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MODERN TRENDS IN POSITION-SENSITIVE NEUTRON DETECTORS DEVELOPMENT FOR CONDENSED MATTER RESEARCH

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Современные тенденции развития позиционно-чувствительных нейтронных детекторов для исследований конденсированных сред

Регистрировать нейтроны сложнее, чем заряженные частицы или ионизирующее излучение, поэтому существует гораздо меньше типов нейтронных детекторов. Между тем различные типы экспериментов предъявляют различные и зачастую противоречивые требования к детекторам. На высокопоточных источниках нейтронов быстродействие детекторов часто является главным параметром. Особенно это оказывается важным для малоуглового нейтронного рассеяния, нейтронной рефлектометрии. Для других экспериментов могут быть важны такие параметры, как эффективность детектора, высокое пространственное разрешение, высокое временное разрешение, надежность дискриминации нейтронов от γ-излучения, большая площадь детектора или, наоборот, его компактность. В современных условиях стоимость детектора также играет немаловажную роль. Сегодня не существует универсального типа детектора, удовлетворяющего всем критериям одновременно. Поэтому неизбежен компромисс, и некоторыми характеристиками приходится жертвовать ради других, более важных параметров для данного типа эксперимента.

В данной работе рассматривается состояние дел с детекторами, работающими в ведущих нейтронных центрах мира, и новые перспективные разработки для нейтронных источников следующего поколения.

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Modern Trends in Position-Sensitive Neutron Detectors Development for Condensed Matter Research

Detecting neutrons is a more complicated task compared to the detection of ionizing particles or ionizing radiation. This is why the variety of neutron detectors is much more limited. Meanwhile, different types of neutron experiments pose specific and often contradictory requirements for detector characteristics. For experiments on the high-intensity neutron sources, the high counting rate is one of the key issues. This is very important, for example, for small-angle neutron scattering and neutron reflectometry. For other experiments, characteristics like detection efficiency, high position resolution, high time resolution, neutron/gamma discrimination, large-area imaging, or compactness, are very important. Today, the cost of the detector also became one of the most important factors. There is no single type of detector which satisfies all the above criteria. Therefore, compromise is inevitable and some of the characteristics are trade off in favor of others.

Present report gives an overview of detector systems presently operating at the leading neutron scattering facilities as well as some development work around the globe.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2007

INTRODUCTION

It is well known that neutron scattering is an intensity limited technique. The brightness of modern neutron sources is many orders of magnitude lower compared to the brightness of advanced synchrotron sources. However, the science which can be made with the use of neutron beams is, in many cases, unbeatable or even inaccessible for any other methods. This fact stimulates the upgrade of existing neutron sources and their instrumentation, as well as construction of next generation facilities for neutron research. The next generation neutron sources, like SNS in USA [1], JPARC in Japan [2], and projected ESS in Europe [3] promise about one-to-two orders of magnitude increase in neutron flux depending on the type of the instrument. Meanwhile, advanced neutron optics, focusing systems and neutron detectors can potentially provide extra two orders of magnitude gain in efficiency of neutron spectrometers. Combination of both factors will lead to a quantum leap in performance opening new scientific horizons, not feasible at present.

It is, therefore, evident why development of advanced neutron detectors and detector systems became one of the key issues at present. At the same time, for almost all instruments at the new neutron facilities, the detectors are the limiting component. The moderator and guide systems will deliver more neutrons than the detectors can process. This shortcoming is magnified by the facts that even the most powerful neutron scattering facilities lack intensity for many experiments. Examples are real-time parametric studies, high-pressure experiments and measurements of microsamples, etc.

Detecting neutrons is more complicated task compared to the detection of ionizing particles or ionizing radiation. This is why the variety of neutron detectors is much more limited. Meanwhile, different types of neutron experiments pose specific and often contradictory requirements for detector characteristics. For experiments on the high-intensity neutron sources, the high counting rate is one of the key issues. This is very important, for example, for small-angle neutron scattering and neutron reflectometry. For other experiments, characteristics like detection efficiency, high position resolution, high time resolution, neutron/gamma discrimination, large-area imaging, or compactness, are very important. Today, the cost of the detector also became one of the most important factors. There is no single type of detector which satisfies all the above criteria. Therefore, compromise is inevitable and some of the characteristics are trade off in favor of others.

1. INTEGRATION MODE NEUTRON DETECTORS

Detectors working in integration mode measure only spatial distribution of integrated intensity of neutron beam. To this type of detectors belong neutron image plates and CCD cameras. Advantages of such a type of detectors include very high spatial resolution, high dynamic range and possibility of large-area coverage. Neutron image plates originate from X-ray image plates developed for synchrotron sources. The only difference is the addition of Gd_2O_3 to create a cascade of γ rays and conversion electrons after neutron capture by gadolinium.

Perhaps the most advanced instrument using the neutron image-plate technique is the VIVALDI single-crystal diffractometer at the Institute Laue–Langevin [4]. Schematic layout of the instrument is shown in Fig. 1.

