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New Trends in Neutron Detection

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Neutron detection is a broad field for fundamental research and applications. Its development is presently following an evolutionary scenario when the known detector technologies are being improved in their performances. Important advances are made by developing Pulse Shape Discrimination capable plastic and polysiloxane scintillators, which combine n/γ separation with handling simplicity of solid scintillators. GEM and MicroMega detectors promise to make a breakthrough in the neutron imaging applications, providing a good spacial resolution combined with a large detector area. Diamond detectors allow to exploit the semiconductor detector advantages in very high neutron fluxes of fission or fusion reactors. These and many other developments are ongoing and will be implemented in upcoming experiments and applied research facilities.

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[†] A footnote may follow.

1. Introduction

Neutrons are electrically neutral particles and therefore can be efficiently detected only through their strong interactions with atomic nuclei. This imposes serious constraints on detection techniques, limiting the efficiency per detector unit volume as well as all kinds of resolution. In fact, the neutron detection efficiency is proportional to the cross section of neutron interaction in the detector material, which for fast neutrons has the order of magnitude of 1 b. Moreover, the deposited energy threshold reduces the probability for a secondary charged particle to be measured. The converter elements with capture cross sections exceeding 800 b are used for the thermal neutron detection. However, when these elements cannot be embedded into detector active material the efficiency is limited by the small converter thickness, allowing the charged products of the neutron capture to escape. The neutron angular resolution is limited by the knowledge of the emission vertex, since the neutron track direction can hardly be measured with a good precision though its nuclear interactions. The neutron energy resolution typically depends on the duration of the source pulse and on the timing of detector signal. The conversion of the incident neutron into charged light nuclei only, in some cases (^{3}He, ^{6}Li), can be used to measure the neutron energy through the calorimetry.

The neutron energy domain can be divided in a number of characteristic intervals, among which the regions of thermal (<0.1 eV), intermediate (<1 MeV) and fast neutrons (<20 MeV) are most significant for the neutron detection. At high energies, of the order of GeV, the neutrons behave like all other long-lived neutral hadrons and they are usually measured by the standard hadronic calorimeters.

The R&D on neutron detectors pursue the following important aspects: 1) large area at low cost combined with a good spacial resolution; 2) n/γ separation for fast neutrons; 3) high resolution neutron spectroscopy both for physics experiments and nuclear applications; 4) radiation hard sensors for nuclear facilities and neutron imaging; 5) low noise detectors for underground experiments; 6) broad energy coverage meV-GeV.

In the following sections I will briefly describe the state of the art for the most common neutron detector types together with some specific projects ongoing within the INFN community.

2. Scintillator Detectors

The scintillators are widely used for the detection of fast and thermal neutrons. The most common are the organic scintillator detectors, featuring a low cost ($\sim$1\$/cm^3) and a large volume (m^3). Some of them, especially liquids, enable the fast n/γ separation through the Pulse Shape Discrimination (PSD). The scintillation light yield, quenching for the highly ionizing particles (light nuclei), precludes the calorimetric measurement of the neutron energy. However, a very fast timing (of the order of ns) enables the Time of Flight (ToF) spectroscopy when a pulsed source is available. Scintillators are relatively resistant to radiation doses, such that the fast neutron fluences above $10^{11} \div 10^{13}$ n/cm^2 (depending on detector size and material) lead to some loss of light yield and transparency. Thermal neutrons can also be detected by the scintillators through ^{6}Li/^{10}B/^{157}Gd loading in small fractions ($<$8% by weight).

Inorganic scintillators are occasionally used for the thermal neutron detection by means of ^{6}Li doping. These are fairly expensive, but feature the high efficiency per unit volume as well as the calorimetric measurement of the neutron energy.

