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The scintillation efficiency of carbon and hydrogen recoils in an organic liquid scintillator for dark matter searches

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Abstract

Dark matter candidates such as the weakly interacting massive particles can be detected through elastic scatterings with a nucleus. The scintillation efficiency of carbon and hydrogen nuclear recoils in an organic liquid scintillator was measured for such a possible dark matter detector. The recoil energies from 50 keV to ~1 MeV were explored for both nuclei. The carbon recoil efficiency, of particular interest for a dark matter detector, was observed to increase from $0.8^{+0.09}_{-0.11}$% of the electron recoil efficiency at 500 keV to $4.8^{+0.85}_{-2.99}$% at 46 keV. Such an enhancement is very encouraging for the purpose of dark matter searches as well as other similar low-energy experiments, and the results are well described by a modified Birks' light yield formula. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Dark matter; Nuclear recoil efficiency; Organic liquid scintillator; Low energy experiment

1. Introduction

The majority of the mass in the universe is now believed to consist of some form of dark matter such as the weakly interacting massive particle (WIMP) [1]. The neutralino, the lightest superpartner from many supersymmetric theories, and other dark matter candidates can be directly detected through elastic scatterings with a nucleus in a detector [2,3]. Strongly depending on target nucleus and models of dark matter candidates, the expected interaction rate of such elastic scatterings ranges from 0.1 to 10^{-5} counts/kg/day [1,2]. The typical recoil energy from a 10–1000 GeV neutralino is in the range from 1 to 100 keV.

So far, the organic liquid scintillators have not been considered suitable for a dark matter detector mainly due to insufficient scintillation light yield. Even the most efficient organic liquid scintillators have only about 80% of the scintillation efficiency of anthracene. In addition to this, the nuclear recoil experiences a considerable reduction in light output relative to electron recoils because of the well-known quenching effect. For example, in the Nuclear Enterprise NE224 scintillator, the carbon recoil efficiency relative to electron recoil was reported to be about 0.7% at 1220 keV [4].

It has been known for quite a while that nuclear recoils in some detectors (e.g. CaF_2 or CsI) show enhancements of the scintillation efficiency as the

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recoil energy decreases [5,6]. In fact, some organic crystal scintillators like trans-Stilbene show a similar enhancement [7], implying that this is a rather common phenomena. Resemblance of the scintillation process between organic liquid and organic crystal scintillators suggests that the organic liquid scintillators are also likely to experience similar enhancements at low energies [8]. In such a case, the premature negative judgement on the usage of organic liquid scintillators as a dark matter detector has to be reconsidered.

To explore the potential of organic liquid scintillators and to understand the physics of their scintillation process, this experiment measured the scintillation efficiency of carbon and hydrogen nuclear recoils in an organic liquid scintillator at low energies (50 keV to ~1 MeV). We employ a Bicron organic liquid scintillator (BC505) attached to two Electron Tube Photomultipliers (PMTs: 9954B) capable of detecting a single photoelectron. Employing two or more PMTs on the same scintillator in a coincidence mode dramatically reduces the noise and background at low energies. Consequently the self-coincidence scheme permits very low light detection thresholds.

The results of this experiment indeed reveal that the nuclear recoil efficiency increases in the organic liquid scintillator as the recoil energy decreases. We demonstrate that the carbon recoil efficiency can be described by a modified Birks' model. We also discuss a few aspects of organic liquid scintillators for a potential dark matter detector.

2. Experiments

The recoil of target nuclei in the organic liquid scintillator was achieved through elastic scatterings with the 2.85 MeV mono-energetic neutron beam at the University of Sheffield [5,9]. The test organic liquid scintillator was a 5×5 cm^2 Bicron scintillator (BC505) containing only carbon and hydrogen (pseudo-cumene). Two Electron Tube PMTs (9954B) capable of detecting a single photoelectron were attached on the scintillator (one on each side).

The experimental setup is similar to the arrangements of other nuclear recoil measurements and its detailed description is given elsewhere [9]. The recoil energy of the target nucleus is calculated from the kinematics of the coincidence measurements between the BC505 unit and the NE213 detector located about 50 cm away from the BC505 unit. By changing the angle subtended by the NE213 detector from the beam direction, one can select events occurring at a particular range of recoil energies. For hydrogen nuclei, seven recoil energies from ~50 keV to 1 MeV were measured at offset angles of the NE213 detector from 5° to 35°. For carbon nuclei, six recoil energies from 50 to 500 keV were explored at angles from 30° to 100°.

