22]. The tables are based on the work of Lindhardt et al. [23], and follow the usual procedure of a screened Rutherford scattering for the nuclear process. The nuclear stopping has its peak at about 260 keV for Xe ions in Xe. The electronic process is based on the Thomas-Fermi treatment. The electronic stopping is expressed as $(d\varepsilon/d\rho)_e = k\varepsilon^{1/2}$ where ε and ρ are dimensionless measures of energy and range. For the recoil ions in the medium containing only one atomic species, k is given by the atomic number, Z, and mass number, A, as $k = 0.133Z^{2/3}A^{-1/2}$. Charge-transfer processes; capture and loss, are included in the stopping power calculations. The ratio of electronic stopping to nuclear stopping is 0.08- 0.17, for 10-120 keV Xe ions in liquid Xe.

Lindhardt et al. [15] give the partition of energy of the incident ions to nuclear motion and electronic excitation. The energy spent in electronic excitation is given in Fig. 3 in ref. [15] as a function of ε for k = 1.0, 1.5 and 2.0 in materials that contain only one atomic species. For Xe ions in Xe, k=0.165 and the nuclear quenching factor $q_{nc} = T/E$ was obtained by interpolation.

The range, R, of recoil Xe ions was obtained using the total stopping power [22] and the electronic LET for recoil ions ($LET_{el} = -dT/dR$) was calculated using q_{nc}. The range for 100 keV recoil Xe ions is 0.1 μm, which gives the total averaged LET of 3,100 $MeV \cdot g^{-1} \cdot cm^2$ and the electronic LET_{el} of 900 $MeV \cdot g^{-1} \cdot cm^2$ using a ratio $q_{nc} = T/E$ =0.3.

3. Electronic quenching

Electronic quenching will be simplified to "quenching" in this chapter in accordance with the common usage in radiation chemistry. Relativistic heavy ions show no quenching in liquid Xe and q=1 [24]. The average energy to produce a vuv photon W_{ph} is estimated to be ~14 eV for those ions. However, for α particles and fission fragments the scintillation efficiency is less than that of relativistic heavy ions because of "electronic" quenching, q_{el}. The observed values are q = 0.77 and 0.24 for α particles and fission fragments, respectively [24,25]. For those ions, the nuclear quenching can be ignored and $q_{TTL} = q_{el}$. β particles and γ-rays show no quenching, but have escaping electrons in liquid rare gases [16]. Some fraction of electrons produced by these particles escape recombination and do not contribute to scintillation in liquid rare gases.

In condensed rare gases, both ionization and excitation produced by the ionizing particles, after recombination and/or relaxation, eventually give the lowest $^1\Sigma_u^+$ and $^3\Sigma_u^+$ self-trapped exciton (excimer) states R_2*, which scintillate in the vuv region through the transition to the repulsive ground state $^1\Sigma_g^+$.

$$R_2{}^* \rightarrow R + R + h\nu \qquad (2)$$

However, the lifetimes of the vuv emission do not depend on LET or the existence of quenching [26]. This fact suggests that quenching occurs prior to self-trapping. Free excitons and/or highly excited species may be responsible for the quenching. The proposed quenching mechanism is biexcitonic collisions,

$$R^* + R^* \rightarrow R + R^+ + e^-(K.E.) \qquad (3)$$

where, R^* is the "free" exciton. The ejected electron, e^- , may recombine with an ion to reform a free exciton and the overall result is that two excitons are required for one photon. Electron-ion recombination in heavy ion tracks is very fast. Thus the recombination component also undergoes quenching in Eq. (3). The diffusion-kinetic equations for free (suffix 1) and the self-trapped (suffix 2) excitons can be written

$$\partial n_1 / \partial t = D_1 \nabla^2 n_1 - k_1 n_1^2 - n_1 / \tau_1 \qquad (4)$$

$$\partial n_2 / \partial t = n_1 / \tau_1 - A_2 n_2 \qquad (5)$$

where n is the exciton density, D_1 is the diffusion coefficient of the free exciton, k_1 is the specific rate of biexcitonic quenching, τ_1 is free exciton lifetime against self-trapping, and A_2 is the radiative decay constant for self-trapped excitons.