The properties of some most common scintillator based neutron detectors are given in the Table 1. The recent developments, indicated by asterisk, are associated with:

1. EJ299 plastic scintillator from Eljen Technologies [1], which combines an easy handling and storing with the PSD properties, previously being a feature of the liquid scintillators only. Although, the produced samples have small sizes ($\sim$15 cm) and PSD power is considerably lower than that for the liquids.
2. Polysiloxane based plastic scintillators [2], which feature a high operating temperature ($<200^o$C) and a better resistance to radiation doses. Also here the available solid samples have relatively small size.

Table 1: Characteristics of scintillators used for the neutron detection. The Light Yield is given as the fraction to anthracene (15,200 photons/MeV$\sim$40% of NaI(Tl)). The asterisk indicates relatively recent developments.

	Light Yield	Attenuation Length	Decay Time	n/γ PSD	ε_n (1 MeV)	ε_n (25 meV)
Liquid/xylene	78-80%	3 m	3 ns	yes	0.2/cm	1/mm
Liquid/oil	28-66%	3-6 m	2 ns	EJ325A	0.29/cm	0.2/mm
Plastic	60-68%	1.6-4 m	2 ns	EJ299-33A*	0.2/cm	0.2/mm
Polysiloxane*	70%		30 ns	some	0.17/cm	0.3/mm
Li-glass	30%	40 cm	60 ns	yes		1.4/mm

The experiments within the INFN community developing scintillator based neutron detectors are the following:

- NEDA experiment (LNL,Na,Pa) is developing the neutron detector cells based on the BC501A and BC537(D) liquid scintillators [3]. Moreover, together with NewChim experiment (Ct,LNS) they are studying the response of the new EJ299-33A plastic scintillator [4]. Thanks to PSD and good timing this scintillator may allow a simultaneous neutron and charged particle detection [5], substituting CsI(Tl) crystals, widely used in nuclear physics. NEDA Collaboration is also implementing modern PSD methods: on-line one, based on SIS3302/50 digitizers (eventually on custom FADC) [6], and off-line one, using the Neural Networks.
- INFN-E/RILF experiment (LNL) is developing the neutron detector based on the optical wavelength-shifting fibers covered by ZnS scintillator grains mixed and ^{6}Li converter in an epoxy binder. The produced light is read out by a photosensor.
- SCINTILLA European FP7 project, developed in collaboration with Ansaldo, used plastic scintillators with Gd wrapping to detect neutrons for homeland security applications [7]. Numerous tests performed at JRC-Ispra demonstrated that the prototype meets all the requirements imposed by the authorities.

- LUNA-MV experiment (LNGS,Ge,Mi,Pa,Rm,Na,To) is developing the neutron detector for measuring $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ reactions at very low beam energies. In the exothermic reaction $^{13}C(\alpha,n)^{16}O$ with $Q \simeq 2.2$ MeV at E_α =0.2-0.8 the energy of the produced neutron varies from 2.2 up to 2.8 MeV. In an organic scintillator coupled to a PMT the neutrons of this energy will produce up to 700 photoelectrons (p.e.). This enables a good detection efficiency and PSD. However, the expected neutron yield of $10^{-6}\div10^{3}$ n/s have to compete with various backgrounds present in the LNGS hall: neutron background $\sim4\times10^{-6}$ n/cm^{2}s and γ background $\sim$0.4 γ/cm^{2}s. For a detector with the external surface of 10^3 cm^2 the environmental backgrounds have to be reduced by 4$\div$8 orders of magnitude. In the endothermic reaction $^{22}Ne(\alpha,n)^{25}Mg$ with $Q \simeq -0.5$ MeV at E_α =0.6$\div$1 MeV the neutron energy is below 0.4 MeV. For such a low energy neutrons the number of expected photoelectrons in an organic scintillator coupled to a PMT will be around 10-60. The slow component (responsible for the PSD) of a few percent will have $<$1 p.e., excluding plain organic scintillator option. ^{6}Li or ^{10}B loaded scintillator can be used in this case, although the noise and background rejection need to be demonstrated.

