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Application of $LiTaO_3$ pyroelectric crystal for pulsed neutron detection

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ABSTRACT

The feasibility of a $LiTaO_3$ pyroelectric crystal for pulsed neutron detection has been studied. The detector consists of a slice of electroded Z-cut $LiTaO_3$ pyroelectric crystal, and no additional neutron converter is required owing to the Li contained in the crystal. The slight temperature increase caused by neutron radiation will lead to the release of bound charges and will give rise to a pyroelectric signal. The response of it has been studied both theoretically and experimentally. Our preliminary experiment on the CFBR-II reactor suggests that the $LiTaO_3$ pyroelectric detector is promising for high intensity neutron – pulse measurement.

1. Introduction

Because the spontaneous polarization of a pyroelectric material [1] is a function of temperature, heating or cooling it slightly will cause bound charges to accumulate on faces normal to the polarization, resulting in a considerably large electrostatic field. The pyroelectric effect is mainly used for beam detection [1,2] and ion acceleration [3,4]. Owing to their ruggedness and simplicity of use, pyroelectric detectors can be used in harsh environment for X-ray [5,6], gamma ray [7,8], neutron [9], ion [10] and atom [11] beams detection.

Pyroelectric $Pb(Zr, Ti)O_3$ ceramics can be used as the sensitive element for thermal neutron detection [9]. The detectors used a pellet of uranium (with 20% enrichment in ^{235}U) or boron (with natural isotopic abundance or with 92.41% enrichment in ^{10}B) to convert thermal neutron flux in to a heat source. It was found that the signal amplitude is proportional to the thermal neutron fluence rate. However, the ranges of the fission fragments are generally on the order of tens of microns, which is only about 10% of the thickness of a normal ceramic disk. As a result, the majority of the $Pb(Zr, Ti)O_3$ ceramic disk has little effect on the performance of the pyroelectric detector, and the detecting efficiency is relatively low. In addition to $Pb(Zr, Ti)O_3$ ceramics, the $LiTaO_3$ single crystal also has promising pyroelectric properties [1,3,4], and a high radiation stability [12]. Compared with $Pb(Zr, Ti)O_3$ ceramics, $LiTaO_3$ has the potential for pulsed neutron detection without additional converters owing to the relatively large neutron reaction cross-section of ^6Li, but the response to a pulsed neutron field has not been reported yet.

For the purpose of developing a pyroelectric neutron detector, the response of a Z-cut $LiTaO_3$ pyroelectric crystal to a transient nuclear radiation field was investigated both theoretically and experimentally in this paper. The response of the pyroelectric detector was formed to depend both on the detection circuit and the properties of the pyroelectric element, and the theoretical relationship among them was developed. In our preliminary experiment, the feasibility of a $LiTaO_3$ pyroelectric crystal for pulsed neutron detection was confirmed.

2. Principles of pyroelectric irradiation detection

A pyroelectric detector is a slice of electroded pyroelectric material polarized in the axial direction. In steady state, the internal polarization of a pyroelectric detector is balanced by surface charges and there will be no observable potential difference between the electrodes.

When a pyroelectric detector is exposed to pulsed neutrons, the pyroelectric element will be heated by the incident irradiation. The heat losses due to thermal conduction or thermal radiation are negligible, because the time scale of the neutron pulse considered in this paper is less than 1 millisecond, and the maximum temperature increase is only about 0.1 °C. Neglecting heat losses, the change of the temperature can be computed by the following equation

$$\frac{dT}{dt} = \frac{E}{hC_v}\dot{\phi}, \quad (1)$$

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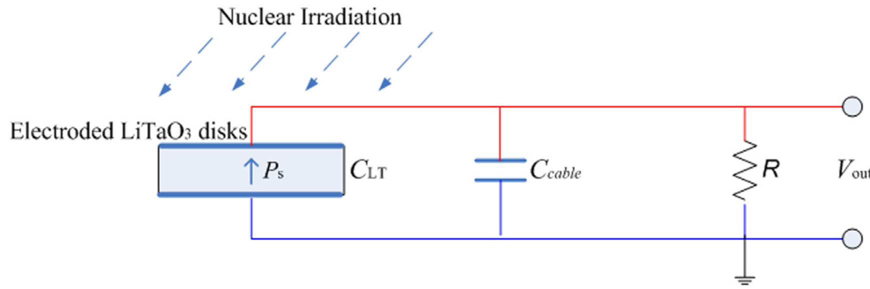

Fig. 1. Schematic diagram of the detection circuit.

where dT is the temperature increase of the pyroelectric material, E is the energy deposited in the pyroelectric material per incident neutron, h is the thickness of the specimen, C_v is the specific heat of the pyroelectric material, and $\dot{\phi}$ is the incident neutron fluence rate.

The change of the polarization is determined by the temperature increase dT of the material [2], and the pyroelectric charge dQ generated on one electrode with an area of A is given by

$$dQ = pAdT \tag{2}$$

Using a nuclear irradiation field as the heating source, the piezoelectric effect and the radiation-induced polarization and conduction might also contribute to the output besides the pyroelectric effect, but the charges generated due to those effects also have linear relationships with dT, and the linear relationship in Eq. (2) is still valid with a coefficient p modified appropriately [8].