The structure of a heavy-ion track can be described as concentric cylinders consisting of a central core and a surrounding penumbra [27]. The core is a region of high excitation density created by direct interaction, glancing collisions, of the primary particle and also**,** to some extent**,** by δ-rays. The penumbra is a zone of low excitation density, surrounding the core, formed by δ-rays produced in head-on collisions. The quenching model [21] assumes that quenching takes place exclusively in the high excitation density core. The total (electronic) energy T given to the liquid is divided into the core T_c and into the penumbra T_p. The energy T_s available for scintillation is,

$$T_s = qT = q_c T_c + T_p \qquad (6)$$

where q and q_c are the overall quenching factor and that in the core, respectively.

The energy partition T_c/T is given by the equipartition principle of stopping power contribution of glancing and head-on collisions, and also the energy left by δ-rays in the core. The equipartition principle has been validated for relativistic ions [28] and also experimentally for α particles [29]. Here we assume T_c/T to be the same as that in liquid argon. The T_c/T was calculated to be 0.51 for relativistic ions and ~0.7 for α particles in liquid argon. The value of T/E is 0.28 for 60 keV Xe from Ref. [15]. We assume many δ-rays produced by recoil ions do not have sufficient energy to effectively escape the core and form a fairly undifferentiated core, i.e. T_c/T =1 for recoil Xe ions.

The track core radius, r_0, for non-relativistic ions is given by the Bohr-criterion, $r_0=\hbar v/2E_1$ where $\hbar$ is Plank's constant divided by 2π, v is the velocity of incident ion and E_1 is the energy of lowest electronic excited state of the medium [27]. For liquid Xe, E_1= 8.2 eV [30]. According to Bohr criterion, r_0 for α particles becomes less than the interatomic distance a, in which case the latter is taken for r_0.

The initial distributions of excitons and holes in the cylindrical track core produced by various particles were estimated as shown in Fig. 1**,** where the radial distributions were assumed to be Gaussian with a size parameter a_0 the same as the core radius.

$$N_0 G(r,0) = [N_0/(\pi a_0^2)]\exp(-r^2/a_0^2). \qquad (7)$$

In eq.(7), N_0 was calculated using averaged electronic LET and the number of excited species $N = N_i + N_{ex}$ produced by incident ions where N_i is the number of ions $N_i = T/W$ and the number of excitons $N_{ex} = 0.06N_i$ [31] [footnote 1]. The W-value in xenon was taken to be 15.6 eV [31]. The excitation density for fission fragments and recoil ions becomes unreasonably high if a_0 is taken from Bohr's criterion or equal to the inter atomic distance. The value of a_0 was determined such that the excitation density does not exceed the density of Xe atoms. For relativistic ions, Fermi's criterion r_0=λβ□□ was used, where λ is the maximum core size and $\beta = v/c$, for a_0 [32].

Equations (4) and (5) can be solved for cylindrical geometry using the method of "prescribed diffusion". The radial distribution of the free excitons is assumed to be always described by a Gaussian. This has been done in liquid Ar and the solution is given as an integral form [21]. A value for A_2 in liquid Xe can be obtained from literature but the outcome of the calculations are not very dependent on the value of A_2 [21]. On the other hand, the important factors, D_1, k_1, and τ_1, are difficult to obtain. For example, one can only estimate the order of magnitude for τ_1 in liquid xenon. Also, there is insufficient quenching data for the various ions to determine a value of k, which has the greatest influence the calculations. The initial radial distributions of excited species in the track core for recoil Xe ions and α particles are similar to each other as shown in Fig. 1. The scintillation measurements for α particles and relativistic heavy ions give q=0.77 [24]. The calculated value of T_c/T is 0.72 for 5.49 MeV α particles [21] in liquid argon and assumed to be the same in liquid xenon. Substituting these values into Eq. (6), $0.77 = 0.72\, q_c + 0.28$, we obtain $q_c = 0.68$ for an α particle track core. Since the initial radial distribution for recoil Xe ions is close to that for α particles, we take a value of $q_c = 0.68$ for recoil Xe ions and $T_c/T = 1$, $T = T_c = 0.28E$ as mentioned above. We obtain $q_{el} = 0.68$ and estimate the average energy required to produce a vuv photon $W_{ph,el} \approx 20$ eV for the electronic energy T given by recoil Xe ions. The total quenching factor $q_{TTL} = q_{nc} \times q_{el} \approx 0.28 \times 0.68 = 0.19$. This calculation gives the total $W_{ph} \approx 75$ eV for 60 keV recoil Xe ions. The quenching factors, q_{TTL} and q_{el} obtained for 60 keV recoil Xe ions are plotted at the total and the electronic LET in Fig 2.