3. Gas Filled Detectors

The thermal neutron detection is a typical application of the gas filled detectors. This is because the small converter thickness $<$3 mg/cm^3 gives a high efficiency only at low energy. Proportional Counters (PC) or GEMs/MicroMegas may cover very large areas (many m^2), although in the case of ^{3}He active gas at high cost ($\sim$6\$/cm^3/1 bar). The gas filled detectors are usually insensitive to γs (except for pile-up of many γs) because an average amount of energy deposited in the active volume by γ-induced event is significantly lower than that from the neutron capture. The active gas converter (e.g. ^{3}He) gives a good calorimetric resolution on the neutron energy ($>$10 keV) at low energies. Most of gas filled detectors are known to be extremely radiation hard, except for B-GEM detectors whose reported limits on aging correspond to $<10^{12}$ n/cm^2. ^{3}He tubes have a very low noise $<10^{-4}$ counts/s, making them suitable for underground experiments.

The properties of some most common gas filled neutron detectors are given in the Table 2, where the indicated new developments are related to:

1. GEM and MicroMega detectors with various converter materials and different readout schemes. Thanks to their large area, good spacial resolution and low cost these detectors may succeed ^{3}He counters in the thermal neutron imaging applications. To this end the efficiency of these detectors is continuously improving and aging limits are extending.
2. GE Reuter Stokes B-lined proportional counters [8] are called to alleviate periodical shortage of ^{3}He supply. These detectors provide a lower cost alternative to ^{3}He tubes, although with lower efficiency (with respect to the high pressure models).

The gas filled neutron detector activities within the INFN community include the following experiments:

- Aforementioned LUNA-MV (LNGS,Ge,Mi,Pa,Rm,Na,To) experiment is considering alternative detector design based on an array of ^{3}He tubes in a moderator matrix (which could be

Table 2: Characteristics of gas filled detectors used in the neutron detection. The asterisk indicates relatively recent developments.

	Active Element	Converter density	Charge Collection	ε_n(25 meV)
^{3}He,BF$_3$ PC	^{3}He,BF$_3$ gas	<3 mg/cm^3	10 μs	<0.3 cps/nv/cm^2
H-PC	H, CH$_4$ gas	<1, 10 mg/cm^3	10 μs	fast n
Fission Chamber	^{235}U,^{239}Pu deposit	<2 mg/cm^2	10 μs	<0.002 cps/nv/cm^2
B-lined PC (GE)*	^{10}B deposit	<0.2 mg/cm^2	10 μs	<0.05 cps/nv/cm^2
PPAC	^{235,238}U	<0.1 mg/cm^2	10 ns	<0.01 cps/nv/cm^2
GEM, MicroMega*	^{6}Li,^{10}B,^{235}U deposit	<0.2 mg/cm^2	50-150 ns	<0.05 cps/nv/cm^2

an organic scintillator). The very low noise of ^{3}He tubes, combined with the high detection efficiency and insensitivity to γs may allow to reach requested pb sensitivity [9, 10].

- INFN-E/GEM experiment (LNF) is developing GEM-based thermal neutron detector for imaging applications [11, 12]. B-lined GEMs are large area, low cost ($\sim$1 \$/cm^2/foil) detectors which combine a high efficiency with good spacial and timing resolutions. Using enriched 1.2 μm thick ^{10}B metal deposit applied on the GEM foils allows to reach 30% efficiency for a four foil detector [13]. The significant length of the produced 1.78 MeV α in GEM gas (about 1 cm) limits the position resolution to $\sim$1 mm, which can be further improved by a sophisticated off-line analysis. The excellent timing resolution of $\sim$5 ns allows to apply ToF technique, although it is more suitable for fast neutrons, requiring a hydrogenated converter and featuring a much lower detection efficiency. Like all other gas filled detectors GEMs supposed to be very radiation hard. However, aging limits established for MIPs of about 3 C/cm^2 [14], due to thousand times larger energy deposition by 1.78 MeV αs, correspond to a relatively low fluence limits $< 10^{12}$ n/cm^2. This limits have to be studied more in detail in the future experiments.