The pyroelectric charge released can be measured with a typical RC-circuit depicted in Fig. 1, which has a response time τ_e equal to $R(C_{LT} + C_{cable})$, where C_{cable} and C_{LT} are the capacitances of the coaxial cable and the pyroelectric detector, respectively. If the output voltage is represented by V_{out}, the response of the circuit is governed by the following equation

$$(C_{LT} + C_{cable})\frac{dV_{out}}{dt} + \frac{V_{out}}{R} = \frac{dQ}{dt}. \tag{3}$$

Expressing the output signal in terms of the incident neutron fluence rate $\dot{\phi}(t)$, we get

$$V_{out} = \frac{pAE}{(C_{LT} + C_{cable})hC_v} e^{-\frac{t}{\tau_e}} \int \dot{\phi}(t) e^{\frac{t}{\tau_e}} dt. \tag{4}$$

If the pyroelectric detector is used for pulsed neutron detection, the incident neutron fluence $\phi(t)$ and neutron fluence rate $\dot{\phi}(t)$ can be calculated with the following expressions:

$$\phi(t) = kU_{\text{int}}(t), \tag{5}$$

$$\dot{\phi}(t) = k\dot{U}_{\text{int}}(t). \tag{6}$$

where

$$U_{\text{int}}(t) = V_{out}(t) - V_{out}(0) + \frac{1}{\tau_e}\int_0^t V_{out}(\tau)d\tau, \tag{7}$$

$$\dot{U}_{\text{int}}(t) = \frac{d}{dt}(U_{\text{int}}(t)), \tag{8}$$

$$k = \frac{pAE}{(C_{LT} + C_{cable})hC_v}. \tag{9}$$

As shown in Eqs. (5) and (6), a linear relationship between the incident neutron field ($\phi(t)$ or $\dot{\phi}(t)$) and the pyroelectric signal ($U_{\text{int}}(t)$ or $\dot{U}_{\text{int}}(t)$) can be obtained, which, as will be discussed in the following text, is favorable for a pyroelectric detector.

3. Experimental setup

The Chinese Fast Burst Reactor-II (CFBR-II) [13,14] was adopted as the neutron source, which is a research reactor of enriched uranium metal to provide intense, short-duration neutron pulses. In burst mode, a large reactivity insertion moves the system to a prompt supercritical state, and then the thermal expansion of fuel reduces reactivity and ultimately shuts the reactor down, resulting in the generation of a neutron pulse. The CFBR-II neutron-pulse is normally measured by a plastic scintillator detector (ST401, Beijing Nuclear Instrument Factory), which is 50 cm away from the core of the CFBR-II. A typical neutron pulse waveform is shown in Fig. 2. The pulse full width at half maximum (FWHM) of the neutron intensity waveform is about 192 μs, the accumulative neutron fluence is about 6.5×10^{12} n/cm^2, and the average neutron energy is 1.12 MeV.

Z-cut $LiTaO_3$ single crystals in the form of disks with 0.75 mm thickness and 76.2 mm diameter were purchased from Huaying Electronics Corporation. The $LiTaO_3$ disks were cut to be quadrate specimens with size of $10 \times 10 \times 0.75$ mm^3. The main surfaces were coated with a conductive layer of sputtered gold. Four electroded $LiTaO_3$ specimens were used, and they were placed on the surface of the CFBR-II reactor. For the Z-cut $LiTaO_3$ single crystal specimens considered in this paper, the density is 7.45 g/cm^3, and the specific heat is 3.2 J/(cm^3 °C) [2]. The capacitance of the circuit was measured to be 6.30×10^{-9} F. The shunting resistance was measured to be 5.07×10^4 Ω and the resistance of data-acquisition and recording system was 1.00×10^6 Ω. Both of them were not exposed to the radiation field. A high-resolution digitizer (NIPIX-5105, National Instruments) is used to observe the signal pulse, and the pyroelectric signal data was digitized at 10 MHz. A Labview program is developed to accomplish data acquisition and processing.

4. Results and discussion

4.1. Theoretical analysis

According to Eq. (4), a small circuit capacitance is favorable to increase the magnitude of V_{out}, thus enhancing the sensitivity and the signal-to-noise ratio of the detector. However, a relatively long coaxial cable of about 100 m is generally required for shielding consideration, and the C_{cable} can hardly be changed. A circuit capacitance of 6.30×10^{-9} F is obtained by the actual measurement, thus the time constant τ_e has a linear relationship with the resistance R. The difficulty with driving small signals over long cables was solved by using a large shunting resistance, and the deformed signal due to the time lag τ_e was treated by Eqs. (5) and (6). Using the parameter k measured in the experiment, the response of a pyroelectric detector can be predicted with different experimental setup.

In accordance with published results [7,2], the time constant τ_e