The scintillations from electron recoils were generated by a ^{241}Am radioactive source equipped with switchable filters. The Ag, Ba and Tb filters provide 22, 32, and 44 keV gamma-rays respectively, and their Compton edges (3.2 and 6.4 keV from 32 and 44 keV) are well identified. Back-to-back 511 keV gamma-rays from ^{22}Na were used to calibrate the timing between the BC505 and NE213 detector.

The signal from the NE213 detector was processed with a LINK system 5020 pulse shape discrimination unit to select only neutron events. The sum of the two PMT signals from the BC505 detector served as the observed scintillation output. A valid event generates three signals from the PMTs – two from the BC505 and one from the NE213 detector, and thus events with three signals occurring within ~1 μs were accepted during the measurements. At low energies (approximately few keV in electron recoil), the dark current of the PMTs on the BC505 detector can generate many false coincident events with the signal from the NE213 detector. The self-coincidence requirement of the two PMTs on the BC505 detector reduces the dark current effects. The NE213 detector is relatively free from such a problem since it can operate with a high operational threshold.

The electron recoil measurements indicate that the 1 keV electron recoil energy results in a yield of roughly one photoelectron in the PMTs of the BC505 detector. At energies above 20 keV (for electron recoils), the pulse-height distribution of the observed energies for a given recoil energy is well described by a Gaussian distribution, and its peak position directly indicates the input recoil energy.

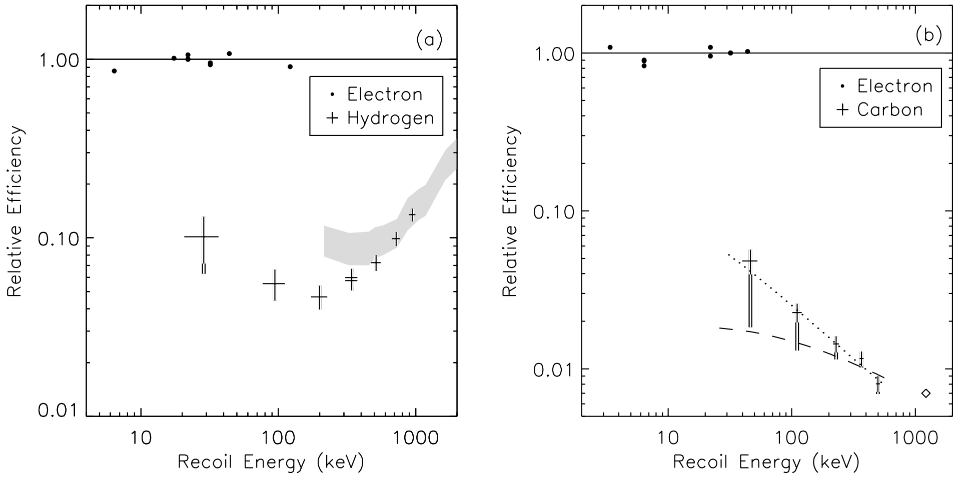

Fig. 1. The relative recoils efficiency of hydrogen and carbon nuclei in the BC505 detector; the shaded region in (a) represents the hydrogen recoil data in an NE213 detector [25]. The diamond in (b) is the carbon recoil data in the NE224 detector [4]. The double-line error bars (vertical) represent the possible nonlinearity effect in the system at low energies. The dashed line shows the model based on the regular Birks' light yield formula and the dotted line is based on the modified Birks' formula.

Below ~10–20 keV, the pulse-height distribution follows a gamma distribution, which reflects the Poisson distribution of the photoelectrons (now less than ~10–20). [1] The average number of photoelectrons, which relates to the input recoil energy, is proportional to the mean value of the pulse-height distribution, but not to the peak location of the distribution. Here we fit the pulse-height spectrum with a gamma function in the region covering at least full-width fifth-maximum and then derive the mean value from the fitted parameters of the gamma distribution.

When the average number of detected photoelectrons is close to one or two, the relation between the recoil energy and the average of the pulse-height distribution from the PMTs deviates from linearity. In this analysis, by using the 3.4 keV Compton edge in electron recoil measurements, we estimate the level of the nonlinearity at low energies.