- n-TOF experiment (Ba,LNL,Bo,Ts,LNGS) is developing MicroMegas, GEM and PPAC neutron detectors for cross section measurements. These detectors are mostly used as beam monitors, measuring the neutron energy spectrum by ToF technique and the beam profile. Various conversion materials were tested: 0.6 μm of ^{10}B for $E_n < 1$ MeV and 1 mg of ^{235}U for $E_n < 1$ GeV, leading to the thermal neutron efficiency of $< 1\%$. The γ-flash background from the primary beam impact on the target obscures the high energy part of the neutron spectrum for detectors with a slow readout. The proton recoil R&D is on-going for the fast neutron reference detector.

4. Semiconductor Detectors

Semiconductor sensors are very expensive ($\sim$80\$/cm^2 for Si and $\sim$10K\$/cm^2 for diamond) and therefore they are used only in very specific areas of neutron detection. A single sensor has typically a small area (<100 cm^2 for Si and <1 cm^2 for diamond) limited by the wafer size. The thin sensor active volume provides a high efficiency only with thermal neutrons through the capture on ^{6}Li or ^{10}B thin (<1 mg/cm^2) converters. Because of the small thickness the semiconductor detectors are insensitive to γs (except for pile-up of many γs). The thin ^{6}Li converter gives a good calorimetric energy resolution (>10 keV), moreover the fast timing of the generated signals (of the order of ns) enables a precise ToF spectroscopy. The semiconductors are more radiation hard than scintillators, however not as much as gas filled detectors. In a thermal neutron flux semiconductor sensors suffer another damage caused by Neutron Transmutation Doping (NTD). In a Si sensor ^{30}Si, present at the natural abundance of 3%, transmutes with $\sigma_{Si(n,\gamma)} \simeq 0.1$ b into n-type semiconductor. Thus, an intrinsic Si layer after a few days in a thermal reactor will lose its resistivity considerably. For GaAs and GaN sensors the NTD effect is thousand times larger due to 100% natural abundance of the transmuted elements: ^{69,71}Ga and ^{75}As and higher capture cross sections: $\sigma_{Ga(n,\gamma)} \simeq 3$ b and $\sigma_{As(n,\gamma)} \simeq 5$ b. The only semiconductor capable to work in high thermal neutron flux is the diamond. The highest carbon isotope ^{13}C occurring at natural abundance of 1% has the capture cross section of 1.5 mb, which gives a factor of 200 suppression with respect to the Si. Moreover, the half-life of the produced ^{14}C is 5700 years and the cross section of the second capture on ^{14}C is less than 1 μb. This makes NTD of diamond very unlikely and permits a long operation in high thermal neutron fluxes.

The properties of some most common semiconductor neutron detectors are given in the Table 3, where the indicated recent developments are given by:

1. High purity electronic grade single crystal diamond detectors. Chemical Vapor Deposition (CVD) technique allowed to reduce dramatically the amount of B and N impurities (down to 10^{-9}) as well as crystal defects. This permits to build detectors with a large charge collection distance, resistant to very high neutron fluences [15].
2. High purity SiC crystals with a thick depletion layer [16] and semi-insulating SiC crystals [17]. These sensors have less attracting properties than those of the diamond, but they are allowing a larger sensor sizes and easier n-type doping.

Table 3: Characteristics of semiconductor detectors used for the neutron detection. The asterisk indicates relatively recent developments.

	Pair Creation Energy	Wafer Size	Depletion layer	n Fluence CCE≃100%
Si	3.6 eV	30 cm	300 μm	$< 10^{14}$ n/cm^2
GaAs	4.3 eV	15 cm	350 μm	$< 7 \times 10^{13}$ n/cm^2
GaN	8.9 eV	5 cm	500 μm	$< 10^{14}$ n/cm^2
Diamond*	13 eV	1 cm	500 μm	$< 3 \times 10^{15}$ n/cm^2
SiC*	8.4 eV	10 cm	100-360 μm	$< 2 \times 10^{13}$ n/cm^2

