Properties of The Neutron Detector Based On Ionisation Chamber With $^6$Li Converters

R. Engels, Member, IEEE, U. Clemens, G. Kemmerling and J. Schelten

Abstract—The ICC neutron detector is an ionisation chamber with three neutron absorbing converter electrodes of $^6$Li metal foils. On both sides the foils face collector electrodes that are positively biased. The neutron detection was investigated at the pulsed neutron source of the Argonne National Laboratory. The induced charge due to drifting electrons that are generated by the energetic $^3$H recoil nucleus in the $C_2F_6$ gas between the electrodes was measured as function of gas pressure, gas contamination, and applied drift voltage. The neutron detection efficiency was determined and the gamma insensitivity was estimated. The pulse heights were calibrated by the induced charge from test pulses. The timing characteristics of the detector pulses were assessed, and TOF measurements demonstrated the usefulness of the detector. First neutron diffraction experiments were made with structured collection electrodes for position-sensitive detection and for estimating the achievable spatial resolution.

I. INTRODUCTION

Neutron scattering experiments often suffer from small scattering intensities and consequently long data collection times due to rather small primary neutron beam intensities even at high flux neutron sources. After collimation and monochromatisation, the neutron beam at the sample position is of the order of $10^7$ neutrons per cm$^2$ and per second. Fortunately, neutron sources have large source areas which can be utilized to increase the scattering intensity into all resolution elements. However, rather large samples are required and the scattered neutrons are nowadays recorded with huge detectors arrays of moderate spatial resolution which are usually positioned at several metres from the sample.

The cross sectional areas of the primary beam, of the sample and of the spatial resolution are in the order of a few cm$^2$, typically between 10 mm$^2$ and 10 cm$^2$. The optimisation of the measurable scattered intensity generally leads to huge area detectors of 1 to 10 m$^2$ that are realized by unfavourable high pressure vessels filled with the expensive $^3$He gas [1] or by an enormous size of scintillator glass plates which are viewed by a large number of photomultipliers [2].

Ionisation chambers with $^6$Li converters offer an alternative development way to the neutron detector giants. Three 0.1mm thin $^6$Li foils are sufficient to stop thermal neutrons with the optimum probability of 67%. Their weight and material costs are 180g and 400$ per 1m$^2$ detector area, respectively. With the fill gas $C_2F_6$, one can operate the ionisation chamber at ambient pressure and still achieves a spatial resolution of about 0.25cm$^2$. The detector depth is less than 30mm, which leads to 0.030 m$^3$ fill gas per 1m$^2$ detector area. The signal processing requires $2xN^{1/2}$ charge-sensitive preamplifiers with a digital discriminator output, were $N$ is the number of spatial resolution elements, e.g. $N=10^3$. In view of these attractive detector parameters it is worthwhile to explore this detector concept which has been previously introduced [3] and patented [4].

In the following paragraphs the detector details and properties are presented.

The principle of the neutron detection with $^6$Li converter foils that are placed into an ionisation gas chamber is described. The largest amount of induced charge and the most uniform pulse heights are obtained with negatively biased collector electrodes in front and behind the converter foils. However, collector electrodes need to be laterally structured in order to achieve spatial detector resolution.

In a the following sections the measured detector properties are presented, e.g. average induced charge per neutron event, pulse height distributions as function of gas, gas pressure, applied drift voltage and gas contamination, timing properties, neutron detection efficiency and gamma insensitivity. In TOF measurements the successful operation of the new detection principle is demonstrated.

Finally a first attempt was made to turn this detector into a position-sensitive neutron detector by structuring the collection electrodes. The very first position sensitive results are presented.

II. DETECTION PRINCIPLE

Fig. 1 is a cross sectional view of the ICC detector with four collector electrodes and three negatively biased converter foils. The converter consists of a 0.1mm thin $^6$Li metal foil covered on both sides by a thin metallised PET film.
A neutron absorption in a \(^6\)Li nucleus releases an energy of 4.78 MeV split into kinetic energy of 2.73 MeV and 2.05 MeV for the two recoil nuclei triton \(^3\)H and alpha \(^4\)He, respectively.