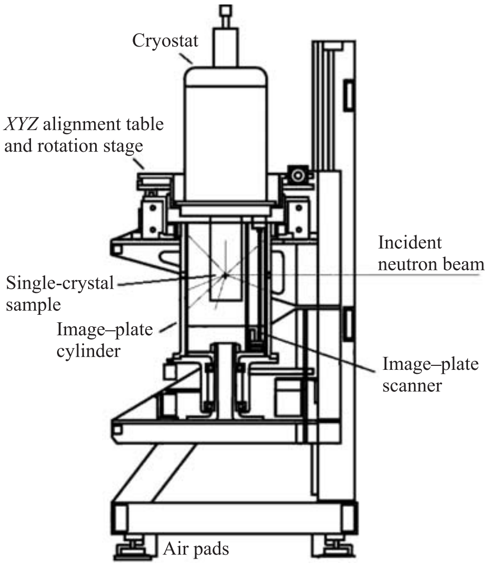

Fig. 1. Schematic layout of the VIVALDI diffractometer

The instrument is using white beam for maximum flux on the sample and large image plates (Gd_2O_3 in $BaFBr{:}Eu^{2+}$) covering 8 sterad (288° horizontally ×104° vertically). As a result, having a very high resolution of $200\times200\ \mu m^2$ and large dynamics range (10^8) this instrument provides a factor 10 to 100 gain over monochromatic data collection (as fast as powder diffraction!) and a possibility of studying small crystals. However, there are also serious disadvantages of this technique. This is a photographic technique and additional device is required to digitize the image obtained for further processing. Image plates are gamma sensitive. As a result, the image accumulates gamma backgrounds. In addition, because of the use of white beam all incoherently scattered neutrons contribute to the accumulated background. Finally, the efficiency of thermal neutron detection is about 20–25% only.

The general tendency for synchrotron sources as well as for neutron facilities is to move towards electronic type of position-sensitive detectors. Such a type of detector working in integration mode is the charge coupled device (CCD). Again, such a type of detectors was first implemented for X-ray instruments. Scheme of neutron CCD camera is shown in Fig. 2.

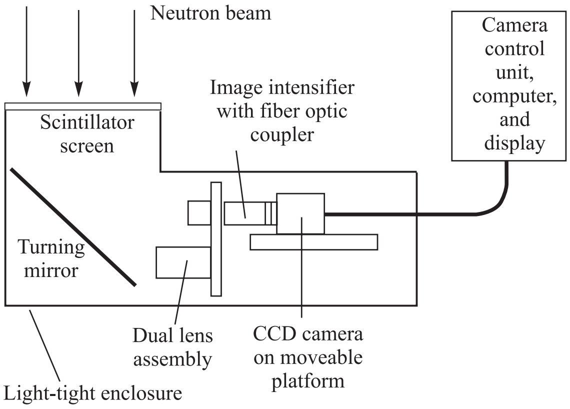

Fig. 2. Typical scheme of neutron CCD camera

Neutron CCD cameras use neutron scintillator ^{6}LiFZnS(Ag) [5] in which lithium isotope captures neutron and decays into charged alpha-particle and triton causing the fluorescence. Created photons are sent to the CCD device with the help of lens and image intensifier with fiber optic coupler. The signal collected is then analyzed by computer. A gain of about 100 in efficiency can be obtained compared to the conventional film method with comparable spatial resolution. Still there is a lot of room for further development of the neutron CCD devices, but it seems that in the future they can completely replace the old film-based detectors.

A very interesting CCD detector is described in [6]. The principle scheme of the device is very similar to that shown in Fig. 2. ZnS scintillator is 16×16 cm^2 and photon sensor has 520×520 pixels. The detector has very high spatial resolution of 0.33 mm, high and homogeneous detection efficiency. Detector prototype was tested in neutron diffraction experiments and small-angle neutron scattering experiments. The results look very promising, especially with good monochromatic incident neutron beam and optimized collimation.

To conclude, integration mode detectors are very efficient for some applications, e.g., single-crystal neutron diffraction, neutron radiography and tomography. Unfortunately, they measure only integrated intensities, while, in many cases, the line shape, line width, background shape, etc., provide crucial information about object under investigation. This fact, in addition to the detector's deficiencies mentioned above, limits their application to other fields of research. Detectors working in counting mode are much more versatile.

