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Position reconstruction in a liquid xenon scintillation chamber for low-energy nuclear recoils and γ-rays

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Abstract

A position reconstruction algorithm was implemented for a liquid xenon scintillation camera aiming to reduce the uncertainty in the measurement of the energy of nuclear recoils from neutron scattering. The algorithm is based on the maximum likelihood (ML) technique. The performance of the algorithm was assessed both with simulated and experimental data. A resolution of $\sigma_{xy} = 6.7$ mm was measured with 122 keV γ-rays at the bottom of the chamber. For 10 keV γ-rays simulated events, a resolution of $\sigma_{xy} \leqslant 20$ mm was obtained for 80% of the active volume of the detector. By means of the position reconstruction, the uncertainty of the nuclear recoil energy in the neutron scattering experiment was reduced by a factor of 2–3, depending on the energy.

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Keywords: Scintillation camera; Position reconsrtuction; Nuclear recoils; Liquid xenon

1. Introduction

Liquid xenon has been recognised as a promising medium for the direct detection of hypothetical weakly interactive massive particles (WIMPs). Therefore, investigation of the response of liquid xenon to nuclear recoils and γ-rays is of primary importance.

We recently measured the scintillation efficiency of liquid xenon for nuclear recoils relative to that for γ-rays by irradiating a liquid xenon chamber with monoenergetic neutrons and detecting the scintillation due to xenon recoils from elastic scattering of the neutrons. The liquid xenon chamber was equipped with seven 2-inch photomultipliers (PMTs) placed on the top of a cylindrical volume $ø16.3 \times 5.5\,\text{cm}^3$ surrounded by PTFE reflectors, which define the active volume of the liquid. The measurements were carried out for nuclear recoils with energies from 140 keV down to 5 keV [1,2]. Details on the chamber design and the experimental set-up can be found in Ref. [3].

The energy of the nuclear recoil was calculated from the neutron scattering angle assuming that the interaction occurred at the centre of the chamber. This introduces a significant uncertainty in the recoil energy, as well as in the determination of the scintillation efficiency [1], as the interaction can take place at any position within the chamber. Thus, the measurement of the interaction position would allow those uncertainties to be reduced. For that we used a maximum likelihood (ML) method previously employed with success for scintillation detectors of similar configuration [4,5].

2. Position reconstruction technique

Good knowledge of the light collection function throughout the detector volume is essential for ML position reconstruction. However, this function is difficult to measure or model. The dependence of light collection efficiency on scintillation position was assessed by means of Monte Carlo simulation of light propagation within the active volume of the detector (see Fig. 1). In this simulation, photons are emitted in random directions from the nodes of a 3D-grid with a step of 2 mm and traced until they either reach a PMT photocathode or get absorbed.

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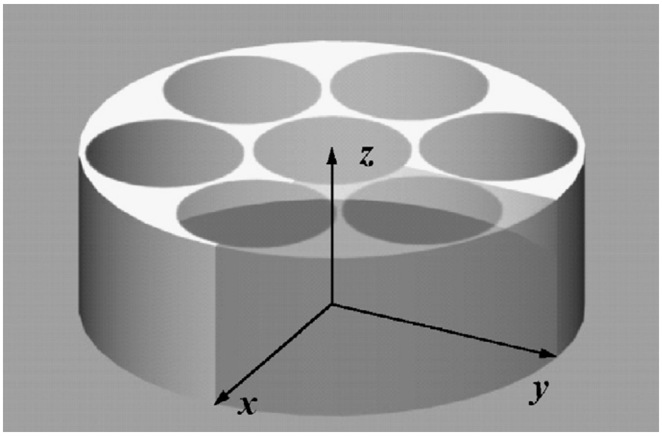

Fig. 1. Schematic drawing of the liquid xenon active volume. The circles on the top represent the windows of the PMTs.

The photon transport, described in detail in [6], takes into account the Rayleigh scattering and the light absorption in the liquid, as well as the refraction and reflection at the optical surfaces. The PTFE reflectivity and the absorption and scattering lengths for the VUV photons in liquid xenon were obtained by finding the best agreement between the simulation and experimental data obtained with a γ-ray source of 122 keV placed at various positions at the bottom of the chamber as described in Ref. [3].