Part of the released energy is deposited in the \(^6\)Li foil itself, in the protecting cover layer of the converter, in one of the counter electrodes and in the gas between the electrodes. Only the latter part \(E_{\text{dep}}\) is useful for the detection of a neutron event. The applied voltage between the electrodes causes a drift and separation of the generated electrons and ions. This leads to an induced charge at one of the collection electrodes.

Provided there are no recombination processes during the drift, the induced charge is

\[
Q_{\text{ind}} = Q_e \frac{X}{d} \quad (1)
\]

where \(X\) is the drifting distance and \(d\) the electrode spacing. \(Q_e\) is the generated electron or ion charge. This quantity is

\[
Q_e = \left( \frac{E_{\text{dep}}}{E_{\text{eff}}} \right) e \quad (2)
\]

with \(E_{\text{eff}}\) the effective energy for creating an ion pair. (\(e=\) elementary charge)

Thus, on average the induced charge is

\[
Q_{\text{ind}} = \frac{1}{2} \left( \frac{E_{\text{dep}}}{E_{\text{eff}}} \right) e \quad (3)
\]

The ionisation gas \(C_2F_6\) was already selected in previous experiments [4] because of its large stopping power. For \(E_{\text{eff}}\) a value of 64 eV was measured.

The ICC detector is designed such that the energy \(E_{\text{dep}} \geq 1\) MeV is deposited in the gas. This leads to an induced charge of \(Q_{\text{ind}} \approx 7800e\) which is far above the noise level of charge-sensitive preamplifiers provided the capacitive load stays below 100 pF.

### III. Detector Properties

In Fig. 2 the ICC detector hardware is shown. All measurements were done with this detector. The size of the electrodes was 80 mm x 40 mm. The distance between adjacent electrodes was 4 mm.

![Fig. 2. Three dimensional view of the ICC detector. The gas cell tube and the cover for shielding the electronics are not shown.](image)

**A. Pulse Height Distribution**

Typical pulse height distributions as measured with the ICC detector at an electrode distance of 4 mm are shown in Fig. 3.

After biased all converter electrodes negatively and after introducing positively biased collecting electrodes the peaked pulse height distribution was measured which is in accordance with simulated results [3] based on SRIM [5] data for the stopping power of \(^3\)H nuclei in matter.

The peak maximum refers to the case that the \(^3\)H nucleus created anywhere in the absorber generates a perpendicular ionisation trace of length \(d\) equal to the electrode separation. At a pressure of 3 bar for \(CF_4\) one estimates with the known \(E_{\text{eff}}\) value of 54 eV and the stopping power values as calculated with the SRIM code an averaged induced charge of about

![Fig. 3. Pulse height distributions for the ionisation gases \(C_2F_6\) and CF\(_4\) at the gas pressure of 3 and 2 bar, respectively. Channel to charge calibration derived from test pulse measurements.](image)
20000e. This value agrees well with the maximum value of 23000. For the calibration of channel numbers into induced charge values, test pulses of known charge levels were fed into the preamplifier. From these measurements the electronic noise could be obtained. Its FWHM value is about 16 times smaller than the measured induced charge at the peak maxima. Thus, the absolute noise level was calculated to be 1250e.

**B. \( E_{\text{eff}} \) Determination**

The pressures of the two gases \( \text{C}_2\text{F}_6 \) and \( \text{CF}_4 \) were deliberately set to 3 and 2 bar in order to set the stopping powers for the \(^3\text{H} \) nucleus to be essentially the same in both gases. In this case, the relative peak shift between the two pulse height distributions is directly related to the effective ionisation energies \( E_{\text{eff}} \) of both gases. With the well known value of

\[
E_{\text{eff}}(\text{CF}_4) = 54\text{eV} \quad \text{[6]}
\]

one determines

\[
E_{\text{eff}}(\text{C}_2\text{F}_6) = 64\text{eV}.
\]

This value is in good agreement with our previously determined effective energy \([3]\).

**C. Bias Dependence**

The bias dependence of the pulse height distributions indicates that recombination effects occur during the drift of electrons towards the collection electrode. This effect is pronounced at voltage values drastically smaller than the reference voltage of 300V. At 50V the average peak height is only half of the value at 300V.