2. COUNTING MODE DETECTORS

2.1. Scintillator Detectors. Detection of neutrons with the use of solid scintillator screen was already mentioned with respect to the CCD camera. However, the use of scintillator detectors working in counting mode is spreading quickly. Today, the most commonly used materials for scintillation screens in neutron detectors are ^{6}LiFZnS(Ag) plastic and GS20 ^{6}Li glass. General principle of the detector operation is shown in Fig. 3. Neutrons are captured by ^{6}Li nuclei and the following reaction is initiated:

$$^6\mathrm{Li} + n \rightarrow {}^4\,\mathrm{He} + {}^3\,\mathrm{H} + 4.8\ \mathrm{MeV}$$

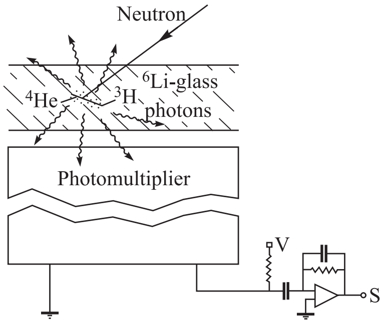

Fig. 3. General principle of neutron scintillator detector operation

Charged particles created, as a result, generate photons in plastic or glass, which are then collected and amplified in a photomultiplier (PMT).

Using a set of scintillator pieces, oriented with respect to the neutron beam in a way to obtain maximum detection efficiency, one can obtain position sensitivity. An example of such an approach is a GEM diffractometer at ISIS facility, UK [7]. Its detector comprises of V-shaped ^{6}LiFZnS(Ag) plastic pieces in a light-tight enclosures, and signals from individual modules are encoded using the fiber optic. Such a special shape of the scintillator screens allows one to obtain 50% efficiency for 1 Å neutrons, which is very high for scintillator-based detectors. Perhaps, the GEM represents the largest scintillator detector operating by now, covering 3.86 sterad of solid angle and having an area of 10 m^2. Instrument is delivering extremely good scientific results in both crystalline and liquid and amorphous samples study. However, strictly speaking, the detector is not used very often in a real position sensitive regime as it is not needed for powder or structurally disordered samples. Moreover, the individual pixel size is relatively big.

Several groups are working on dedicated scintillator-based position-sensitive detectors. The approach is based on the use of wavelength shifting fibers (WLS). Two sets of WLS are attached to scintillator screen as schematically shown in Fig. 4.

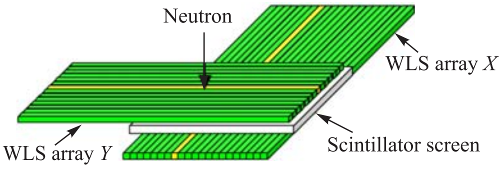

Fig. 4. Schematic layout of the PSD using scintillator screen and crossing fibres for signals read-out

Signals from WLS fibres are then collected by multianode PMT's, and a two-dimensional image of the neutron beam is obtained. Compact device for neutron imaging based on this principle is described in [8]. It has 50×50 mm^2 sensitive area, uses ^{6}LiFZnS(Ag) scintillator 0.4 mm thick. X and Y WLS arrays consist of 128 fibers each with 0.4×0.4 mm^2 cross section. Excellent pixel resolution equal to the fibre cross section was obtained and detector provides parallax and distortion-free, spatially uniform image. In the same reference [8], larger detector of this type planned for use in the focussing small-angle scattering instrument is described. However, there are some problems with such a type of detectors. The efficiency obtained is only 6% for 4 Å neutrons; counting rate is rather low in the order of 10 KHz. This is caused by low light yield reaching the PMT anodes. The efficiency can be increased by using the stack of modules shown in Fig. 4. According to [9], such stacks provide about 45% efficiency for 2.5 Å neutrons. The concept of scintillator screen and crossing WLS fiber read-out is planned to be used at SNS neutron facility [1] for the construction of powder diffractometer [10].

Alternatively, some groups are trying to employ the concept of Anger camera [11]. Using modern flat panel PMT's good spatial resolution of the order of 1×1 mm^2 is obtained [12]. It is presumed that using new advances in neutron scintillators, PMT's and new electronics, large area neutron detector having high efficiency and good spatial resolution could be constructed.

As one can see, the most commonly used scintillator screen today is ^{6}LiFZnS(Ag) plastic. This is because it is producing high light yield compared to the Li glass, it has much lower gamma sensitivity, technology of this material production is well developed and neutron screens are available on the market. The response to gamma rays in the ^{6}LiFZnS(Ag) plastic is much shorter than for neutrons. This gives a very good opportunity to discriminate neutron signals from gammas. At the same time, it is not free of some deficiencies. The maximum thermal neutron efficiency is only about 50%; material is opaque, which limits light output, long-time component in its response to neutrons limits the count rate capability. Therefore, new materials are needed and active work is going on to develop them. Those interested can find more information about new neutron scintillators in [13–16].