3. Results and modeling

Fig. 1 and Table 1 show the results of the recoil efficiency measurements for hydrogen and carbon nuclei in the BC505 detector relative to the electron recoil efficiency. All the observed energies of hydrogen and electron recoils in Fig. 1(a) were calibrated with respect to the 22 keV gamma-ray from the Ag-filtered ^{241}Am source. For carbon recoils in Fig. 1(b), the 32 keV gamma ray from the Ba-filtered ^{241}Am source was used as a calibration point.

The results for electron recoils show that the linearity of the system maintains at least from 3.4 to 120 keV within ~10%. The average deviation from linearity (~6–10%) is used as an estimate for the systematic error in the observed energy for nuclear recoils. The systematic errors are usually caused by temperature changes of the system, a slight misalignment of illumination, etc.

The error bar on nuclear recoil measurements (single-line error bar in the plot) includes the systematic and statistical errors for both axes. The error of nuclear recoil energies is estimated from the width of the neutron beam, the size of the detector, the uncertainties of the location of two detectors (~1 cm), etc. The error of each efficiency

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[1] In general, the output of PMT can be described by a Polya distribution (or compound Poisson distribution) – a generalized functional form for various types of distributions from a Poisson to an exponential shape [10].

Table 1
The relative recoils efficiency of hydrogen and carbon nuclei in the BC505 detector

Hydrogen		Carbon	
Recoil energy (keV)	Relative efficiency (%)	Recoil energy (keV)	Relative efficiency (%)
28.7 ± 8.04	$10.1^{+2.97}_{-3.86}$		
94.3 ± 17.3	$5.5^{+1.09}_{-1.10}$	46.3 ± 6.57	$4.8^{+0.85}_{-2.99}$
200 ± 27.1	$4.7^{+0.71}_{-0.71}$	111 ± 9.8	$2.3^{+0.31}_{-0.97}$
341 ± 34.6	$5.8^{+0.69}_{-0.69}, 6.0^{+0.71}_{-0.71}$	229 ± 12.5	$1.4^{+0.17}_{-0.29}$
516 ± 41.9	$7.3^{+0.74}_{-0.74}$	368 ± 13.6	$1.2^{+0.13}_{-0.14}$
719 ± 48.8	$9.9^{+0.89}_{-0.89}$	500 ± 19.0	$0.8^{+0.09}_{-0.11}$
943 ± 53.1	$13.5^{+1.11}_{-1.11}$		

point in the plot includes the contribution from the uncertainty of the recoil energy and the error of the observed energy. The double-line error bars (vertical) in the figure represent somewhat conservative estimates of the nonlinearity at low energies. The estimations are derived from the 3.4 keV Compton edge for electron recoil events and its deviation from linearity.

The other potential source of error in nuclear recoil measurements is the background counts from (n,γ) and (n,nγ) interactions in the BC505 detector. The gamma-rays from such interactions have a relatively high energy, and their energy distribution is rather broad and independent of the offset angle subtended by the NE213 detector. Given the low level of the overall back-ground and the distinct features (e.g. the peak position) in the pulse-height histogram at each recoil energy, the contributions from such gamma-rays are considered to be very small.

In Fig. 1(a), the hydrogen recoil efficiency at high energies ($\gtrsim 500$ keV) shows a rapid drop as the recoil energy decreases. As the recoil energy decreases below 200 keV, the efficiency rises again. In Fig. 1(b), the carbon recoil efficiency also shows a dramatic enhancement as the recoil energy decreases. Because of its higher cross section with a neutralino, carbon is of much more interest as a target nucleus for dark matter searches than hydrogen. The dramatic increase of the light yield efficiency of the carbon nucleus at low recoil energies is encouraging in this sense.

The regular Birks' formula, which relates the light yield (dL) and the energy loss (dE) per unit length (dx) for a given ion in a unimolecular system, did not effectively describe the sharp rise of the carbon recoil efficiency at low energies within a reasonable range of the quenching parameter kB (the dashed line in Fig. 1(b), reduced $\chi^2 = 4.88$ without considering x-error bars, $kB = 30.2$ mg/cm^2/MeV) [11,12].