4. Scintillation decay shapes

The decay shape of scintillation may be used to separate nuclear recoil signals from dominant background (β,γ). The scintillation decay [26,33] due to heavy ions shows components that originate from the self-trapped exciton states (excimers). The recombination in the heavy particle track core occurs very fast and does not affect the decay shape. The decay depends on the singlet and triplet state lifetimes of excimers. On the other hand, the decays due to electrons and γ-rays are dominated by a slow, non-exponential, recombination component (with an apparent decay time of 45 ns).

The lifetimes for the singlet and triplet states are about 4 ns and 22 ns, respectively. They do not depend on energy or quality of particles, and are practically the same for the liquid [26,33] and the solid [34]. The electronic states, $^{1}\Sigma_u^+$ and $^{3}\Sigma_u^+$, of the excimers are essentially the same and affected little by the surroundings except for corrections due to the dielectric constant of the medium. Recombination depends on the density and distributions of thermal electrons and ions. Therefore, it can change with the energy and the LET of β and γ-rays. Baum et al. [34] reported a recombination component, with time constants of 35-45 ns**,** for α particles and heavy ions in solid Xe which is not observed in the liquid. This component may be due to energetic δ-rays or the energy deposited in bubbles in the solid.

The intensity ratio of singlet and triplet excited states, S/T ratio, changes as LET changes. In organic scintillators, electrons and ions produced by β and γ-rays recombine through geminate recombination, which favors the production of the singlet state. For heavy ions, homogeneous recombination becomes the main process and the S/T ratio will become roughly 1/3 (statistical weight) [35]. However, the S/T ratio increases as LET increases in liquefied rare gases [26], which is the opposite trend from organic scintillators.

The S/T ratio in liquid rare gas may be explained as follows [26]. The thermalization and recombination for low LET particles are very slow in liquid rare gases. The excimer can find thermal electrons in its vicinity. The thermal electron can collide with an excited state, the singlet S in this case, and transfer it to a lower excited state, the triplet T,

$$S + e^- \rightarrow T + e^-, \tag{8}$$

producing more triplet states. The reverse process is not likely because of the energy difference of the singlet and triplet states. On the other hand, recombination is rapid as mentioned above and process (8) does not occur for high LET particles. This process makes the S/T ratio increase as LET increases. This superelastic collision is known in gaseous states [36]. However, the process does not occur in organic scintillators since both the thermalization and recombination processes are very fast in organic scintillators.

The decay shape for Xe recoil may be similar to that of an α particle and a fission fragment. The track structure due to recoil Xe ions is similar to an α particle track as discussed in Chapt. 3. Quite recently, Aprile et al. [10] observed that the electric field dependence of the scintillation yield for recoil Xe ions is not very different from that of α particles in liquid xenon. This result suggests that charge collection from the recoil Xe track is not easy and the recombination component is not significant. The scintillation decay due to recoil Xe ions probably has singlet (4 ns) and triplet (22 ns) components without a slow decay, which represents recombination process. The S/T ratio may be similar to that for α particles (S/T =~1/2 [26]) or smaller.