2.2. Gas-Filled Detectors. Neutron converter used in the detectors could be either solid, similar to what was discussed in the previous section, or gaseous. Most commonly today the following reaction is used:

$$n +^3 \mathrm{He} \rightarrow p +^3 \mathrm{H} + 764\ \mathrm{keV}$$

Primary ionization produced by proton and triton results in about 25000 electron–ion pairs. Created due to the primary ionization electrons are accelerated in the electric field between cathode and anode and cause the ionization of the added Ar or Xe gas. The electron–ion multiplication factor during ionization is exponentially proportional to the electric field strength, and in the so-called proportional regime the final number of electron–ion pairs is proportional to the number created during primary ionization process. For better spatial localization of the neutron capture in a gas volume of the detector, the stopping gases reducing the proton range (triton is heavier, so its range is much lower) are used. Typical stopping gases are CF_4, propane and other hydrocarbons. The simplest neutron detector of this type is cylindrical gas-filled shell which outer wall being a cathode and a central thin wire anode. To obtain positional sensitivity of neutron detection several methods can be used. The simplest one is to use a set of individual detectors or, for better spatial resolution, a number of individual anode wires in a common gas volume. Reading out signals from each wire gives one-dimensional localization of neutron detection. Schematically this is shown in Fig. 5.

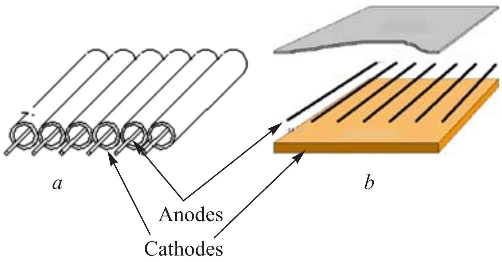

Fig. 5. A set of individual gas tubes (*a*) and multiwire proportional chamber (*b*)

Alternatively, one-dimensional position sensitivity can be obtained in a single gas tube if the anode is made of highly resistive wire. Then, analyzing the signal amplitude from both ends of the anode, the position of neutron capture in a volume is obtained. If the solid cathode in Fig. 5, *b* is segmented perpendicular to the anode wires, two-dimensional sensitivity for neutron coordinate can be obtained. One highly resistive wire can be attached to all the cathode segments and another one — to all anode wires, and position of neutron detection is again obtained through the analyses of signal amplitudes from the two ends of the resistive wire. Another method, which is widely used at present for analyses of signals from gas proportional chambers, is the so-called delay-line read-out. In this case, the time needed for electric signal to reach opposite sides of the delay line is used to obtain the position coordinate of detection. Schematically all three methods of read-out are shown in Fig. 6.

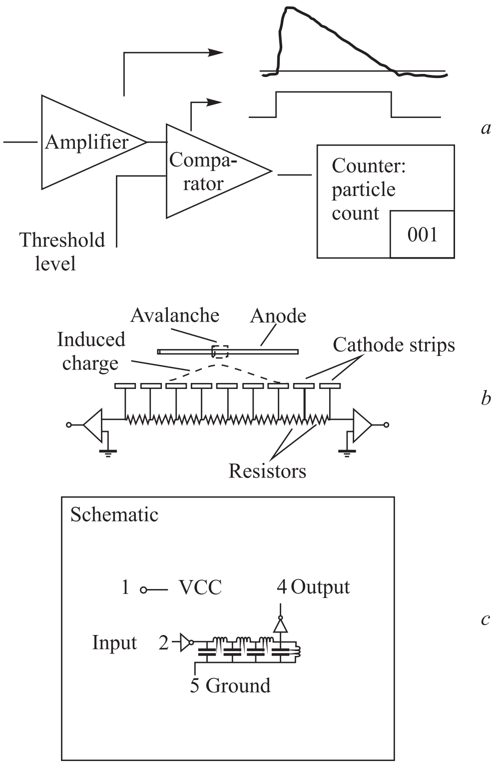

Fig. 6. Different read-out schemes for gas-filled proportional neutron detectors: *a*) individual wire read-out scheme; *b*) resistive wire read-out scheme; *c*) delay-line read-out scheme