The energy loss can be attributed to two terms, nuclear energy loss and electronic energy loss. It is more likely that these two energy-loss processes contribute differently to the quenching effects or the scintillation process, and such a difference will be more noticeable for a heavy ion with a low recoil energy. To account for such a possible difference, we generalize the Birks' light yield formula as

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S_\mathrm{e}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{e} + S_\mathrm{n}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{n}}{1 + kB_\mathrm{e}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{e} + kB_\mathrm{n}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{n}}.$$

There are four free parameters in the above light yield formula, but some of them can be constrained. For instance, the kB represents the density of quenching centers produced per specific energy loss, and so the ratio, $kB_\mathrm{e}/kB_\mathrm{n}$, is roughly proportional to the ratio of nuclear to electronic energy loss per collision, which is about 3250 in the case of a head-on collision. And many previous measurements suggest that $kB_\mathrm{e} \sim 10$ mg/cm^2/MeV [11].

For this experiment, we assume $kB_\mathrm{e}/kB_\mathrm{n} = 3250$ and $kB_\mathrm{e} = 10$ mg/cm^2/MeV, and the other two parameters – the ratio of S_e to S_n and the overall constant – are left free. The dotted line in Fig. 1(b) is the result of the best fit to the data with the two free parameters (reduced $\chi^2 = 1.04$ without considering x error bars, $S_\mathrm{e}/S_\mathrm{n} = 5.23$) [13–17].

A threshold effect is expected when the energy of the recoil particle drops below the excitation level of the medium [18]. The expected threshold is about 2.8 keV for carbon recoil in the BC505 detector. The regular Birks' formula with such a threshold effect is less favorable for describing the data. The modified Birks' formula with the threshold effect can still explain the carbon recoil results, but the precise strength of the threshold effect remains undetermined due to the uncertainties of the data.

4. Discussion

Assuming 4.8% relative scintillation efficiency, we estimate that the tested BC505 scintillator will generate, on average, about six scintillation photons from a 10 keV carbon recoil. The mean free path of the scintillation photon is $\sim$5 m in the above organic liquid scintillators, so that a single unit of about 1 ton can be used without severe loss of scintillation light. This result may open possible low-energy applications for organic liquid scintillators, which have been already utilized for relatively high energy applications such as BOREXINO and KARMEN [19,20].

It would be very interesting to investigate the scintillation efficiency of other heavy nuclei in properly loaded organic liquid scintillators. This would allow studies on a wider parameter space of WIMPs or measurements on the modulation of the interaction rates due to different target nuclei. For example, fluorine-loaded organic liquid scintillators such as NE226 (BC509) are interesting due to the advantageous spin-coupling properties of ^{19}F with WIMPs. However, since the light yield of NE226 is only about 20% of anthracene, NE226 has not been considered useful for dark matter searches. Further studies beyond conventional organic liquid scintillators are required to find proper combinations of the solute/solvent/loader for a higher scintillation efficiency.

The radiation from ^{14}C present in organic materials could impose a serious problem for a dark matter detector. Using a proper beta decay spectrum of ^{14}C ($Q = 156$ keV) [21–23] and assuming $^{14}\mathrm{C}/^{12}\mathrm{C} = 5 \times 10^{-21}$ in pseudocumene (the same as in natural pure petroleum [21]), we estimate that the expected background count rate of the beta decay in ^{14}C is only 8.2×10^{-3} counts/kg/day below 10 keV. In the case of using carbon as a target nucleus in an organic scintillator, the potentially interesting energy region is up to approximately few keV (in terms of electron recoil energy), and thus, the contribution of the beta decay to the background is not substantial.

Besides radiation from ^{14}C, there are always some nagging backgrounds from unremovable radioactive contaminants in the detector. Consequently, a good background rejection scheme at low energies is also required for organic-liquid based dark matter detectors. For example, another organic liquid scintillator BC501A is proven to have excellent discrimination power between nuclear and electron recoil events at high energies, while the light output of BC501A scintillator is equivalent to that of BC505 [24]. It remains to be checked if such discrimination power holds at low energies, and other approaches such as utilizing multiple PMTs for rejecting electron recoil events must also be studied.

5. Conclusion

This experiment shows that there is a substantial enhancement of the carbon recoil efficiency at low energies. This implies that it is plausible to use organic liquid scintillators for dark matter searches with a good light collection system. The results may also be useful in other experiments where a low energy threshold detector is important. The sharp rise of carbon recoil efficiency is well described by the generalized Birks' model which separates the contributions from nuclear and electronic energy loss on the quenching effects and the scintillation process.

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