5. Ionization and photoionization

Simultaneous measurements of ionization and scintillation, including that in liquid-gas two phase detectors [10,37,38], can be a powerful tool for particle discrimination. The electronic LET and the initial distribution of excited species for recoil Xe ions, shown in Fig. 1, suggests that the charge collection by an external field is as difficult as for α particles. No satisfactory theory exists for the saturation characteristics of ionization yields $Q(F)/Q_0$ due to heavy ions as a function of applied electric field F in condensed rare gases. Here $Q(F)$ is the charge collected and $Q_0=N_i=E/W$ is the charge produced by an incident particle in unit of electrons. The W value is 15.6 eV in liquid xenon [31]. The main difficulty arises from differences in the charge distributions and in the mobility of positive and negative charges. An empirical form, obtained from ref. [39] for 5.305 MeV α particle in liquid Xe at $1 \le F \le 10$ kV/cm, gives

$$Q(F)/Q_0 = 0.032F^{0.40}. \qquad (9)$$

For recoil ions, the energy $T=q_{nc}E$ given to electrons can produce ionization, and $Q_0=T/W=q_{nc}E/W$. One expects only about 6 % collection, i.e., 1.7 % that calculated from the total energy of the recoil Xe ion, at a field of 5 kV/cm, whereas more than 95 % can be collected for ~1 MeV electrons and γ-rays at the same field. Measurements in liquid-gas two phase detectors show quite small ionization yields for recoil Xe ions compared to that for γ-rays. [38]. A 60 keV recoil Xe ion may use 17 keV for ionization and excitation. This energy will produce about 1000 electrons in liquid xenon. The number of electrons collected at a field of 1 kV/cm is estimated to be ~35 from Eq. (9). Akimov et al. [40] reported a charge collection of 7 % of that calculated from the total energy for 65 keV recoil Xe ions at 4 kV/cm, which is considerably larger than the 1.6 % value predicted similarity with α particle tracks. An α particle track is almost straight which gives a cylindrically symmetrical electric field. The charge collection by an external field from such a track is difficult. Charge collection from the track of recoil Xe ion may be a little easier because of the shortness and a zigzagged shape of the track due to the elastic scattering with Xe nuclei. Further measurements for charge collection for recoil Xe ions as a function of external field are required.

Photoionization due to the addition of a small amount (≤200 ppm) of organic molecules may be helpful [39,41-44]. Molecules like TMA (trimethylamine) and TEA (triethylamine) have a quantum efficiency ϕ as large as 0.8 [39] for converting vuv photons to electrons in liquid Xe. Collecting these photoelectrons is easy. However, one needs some way to distinguish recoil-ion signals from γ-ray and β backgrounds other than using the difference in scintillation and ionization signal ratios.

The charge $Q_{PhI}(F)$ expected in a photoionization detector for recoil ions in doped liquid Xe can be written as,

$$Q_{PhI}(F) = Q_D(F) + \phi[q_{el} N_i - Q_D(F)] Y_{iso}(F) + \phi q_{el} N_{ex} Y_{iso}(F)\,, \qquad (10)$$

at a concentration of the dopant high enough to absorb all the vuv photons in liquid Xe. Here the charge is measured in electrons. The first term $Q_D(F)$ is a contribution from direct ionization and the charge obtained for recoil Xe ion in pure liquid Xe is used. N_i is the number of ions produced by an incident particle and is equal to $q_{nc}E/W$ for recoil ions. The second term is due to the contribution from recombination, and the third from excitation. The electronic quenching factor q_{el} appears in Eq. (10) because quenching affects charge collection in an ordinary electric field [45]. $Y_{iso}(F)$ is the fraction of collected charge for isolated electron-ion pairs, and the same values for electrons or γ-rays can be used. For recoil ions, all the vuv photons can be observed whereas for α particles, for which most of the basic studies were performed, only one half of the photons emitted are used because the other half is lost to the wall.

Photoionization can also improve the energy resolution considerably [43,44] by reducing the statistical fluctuation between ionization and excitation [46]. The best energy resolution of 0.37 %FWHM has been obtained for 30 MeV/n O ions in liquid Ar doped with 80 ppm allene [44]. It should be noted that solid photoionization detectors would not work properly because of the space charge effects due to doped molecules ionized by the vuv photons [47].