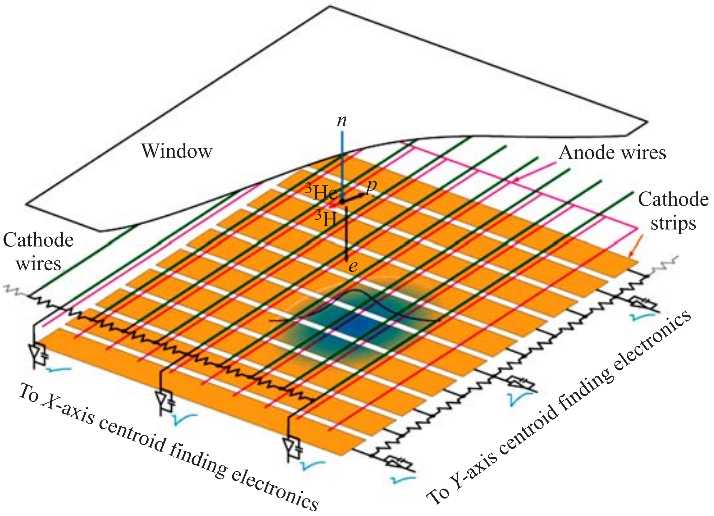

Fig. 7. Principal layout of two-dimensional proportional neutron gas chamber

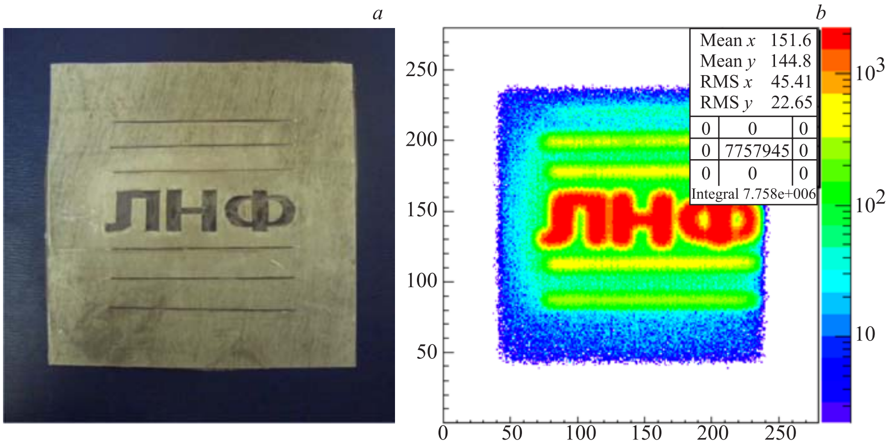

Fig. 8. Detector image obtained using the two-dimensional position-sensitive monitor (*b*) of the cadmium mask (*a*) irradiated by the direct neutron beam from IBR-2 reactor

Using a frame with a set of anode wires and two cathode planes with mutually perpendicular sets of wires, the two-dimensional localization of neutron can be achieved. For practical reasons when delay-line read-out is used it is easier to collect signals from the cathodes rather than from anodes. Schematically two-dimensional multiwire proportional chamber is shown in Fig. 7. Such detectors are widely used in many neutron centers all over the world. As an example the two-dimensional position-sensitive neutron monitor developed and tested at the Frank Laboratory of Neutron Physics, JINR, Dubna can be mentioned [17]. Important feature of this monitor is the possibility to measure spatial distribution of neutron beams having intensity up to 10^8 n/(cm^{2}s) with the resolution 4×4 mm^2 (see Fig. 8). Using the same ideology, it is possible to construct not only monitors, but high-efficiency thermal neutron detectors of different size, shape, resolution, ultra-high count rate and long-term stability. For small detector size resolution as high as 400 μm was obtained. The moderate resolution (several mm) detectors can be as large as one square meter. Curved detectors are also operating at several neutron centres [18, 19].

As one can see from Fig. 7, instead of wires as electrodes the metallic strips on a substrate can be used. This technology was first invented at ILL for neutron detectors [20]. Since then, optimized geometry of strip electrodes to increase their lifetime and technology of microstrip manufacturing matured very much. Example of microstrip structure is shown in Fig. 9. It is often the case that combination of wires and strips is used in the neutron detectors. Microstrips have several advantages over the wires. They are deposited on a solid support, therefore, such problems like wires instability, nonuniform wire tension or wire distances are absent. This guarantees excellent counting uniformity. The distance between microstrip electrodes can easily be made very small, thus improving the spatial resolution. The layout of the strip electrodes can be made of very different designs. This allows obtaining very high counting rate.

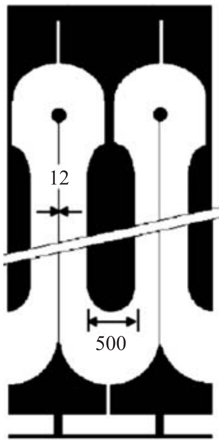

Fig. 9. Schematic drawing of the microstrip signal read-out structure. Thin lines represent anode stripes and thick pads — cathode electrodes. Dimensions are in μm

Examples of different type microstrip detectors already operating and under development can be found in [19, 21–23]. However, microstrip detectors have deficiencies as well. Microstrip plates have limited size because of technological limitations and difficulties of 2D localization of neutrons for large plates. Practically the largest size doesn't exceed 25×25 cm^2. For microstrip detectors the cleanliness of the substrate and gas purity are critical. They need to be assembled in a clean room and extra precautions required when electrical connections are made.

There exist common deficiencies of neutron gas-filled detectors. Among them one can mention limited spatial resolution (about 1 mm), limited count rate (1–2 MHz), parallax correction problem, difficulty to achieve high spatial uniformity for detection efficiency, the need of gas replacement every 3–5 years (expensive). In addition, for high efficiency one needs high gas pressure and, therefore, complicated mechanical design and heavy weight of large area detectors. This fact stimulates the R&D work on new types of neutron PSD devices.

2.3. New Developments.

2.3.1. CASCADE Detector. The problems with gas-filled detectors are mainly connected with the necessity to use high gas pressure to increase the efficiency of neutron capture. Problems can, in general, be solved if instead of gas neutron converter (like ^{3}He) the solid state converter is used or the detector efficiency is trade off in favor of other characteristics, like spatial resolution, count rate, etc. The most common solid state converters are ^{10}B (cheap, but absorption cross section is not very high) or ^{155}Gd or ^{157}Gd (record absorption cross section, but very expensive). The simplified picture of the low gas pressure detector with solid state converter is shown in Fig. 10.

