Position-sensitive spectroscopy of ultra-cold neutrons with Timepix pixel detector

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Abstract

We present an implementation of the silicon pixel device Timepix for position and energy-sensitive detection of ultra-cold neutrons (UCN) with an efficiency of 70% and a spatial resolution of 5.3 μm. A layer of 400 mg/cm² of ⁶LiF deposited onto the Timepix sensor surface was used as a neutron converter. The energy of each detected neutron is measured using standard time-of-flight (TOF) technique. Thus, for each detected neutron the position and energy is determined. We demonstrate this technique on the real-time measurement of energy- and position-dependent reflection of UCNs from a bent foil of stainless steel making direct visualization of total reflection angle for different neutron energies.

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1. Ultra-cold neutrons

Ultra-cold neutrons (UCN) are neutrons with very low kinetic energy (below 300 neV). This energy corresponds to a velocity of 7.6 m/s, effective temperature 3.5 mK and wavelength 52 nm. The neutron velocities are so small that UCNs undergo total reflection from the surface of most materials under any angle of incidence.

Unique properties of UCNs are used in many experiments studying fundamental physical phenomena such as neutron lifetime, neutron dipole moment or observation of their quantum states in the earth's gravitational field [1–3]. The need of efficient on-line digital detector with spatial and time resolution is shared by all these studies.

In this article we present the first experiments using time-of-flight (TOF) technique with a novel digital UCN detector offering both good spatial resolution and per-pixel time measurement.

2. Timepix detector and its adaptation for UCNs

The hybrid silicon pixel device Timepix [4] consists of a semiconductor detector chip with matrix of electrodes (256 × 256 square pixels with a pitch of 55 μm) bump-bonded to a readout chip. Each Timepix pixel is equipped with a counter operating in one of the three modes: Medipix mode (counting of incoming particles), Timepix mode (measurement of particle detection time) and Time over threshold (TOT) mode allowing direct energy measurement in each pixel.

As ultra-cold neutrons are uncharged and have very low energy they cannot be detected in the silicon detector itself. In our experiments UCNs are converted into charged particles in a thin layer of ⁶LiF (400 mg/cm²) deposited onto the detector surface by vacuum evaporation. This material captures an ultra-cold neutron and converts it into a pair of highly ionizing particles (alpha and triton) ejected into opposite directions (see upper right corner of Fig. 1). Consequently, one of the ionizing particles is detected in the silicon with high probability. The detection efficiency of such UCN detector is about 70% and the spatial resolution reaches 5.3 μm [5].

3. Time-of-flight measurement

We measure the kinetic energy of the neutrons by the time-of-flight technique. The measurements were performed using the source of ultra-cold neutrons PF2 at the Institut Laue-Langevin in Grenoble [6]. The UCN beam was periodically punctuated by a dedicated chopper [7] with an opening time of 38 ms (Fig. 1). Distance between the chopper and the detector (flight length) was 128 cm. The time of flight was measured in each detector pixel independently in the Timepix mode. The time resolution of this mode is 10 ns exceeding the required resolution in this application. Therefore, an external clock generator with a period of 100 μs...
was used. The energy spectrum of the UCN beam derived from TOF data is shown in Fig. 2. The mean time-of-flight is 0.174 s resulting in a mean UCN velocity of 7.35 m/s and an energy of 283 neV.

4. Position-sensitive time-of-flight spectrometry

To reliably demonstrate the position- and energy-sensitive detection of UCNs, we measured the energy-dependent intensity changes due to reflection from the surface of the bent foil (15 μm thick stainless steel), see Fig. 3A. Neutrons hitting the foil either penetrate into it or are reflected depending on their angle of incidence and energy. Neutrons with energy lower than 180 neV (Fermi potential of stainless steel) are always reflected. The UCN intensity as a function of energy and position (angle) is shown in Fig. 3B.

Fig. 3C shows the intensity profile across the detector for UCNs with an energy of about 340 neV. The left-hand side of the chart corresponds to the uncovered region of the detector registering all UCNs coming directly with the beam plus those reflected from the steeper parts of the foil. Beyond the edge no UCNs can penetrate through the foil. Moving further right, the foil tilt decreases crossing the angle of total reflection. Starting from this point some neutrons are able to penetrate the foil and reach the detector.

5. Conclusions

It was demonstrated that the Timepix detector adapted for detection of UCNs by 6LiF coating can be effectively used for...
position-sensitive spectrometry with real-time visualization of UCNs using the TOF technique. The per-pixel time resolution of Timepix device is more than sufficient for such measurements.

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