6. Discussions

The calculation of stopping power for slow ions is difficult. The errors in the stopping power calculation for the Lindhard model (the HMI tables) may be no better than 15 %. Nonetheless, q_{nc} is not strongly dependent on the stopping powers and errors included in stopping powers do not have a large effect on using $q_{nc} = T/E$. The agreement with measurements of q_{nc} for recoil ions in Si and Ge semiconductors is good [12-14]. The errors in q_{nc} may be 5-15 % in the present case. By using values interpolated for k=0.165, we have q_{nc} values of 6-8 % larger than values for k=0.15 for 10-120 keV Xe recoil ions. The present calculation assumes that the electronic quenching in a recoil Xe ion track is the same as that in α particle track core. However, the excitation density in a recoil Xe ion track is higher than that in α particle track core, particularly for higher energy. This result will lead to an over estimation of electronic quenching. Therefore, the uncertainty in the total quenching factor is estimated to be +/-15 % at lower energy and +10/-20 % at the higher energy region.

Recoils ions are at the end of the Bragg curve and the LET averaged over the Bragg curve was used in present calculation. It was expedient to make a simple model and to obtain a rough estimate. We assumed also that q_{el} for Xe ions in liquid Xe is constant for the energy range of 10 to 120 keV; however, LET changes greatly in this energy range. The tracks of α particles include the Bragg peak. Nonetheless, the scintillation efficiency obtained for 5.3 to 8.8 MeV α particles in liquid argon and xenon [25] did not show the strong dependence on energy if quenching took place only at the Bragg peak. The Bragg peak for He ions in Xe is at about 0.8 MeV. The scintillation ratio for α(8.785MeV)/ α(5.305MeV) should be 1.11 if quenching took place only in the vicinity of the Bragg peak (that is no quenching between the energy between 5.3 to 8.8 MeV) while the observed ratio is considerably less, 1.05±0.02 in liquid Xe. The present quenching model also predicts q_c is slow function, particularly for narrow track cores.

We took a value of T_c/T = 0.72 for α particles in liquid argon. This value may be slightly underestimated, since the range for δ-rays is shorter and r_0 is larger in liquid Xe than in liquid Ar. On the other hand, assuming T_c/T =1 may overestimate the excitation density for a recoil Xe track core. These factors compensate each other.

The electronic quenching has been treated separately from nuclear quenching. The estimated scintillation efficiency q_{el} for 60 keV recoil Xe ions is shown in Fig. 2 in relation with experimental efficiencies reported for various particles as a function of LET [34,48-51]. Relativistic heavy ions, 400-650 MeV/n C to Fe ions, show no quenching in liquid Xe and the scintillation efficiency or q was set to unity for those particles. The efficiency for 60 keV recoil Xe ions is plotted for q_{el} at the electronic LET and also for q_{TTL} at the total LET for comparison. Except for recoil Xe ions, nuclear quenching can be neglected. The q values for electrons and γ-rays are smaller than one because of the escaping electrons. The escaping electrons can easily be collected by an external electric field and a proper summation of ionization and scintillation signals gives the efficiency of one [16]. Some results for γ-rays are normalized for 1 MeV electrons [49,51]. The values reported for 1.4 MeV/n ^{50}Ti, ^{58}Ni and ^{238}U ions, normalized for α particles, in solid xenon are also shown for comparison [34]. They agree fairly well with the results for the liquid.

The experimental neutron recoil studies show the scintillation efficiency ratio of recoil Xe ions to that for γ-rays, *RC*/γ. To compare the calculation with the measurements, one needs to account for the fact that the scintillation efficiency for γ-rays are less than 1 as shown in Fig.2. No values are available for the ratio of recoil Xe ions to α particles nor to relativistic heavy ions. The α/β or α/γ ratios reported so far are scattered around 1.00-1.33 [34,48-51]. While some researchers reported considerable dependence of scintillation efficiency on the energy for γ-rays, others showed nearly constant. This result gives an extra uncertainty of about +/- 15% in the process of converting the calculated quenching factor to the recoil/γ ratio. The energy dependence can be due to inefficiency in electron-ion recombination (escaping electrons), photoelectrons from the K or L-shell of an atom and also by the shape of the energy loss distribution, the difference between mean energy loss and the most probable energy loss [17]. The discrepancies may be attributed partly to differences in the solid angle seen by the photomultiplier, reflective index of the wall and the time constants of shaping amplifiers. Accurate measurements for α/β, α/γ ratio or relativistic heavy ion to electron, *RHI*/β ratios are necessary to compare quenching calculations with experimental results and for calibration of WIMP detectors.