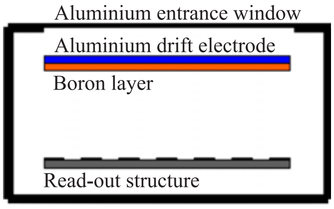

Fig. 10. Schematic layout of low pressure gas neutron detector with solid state converter

Conversion of neutron into charged particles is realized in a boron layer, electron amplification in a low pressure gas volume of the detector and microstrip or other type of read-out scheme allows the two-dimensional localization of neutron detection. The problem is that boron layer should be thin enough to allow the charged reaction products to reach the gas volume. This naturally limits the efficiency of neutron capture. The possibility to overcome this obvious problem was provided by the development of gas electron multipliers (GEMs) [24] schematically shown in Fig. 11.

Thin insulating film (shown in the central part of Fig. 11, a), both sides of which are coated with metal, chemically processed to obtain a regular set of small holes. Diameter of a hole is 50–100 μm and the distance between them is 100–200 μm. The electric potential is applied to both sides of the film which creates in combination with the field between cathode and anode of the detector the field structure schematically shown in Fig. 11, a. Inside the holes the field strength is very high and the electron multiplication forming the electron avalanche is realized inside the holes. This allows reducing considerably the electric field strength between cathode and anode, thus minimizing the risk of electrical discharge on the read-out electrodes. Several GEM structures placed one after another allow obtaining the necessary amplification of a signal at a moderate voltage on each foil. What is important is the fact that at amplification level equal 1, the GEM structure is 100% transparent to the drifting electrons. This feature is used in a CASCADE detector [25]. Principal scheme of the detector is shown in Fig. 12. Subsequent GEMs coated both sides by ^{10}B layers allow one to increase the efficiency of neutron conversion into charged reaction

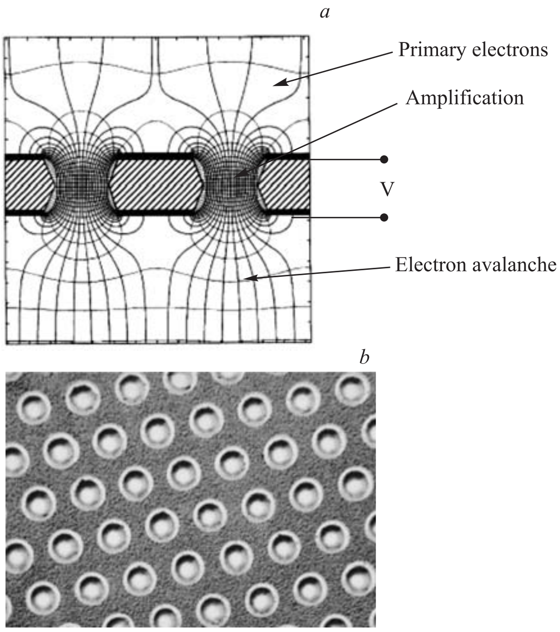

Fig. 11. *a*) Schematic representation of gas electron multiplier and electric field structure in it; *b*) enlarged view of real GEM foil structure

products. According to the tests [25], ten GEM foils allow one to reach 50% efficiency of thermal neutron ($\lambda > 1.8\,\text{Å}$) detection. All but last GEM foils are transparent to the charges generated by fragmentation products. The last GEM is operating as charge amplifier. The advantage of this principle is that detector operates with low cost counting gas at ambient pressure. As a result, its weight is reduced considerably; detector has very small blind areas which allow the modular concept for construction of multidetector systems. There is no need for ultra high vacuum cleaning of detector volume as it can operate with continuous gas exchange. The proven resolution of the detector is 3×3 mm^2 and count rate is 4 MHz/cm^2. It is projected that 1 mm resolution could be achieved and count rate capability could be increased to 10 MHz/cm^2.

However, some development work is still needed. At present the foils are produced from hydrogen containing polymers. With large number of foils this hydrogen produces incoherent scattering background inside the detector volume, thus deteriorating the detector characteristics. In addition, tests are needed to verify the long term stability of the detector characteristics. Nevertheless, potentially this can be a very successful project as large area detectors with good spatial resolution and high counting rate in a broad dynamic range are possible.