To reduce the time necessary to calculate the light collection efficiency for the whole active volume of the detector, (i) the symmetry of the detector was taken into account so that the number of points to calculate was reduced by a factor of 12, and (ii) the photon tracing algorithm was optimised for speed. The light collection template with 2 mm step in 3D was obtained in this way.

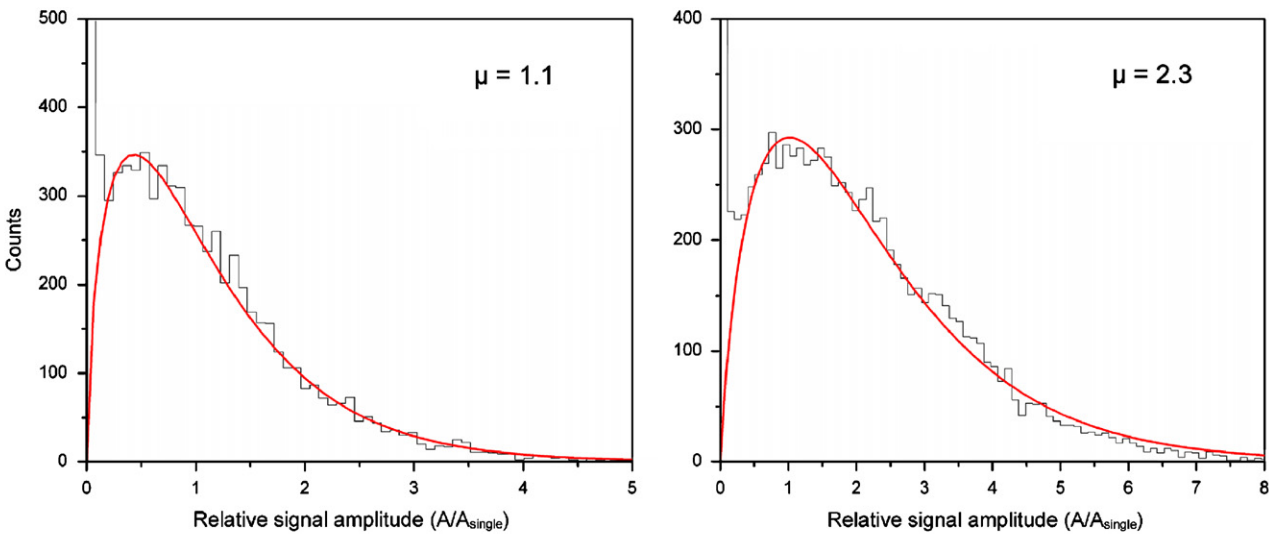

Fig. 2. Spectra of low-amplitude PMT signals fitted with γ distribution.

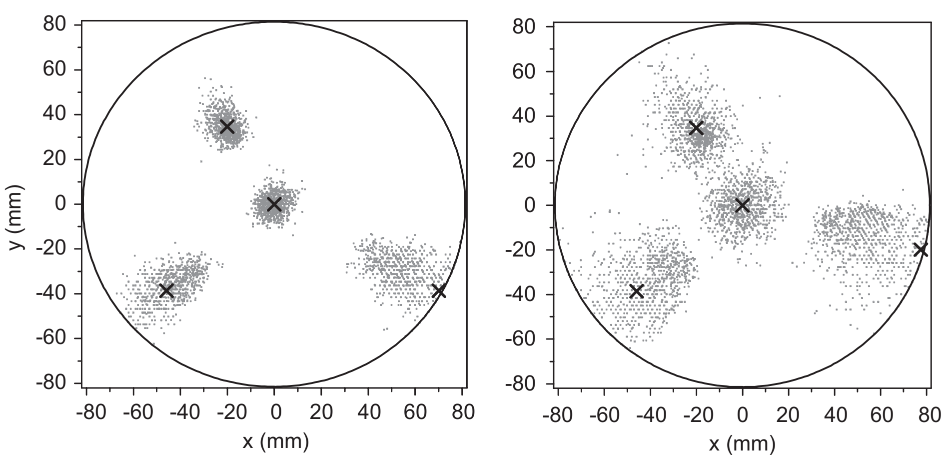

Fig. 3. Distributions of the reconstructed points (grey dots) for several positions of the event (black cross) over the sensitive volume in the plane $z = 20$ mm. The simulated energy depositions correspond to 122 keV (left) and 30 keV (right) γ-rays.