Quenching factors in liquid xenon are shown as a function of recoil ion energy in Fig. 3. The solid curve represents q_{nc}, the calculation of Lindhard et al. [15]. The broken curve shows present estimate of $q_{TTL} = q_{nc} \times q_{el}$. The value of $q_{el} = 0.68$ is assumed to be the same for recoil Xe ion of energy 10-120 keV. The reported experimental values for Xe are plotted using α/γ ratio of 1.01 reported for 60 keV γ-rays [50], i.e., the scintillation efficiency of 0.77 for γ-rays. The agreements between present calculation and experimental results of ICARUS [6], ZEPLIN [8,9] and XENON [10] are good, however, the calculated values are considerably smaller than those of DAMA [7].

The results for Si detectors are also shown in Fig. 3 [11,12]. Data for Si agrees well with predictions by Lindhard et al. Unlike most scintillators, the semiconductors have good linearity for a wide range of LET, therefore these materials do not need consideration for electronic quenching. Other scintillators such as, NaI(Tl), CaF_2(Eu), CsI(Tl) and TeO_2 , which are also used for Dark Matter searches, will have strong electronic quenching and some considerations for these process will be needed.

7. Summary

Electronic quenching as well as nuclear quenching have been considered for scintillation due to Xe ions recoiled by WIMPs in liquid xenon. A cylindrical track structure was considered and the excitation density was calculated. A biexcitonic diffusion-reaction mechanism is proposed for electronic quenching. Nuclear quenching was obtained based on the model of Lindhard et al. The present calculation predicts that scintillation efficiencies for 10-120 recoil Xe ions are 18-27 % those for γ-rays. We estimate W_{ph} ≈75eV, i.e., 13-14 photons/1keV for 60 keV Xe recoil ions. The calculated *RC*/γ ratio compares fairly well with neutron recoil measurements of ICARUS, ZEPLIN and XENON groups, but it is much smaller than the DAMA results.

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Footnote 1.

A value determined by the optical approximation using the oscillator strength data for solid Xe. The electric field dependences of ionization and scintillation yields have given N_{ex}/N_{i}=0.13-0.2 [52].

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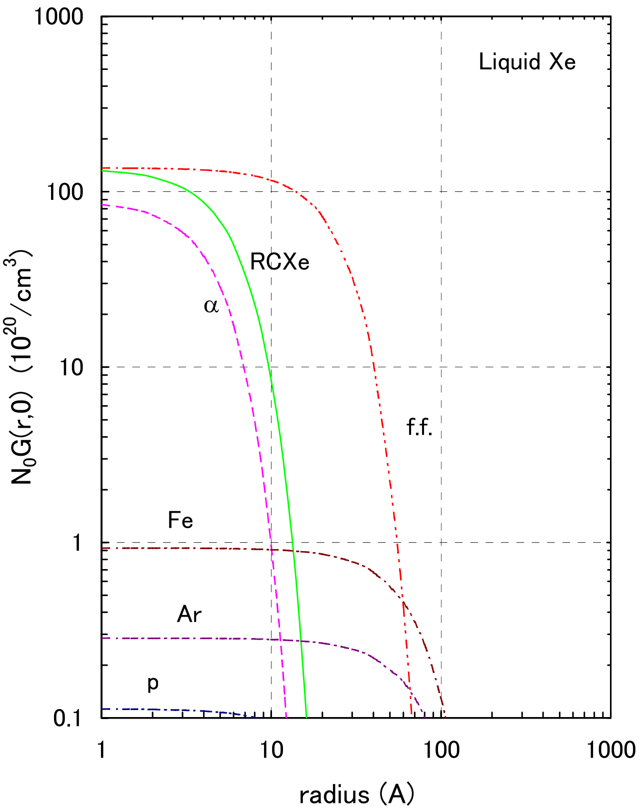

Figure 1. The initial radial distribution of excited species in the cylindrical track core in liquid Xe due to various ions. Solid curve shows 60 keV recoil Xe ions. Proton is 38 MeV and, Ar and Fe ions are relativistic.