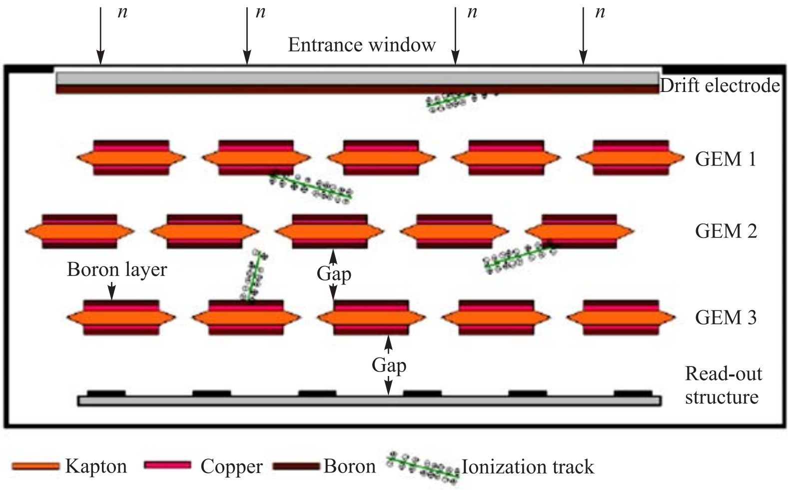

Fig. 12. Schematic layout of the CASCADE neutron detector. Number of GEM structures can be up to 20

Importantly, this alternative to currently existing technological approach can be industrially exploited on a large scale and can be easily serviceable.

2.3.2. Large-Area Hybrid MSGC Detector [26, 27]. Another approach to construct a high-efficiency neutron detector with the solid state neutron converter is based on the use of ^{157}Gd foil (evaporated on a support foil) and two-stage electron amplification process in a detector volume. The scheme of decay of the exited gadolinium nuclei after neutron capture is shown in Fig. 13. Internal gamma cascades produce conversion electrons of energy 29–182 keV. Taking into account that thermal absorption length for this gadolinium isotope is just 1.3 μm and the conversion electrons attenuation length is more than 10 μm, one can combine high efficiency of neutron conversion with high efficiency of electrons escape from the gadolinium foil having thickness 1–3 μm. Energetic electrons are first being converted in electronvolt energy electrons using the CsI 100 μm thick layer on the top of gadolinium foil. To increase the release capability of the secondary electrons, CsI layer is made as a columnar structure, thus considerable increase in an effective surface of the layer is obtained. Such a scheme allows a very good localization of the secondary electron bunches at the neutron impact location.

The first stage amplification process is realized in a low-pressure gas volume of the detector as shown in Fig. 14. Electrons drift to the microstrip read-out structures, located both sides with respect to the converter layer in a constant electric field and being multiplied.

Close to the anode strips, at a distance of about 0.5 mm, the second amplification stage is realized. This amplification is due to the strong alternating

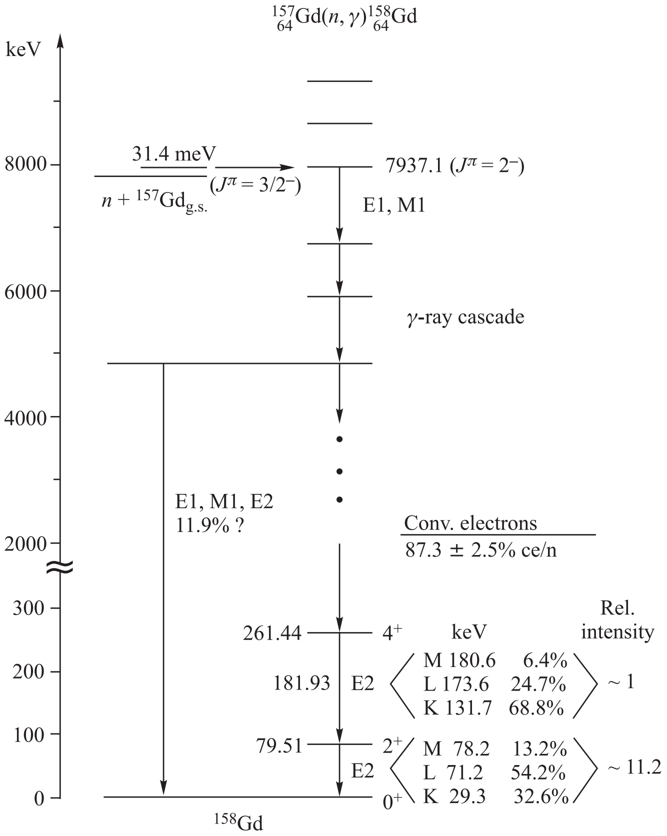

Fig. 13. The scheme of excited ^{157}Gd nuclei decay after neutron capture (Greenwood R. C. et al. // Nucl. Phys. A. 1978. V. 304. P. 327.)

fields caused by the potential differences between anode and cathode strips near the microstrip plate. Such a scheme allows constructing a rather thin detector, as shown in Fig. 14, thus high spatial resolution for neutron detection, high and short signals in a two-stage low-pressure operation mode are obtained. It is believed that, when realized, the detector can be made as large as 0.5–0.8 m squared sensitive area, with 0.1–0.3 mm position resolution, 10 ns time-of-flight resolution and peak count rate capability up to 10^7 events/s. Unfortunately, the practical realization of the concept described above requires development of new and very sophisticated technologies, including the preparation of uniform columnar CsI structures, microstrip plates with desired characteristics, etc. However, it promises the combination of detector characteristics which are not feasible in any of the existing prototypes.