The semiconductor neutron detector activities within the INFN community include the following experiments:

- n-TOF experiment (Ba,LNL,Bo,Ts,LNGS,LNS) is developing SiMon2 and SiMon2D neutron beam monitors [18] based on 3×3 cm^2 Si sensors. Both detectors use a plastic foil with 0.1 mg/cm^2 of ^{6}LiF deposit inserted into the neutron beam. SiMon2 detector has four

Si sensors installed around the beamline to detect the produced t for the neutron spectrum measurements. This is performed by the ToF technique, thanks to a few ns resolution of the Si detector. Instead SiMon2D has only one Si sensor with 2D readout, installed just behind the foil, for the 2D beam profile measurements. Thanks to $<$50 μm track length of the produced t in the Si the profile granularity can be very high. First measurements performed with $10^5 \div 10^7$ n/cm^{2}s showed excellent detector performances [18].

- INFN-E/HELNEM experiment (LNS) uses a similar detector technology, applied to the thermal neutron imaging [19, 20]. To improve the detection efficiency 4 layers of 16 μm thick ^{6}LiF combined with 2 double sided Si detectors 3$\times$3 cm^2 are used. This allowed to exceed the efficiency of the standard 5 bar ^{3}He reference detectors at INES at ISIS (UK). It has to be noticed that despite the excellent detector performances its cost per unit area seems to be excessive for large imaging facilities in construction at ESS (0.3-80 m^2). Although the wafer cost is $<$1\$/cm^2 it accounts for $<$1% of the detector cost only.
- INFN-E/MAFLUNE experiment (Ge,To) is developing the diamond neutron spectrometer for fast nuclear reactors. The detector is based on a sandwich of two diamond sensors with interposed ^{6}LiF converter. The measurement of both products of the neutron conversion in a fast (ns) coincidence allows simultaneously to obtain the neutron energy event-by-event and to reject the noise. The background is strongly reduced by a high threshold allowed by the conversion reaction Q-value. The spectrometer is aimed for a typical fission spectrum $<$ 6 MeV, where no other open reactions with two charged particle products appear. The first prototype of the spectrometer was calibrated at TRIGA of LENA (Pavia) to determine its response to the thermal (graphite column) neutrons and FNG of ENEA (Frascati) to determine its response to the fast (DD-fusion) neutrons [21] and then measured the neutron spectrum of the fast reactor TAPIRO of ENEA (Casaccia) [22]. We obtained the neutron energy resolution of 73 keV with the standard charge sensitive electronics and $<$160 keV with fast electronics. The reactor neutron spectrum was measured in 12 bins 0.4 MeV wide up to 5 MeV at the power of 5$\div$12 W, corresponding to the neutron fluxes of $10^8 \div 10^9$ n/cm^{2}s.

5. Conclusions

It was impossible to cover all the new developments on neutron detection in this short article. Hence, only those detectors most relevant to the INFN community were selected. In the following I summarize the mentioned technologies indicating in parenthesis the most critical aspects which need to be studied in more detail.

- New developments in detector technologies:
  - PSD capable organic solid scintillators: EJ299-33A plastic and PolySiloxane (large size samples, attenuation length, PSD quality, radiation hardness),
  - ZnS-^{6}LiF-WLS fiber detectors (light collection, radiation hardness),
  - GEM/MicroMega detectors with ^{10}B converter for thermal neutron imaging at ISIS and ESS (track length and spacial resolution, aging limits, real cost of operation),

  - B-lined proportional counters as ^{3}He replacement (neuron detection efficiency),
  - Si-^{6}LiF detectors (cost per unit area, radiation damage),
  - diamond detectors for harsh environments (radiation damage, signal readout).

- Detectors under construction:
  - NEDA based on BC501A liquid scintillators (2n efficiency),
  - LUNA-MV based on ^{3}He tubes or scintillators (noise and backgrounds),
  - ESS GEM beam monitor (aging, cost of operation),
  - n-ToF SiMon2 based on Si^{6}LiF, GEMs, MicroMegas, p-recoil (fast 2D readout),
  - INFN-E diamond spectrometer for fast reactors (ohmic contacts, signal amplification).