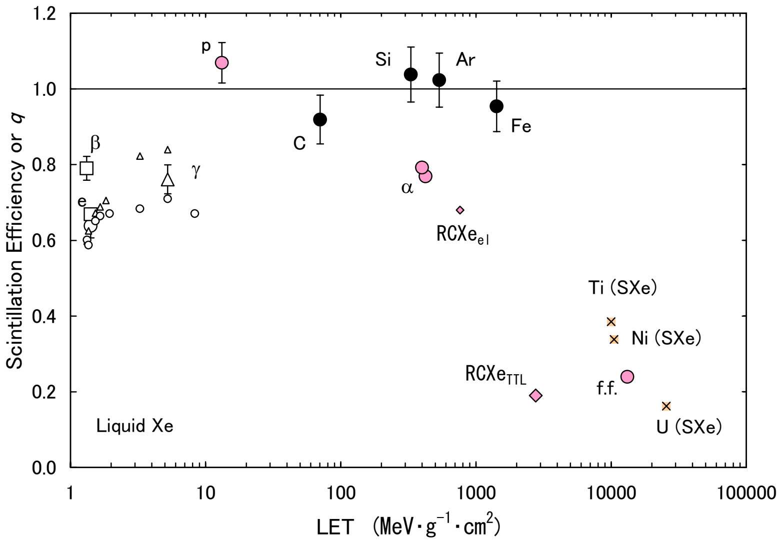

Figure 2. The scintillation efficiencies for various particles as a function of LET in liquid Xe. Solid circles represent efficiencies observed for relativistic heavy ions [24]. Open symbols represent electrons, β and γ-ray (○,Δ,□) [34,48-51]. Estimated efficiency for 60 keV recoil Xe ions is plotted at the total LET (q_{TTL}) and electronic LET (q_{el}). Ti and Ni ions of 1.4 MeV/n observed in solid Xe are also shown for comparison [34]. β and γ-ray values are less than 1 because of reduced efficiency in electron-ion recombination.

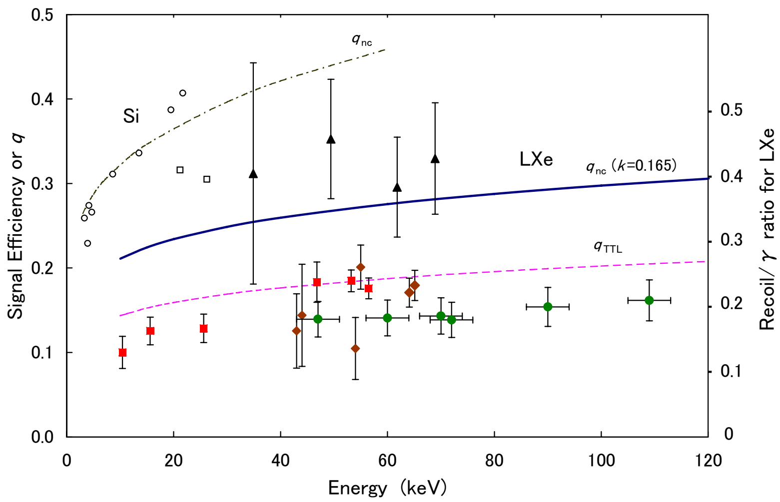

Figure 3. The scintillation efficiency or q as a function of recoil ion energy. The α/γ ratio of 1.01 [43] and q=0.77 for γ-rays are assumed for the experimental results for liquid Xe (closed symbols); ●: Arneodo [6], ▲: Bernabei [7], ♦: Akimov [9], ■: Aprile [10]. The calculation q_{nc} of Lindhard [15] are shown for Xe (solid line) and Si (dot-dashed line). Broken line is present calculation, q_{TTL}. Open symbols are ionization data reported for Si by Satter (□) [11] and Gerbier (○) [12]. NB: For RC/γ ratio, the values for liquid Xe should be divided by factors 0.77 as shown on the right hand axis. The difference between q and RC/γ is due to reduced efficiency in electron-ion recombination for γ-rays (see the text).