**D. Pressure Dependence**

The pressure dependence is governed by two competing effects. With increasing pressure the pulses become higher because the stopping power increases proportionally with pressure. On the other hand, the recombination effects become more dominant at higher pressures because the electron mobility decreases proportionally with gas pressure.

**E. Contamination Influence**

Gas contaminations by air have a pronounced effect on the average pulse height. This is mainly caused by the electronegative property of the oxygen in air. As shown in Fig. 4, at 5% air contamination the pulse reduction is clearly visible. At 20% the effect is dramatic. On the other hand, contaminations of less than 1% are tolerable which means that for ionization chambers one does not need purification circuits but merely tight detector vessels.

**F. Pulse Timing**

For determining the timing properties of the new detector TOF diffraction measurements were performed with a polycrystalline iron rod and with crystalline pyrolytic graphite as samples in the neutron beam. The detector was bathing in the scattered beam of the 90° channel of the IPNS test facility QUIP. Data recording was done simultaneously with a \(^3\text{He} \) proportional counter and the ICC detector.

Sharp Bragg peaks are observed with both detectors Fig. 5. In both cases the peak widths are completely caused by geometrical effects.

There is no indication that the charge collection time limits the temporal resolution in this TOF experiments.

Measurements of the preamplifier signals indicated charge collection times of less than 300 nsec.

With the known electron mobility in Argon one estimates that the charge collection time is about 200nsec. This value is a crude estimate for the \( \text{C}_2\text{F}_6 \) ionisation gas. For the much larger time jitter, caused by the uncertainty of not knowing where along the detector depth the thermal neutron is absorbed, a value of \( \pm 2\mu \text{s} \) is calculated. For the \(^3\text{He} \) proportional counter this time uncertainty was three times larger.

**G. Counting Efficiency**

By comparing the count rates of both detectors the counting efficiency of the ICC detector was determined. The value was disappointingly low, only 10% of the \(^3\text{He} \) counter, although the absorption probability was measured to be 70% for thermal neutrons as expected. This discrepancy was probably caused by the cover layers of the \(^6\text{Li} \) films which turned out to be too thick and hence absorbed too much \(^3\text{H} \) energy. This problem is
not completely solved yet although a promising solution has been proposed [7].

H. Gamma sensitivity

Concerning gamma sensitivity an ICC detector with no neutron sensitivity was exposed to gamma irradiation from radioactive $^{60}\text{Co}$ and $^{137}\text{Cs}$ sources. No signals beyond the set neutron threshold could be detected which is an excellent property making the detector even more attractive.

I. Position Sensitivity

In order to demonstrate the first position-sensitive detection with this new detector the collector electrodes were structured and contained eight copper line pads of 5mm width. The detector was set-up in a horizontal position in order to ensure that each copper strip had its own scattering angle. The eight scattering angles of strip 1,2,...,8 increased from a value 90°-10° to a value of 90°-5°. Thus, in a TOF experiment a Bragg peak is recorded sequentially in time, first with strip 1 and last with strip 8.

The clear separation of the eight Bragg peaks is a demonstration that the position resolution is better than the width of the line pads. This result is in accordance with calculations of spatial resolutions from ion traces in the detector.

IV. Conclusion

From these experimental results the following specifications can be realized with an ICC detector consisting of three converter foils and four collection electrodes:

1. 70% neutron absorption with three 100µm $^6\text{Li}$ foils
2. Energy deposition of at least 1MeV in the surrounding gas
3. Sufficiently large induced charge per neutron event
4. A signal-to-noise ratio of 16:1
5. Excellent pulse height discrimination against noise pulses and gamma pulses
6. Pulse height distribution in accordance with calculated results.
7. Agreement between measured and calculated average pulse heights. The calculation is based on stopping power values from SRIM and effective energy for ion pair generation from literature.
8. Optimal detector parameters are: blank 2 bar $\text{C}_2\text{F}_6$, <1% air contamination, 300V, 4mm electrode spacing
9. Temporal pulse width ~0.20µsec
10. Time resolution 2µs for thermal neutrons
11. Estimated spatial resolution <5mm

With an appropriate cover layers of the 6Li-foils one may obtain 60% of absorbed events detectable in an optimized cover layer

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VI. References


Fig. 6 TOF diffraction patterns versus wavelength for the eight line pads at the collection electrodes.