References

[1] Eljen Technology, `http://www.eljentechnology.com`.

[2] A. Quaranta et al., *Doped polysiloxane scintillators for thermal neutrons detection*, *J. of Non-Crystal. Sol.* **357** (2011) 1921.

[3] G. Jaworski et al., *Monte Carlo simulation of a single detector unit for the neutron detector array NEDA*, *Nucl. Instr. and Meth.* A **673** (2012) 64.

[4] D. Cester et al, *Experimental tests of the new plastic scintillator with pulse shape discrimination capabilities EJ-299-33*, *Nucl. Instr. and Meth.* A **735** (2014) 202.

[5] S. Nyibule et al, *Radioluminescent characteristics of the EJ 299-33 plastic scintillator*, *Nucl. Instr. and Meth.* A **728** (2013) 36.

[6] V. Modamio et al, *Digital pulse-timing technique for the neutron detector array NEDA*, *Nucl. Instr. and Meth.* A **775** (2015) 71.

[7] E. Fanchini,*Performance of an RPM Based on Gd-lined Plastic Scintillator for Neutron and Gamma Detection*, doi:10.1109/TNS.2016.2514983, TNS-00319-2015 (in presss).

[8] GE Reuter Stokes, `https://www.gemeasurement.com`.

[9] M. Heil et al.,*N22(a,n)M25: The Key Neutron Source in Massive Stars*, *Phys. Rev.* C **78** (2008) 025803.

[10] M. Jaeger et al.,*The 13C(a,n) reaction and its role as a neutron source for the s process*, *Phys. Rev. Lett.* **87** (2001) 202501.

[11] G. Croci et al., *Diffraction measurements with a boron-based GEM neutron detector*, *Eur.Lett.* **107** (2014) 12001.

[12] E. Aza et al., *Neutron beam monitoring for time-of-flight facilities with gaseous detectors*, *Nucl. Instrum. Meth.* A **806** (2016) 14.

[13] S. Uno et.el, *Development of a two-dimensional gaseous detector for energy-selective neutron radiography*, *Physics Procedia* **37** (2012) 600.

[14] L. Guirl et al., *An aging study of triple GEMs in Ar-CO2*, *Nucl. Instrum. Meth.* A **478** (2002) 263.

[15] M. Osipenko et al., *Response of diamond detector sandwich to 14 MeV neutrons*, *Nucl. Instr. and Meth.* A (2016), doi:10.1016/j.nima.2016.02.008, (in presss) [`arXiv:1510.05415`].

[16] G. Bertuccio et al., *Silicon carbide for high resolution X-ray detectors operating up to 100o C*, *Nucl. Instrum. Meth.* A **522** (2004) 413.

[17] F. Ruddy et al., *Development of Radiation Detectors Based on Semi-Insulating Silicon Carbide*, *Nuclear Science Symposium Conference Record*, IEEE (2008) 449.

[18] L. Cosentino et al., *Silicon detectors for monitoring neutron beams in n-TOF beamlines*, *Rev. Sci. Instrum.* **86** (2015) 073509.

[19] A. Pappalardo et al., *Direct comparison between solid state Silicon+6LiF and 3He gas tube neutron detectors*, *Res. Phys.* **6** (2016) 12.

[20] A. Pappalardo et al., *Characterization of the silicon+6LiF thermal neutron detection technique*, *Nucl. Instrum. Meth.* A **810** (2016) 6.

[21] M. Osipenko et al., *Neutron spectrometer for fast nuclear reactors*, *Nucl. Instr. and Meth.* A **799** (2015) 207 [`arXiv:1505.06654`].

[22] M. Osipenko et al., *Test of a prototype neutron spectrometer based on diamond detectors in a fast reactor*, *Trans. Nucl. Sci.* (in review) [`arXiv:1505.06314`].