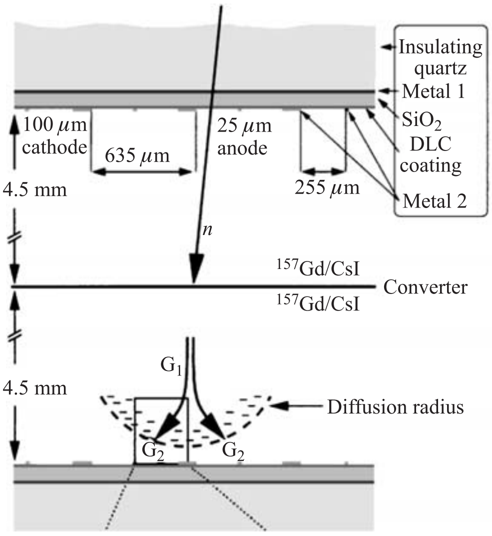

Fig. 14. Schematic layout of the hybrid MSGC detector

2.3.3. Micro-Pattern Neutron Detector. Time projection chamber with micro-pixel read-out was originally developed for the registration of charged particles, X-rays and gamma rays [28]. Schematic layout of the chamber is shown in Fig. 15. In fact, the detector is utilizing the microstrip ideology, but instead of thin metal anode strips placed on a support structure, anodes in a micro-pixel detector are made in the form of small dots. This allows avoiding completely the serious problem characteristic for microstrip plates, namely, the damage caused by discharges between anodes and cathodes. In addition, the required electron amplification near the dot-shaped anode is reached at a lower potential on a cathode, again reducing the risk of discharge damaging. But the most important advantage of this approach is, perhaps, the use of traditional printing circuit board technology for the manufacturing of the read-out structure.

As one can see from Fig. 15, the structure is made on a double-sided printing circuit board (PCB). On one side anode electrodes and on the other cathodes are printed. Typical sizes of different elements are present in the figure. Anode and cathode electrodes are perpendicular to each other. Therefore, measuring signals from both sides of the PCB, one obtains a two-dimensional localization of the particle. Additional advantage is that signals from anode and cathode are of different polarity, but have the same amplitude.

Such a type of detector was used for the neutron time resolved imaging to improve the spatial resolution [29]. It is possible to separate tracks created by protons and tritons generated inside the detector volume filled with Ar-CF_4(20%)-

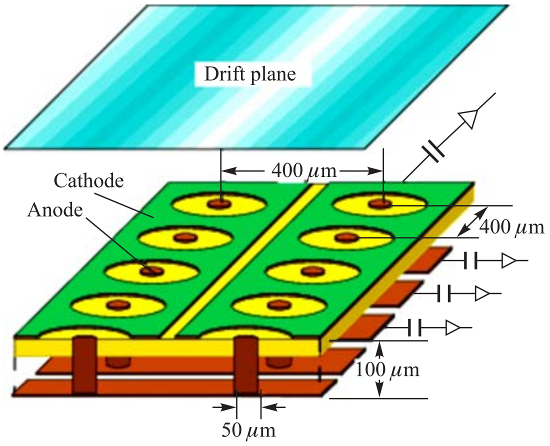

Fig. 15. Schematic layout of the detector with micro-pixel read-out structure

^{3}He(2%) mixture at 1.1 atm pressure. By doing this it is possible to reach the spatial resolution of the detector of submillimeter range and to obtain 100% rejection of gamma rays. A lot of work is still needed to make a detector suitable for practical purposes, but authors believe that the device will be a good candidate for use at the next generation neutron source.

Meanwhile, using such a read-out structure in traditional high-pressure ^{3}He proportional chambers seems to be very promising. The PCB technology is much more readily available than that for production of the microstrip plates. One can make large-area micro-pixel read-out structures for much lower cost compared to the small microstrip plates. The resolution around 0.4 mm with larger amplification gain compared to microstrips can be obtained.

CONCLUSIONS

Obviously, many other development works were left behind. Semiconductor, superconducting, cryogenic neutron detectors were not discussed. This is because their application would be rather limited and there cost is still extremely high.

The author tried to concentrate on the approaches which allow creating in near future large-area detectors with good spatial resolution and high counting rates. Very likely is that the future belongs to the hybrid type of detectors which are fully utilizing the advantages of different types of existing detectors and minimize their deficiencies. Design of new materials, development of advanced technologies for their mass production and growth of microstructures with the required characteristics play the key role in this direction. Commissioning of the next generation neutron sources in USA and Japan as well as planned ESS project in Europe greatly stimulate neutron detector's development activity. However, the market for neutron detectors will always be much smaller compared to the market for ionizing particles/radiation detectors. Therefore, broad use of ideas and components developed for particle and nuclear physics detectors as well as detectors for commercial use in different fields will have a great impact on neutron detector's development.

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