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HIGH-ENERGY QUASI-MONOENERGETIC NEUTRON FIELDS: EXISTING FACILITIES AND FUTURE NEEDS

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The argument that well-characterised quasi-monoenergetic neutron (QMN) sources reaching into the energy domain >20 MeV are needed is presented. A brief overview of the existing facilities is given, and a list of key factors that an ideal QMN source for dosimetry and spectrometry should offer is presented. The authors conclude that all of the six QMN facilities currently in existence worldwide operate in sub-optimal conditions for dosimetry. The only currently available QMN facility in Europe capable of operating at energies >40 MeV, TSL in Uppsala, Sweden, is threatened with shutdown in the immediate future. One facility, NFS at GANIL, France, is currently under construction. NFS could deliver QMN beams up to about 30 MeV. It is, however, so far not clear if and when NFS will be able to offer QMN beams or operate with only so-called white neutron beams. It is likely that by 2016, QMN beams with energies >40 MeV will be available only in South Africa and Japan, with none in Europe.

Neutron sources are used and neutron radiation fields are generated in various scientific research areas and applications. Examples include radiation therapy, radionuclide production, material science studies, design of electronic components and energy production. High-energy neutrons are the dominant component of the prompt radiation field present outside the shielding of high-energy accelerators and are a significant component of the cosmic radiation fields in aircraft and in spacecraft. In radiotherapy using high-energy medical accelerators, high-energy neutrons are a secondary component of the fields in the beam delivery system and in the patient's body. The energy range of neutrons in these fields extends from thermal energies to several GeV. High-energy neutron fields are gaining more attention owing to the increasing number of high-energy accelerators in research and medicine, and the special consideration given to the occupational exposure to cosmic radiation. In order to study the physics of neutron interactions in these applications, in particular concerning dosimetry, radiation protection monitoring of workplaces, and radiation effects in electronics, especially those used in aircraft and in spacecraft, well-characterised neutron fields for high energies are needed.

In medical applications, using high-energy photons and ion beams for cancer treatment, one must consider the contribution of secondary neutrons to organs in the human body outside the target area[1, 2]. The neutron exposure of staff has to be included in the design and operation of the facility: the contribution of fast neutrons outside of the shielding was for a long time underestimated. In the environment outside the primary beam the neutron contribution to human radiation exposure can dominate, and neutrons with energies >10–20 MeV account for up to 50 % of the ambient dose equivalent.

Dosimetry for exposures to cosmic radiation in aircraft is specified in International Organization for Standardization (ISO) standards, see for example ref. (3), and a compilation of exposure data has been given by the European Commission[4]. The radiation field in aircraft and in space is a complex mixture of particles of galactic origin and solar origin, as well as their secondary products produced in interactions with the atoms of the Earth's atmosphere, the material of the aircraft or spacecraft, the human body, and, for space, particles retained in the Earth's magnetosphere. Secondary neutrons are produced which cover the complete range from thermal neutrons up to neutrons of several GeV. For aircraft crew the neutrons can contribute up to 70 % of the total exposure. The International Commission on Radiological Protection has given recommendations, and there is national legislation on the exposure of persons to cosmic radiation: millions of passengers are exposed in aircraft, and aircraft crew are among the most highly exposed radiation workers[5]. There is concern about the radiation exposure of astronauts, a small group, but with special radiation protection procedures which differ significantly from those applied on Earth[6]. The contribution of neutrons to the exposure of astronauts is between 10 and 50 % of the total exposure[7−11]. There is still a lack of information on the biological effectiveness of high-energy neutrons and this is an area which calls for further research.

To make measurements of high-energy neutron fields, or for benchmark measurements of calculated fields, it is necessary to calibrate instruments in reference fields at energies from 20 MeV up to an energy approaching 1 GeV. There are ISO reference fields which extend up to 20 MeV but not at higher energies. For the calibration of instrumentation, which includes the characterisation of the response, neutrons of energies $>$ 20 MeV are required.

Reference high-energy neutron fields, in particular quasi-monoenergetic neutron (QMN) fields, are of importance, because they allow for detailed studies of energy-dependent responses of both active and passive devices. QMN fields have been made available over recent years for energies up to several hundred MeV, each with its own characteristics, advantages and short comings. Some of these facilities have been shut down. At some of the facilities that are currently in operation, efforts have been made to develop standard reference fields and to compare their characteristics. However, these efforts are still incomplete and, furthermore, it has become increasingly difficult to keep the current facilities in full operation. For the determination of the neutron response characteristics of devices at these higher energies, measurements may sometimes be made in monoenergetic proton beams in combination with calculations, or in broad energy distribution neutron fields, also in combination with calculations. Most instruments will require their responses to non-neutron components of the radiation field to be determined. This is of particular importance for space radiation.

NEUTRON PRODUCTION IN QMN FACILITIES

There are six QMN facilities currently in existence worldwide. These operate in less than optimal conditions, especially when seen from the viewpoint of dosimetry. All six facilities make use of the ^{7}Li(p,n) reactions for neutron production. The resulting neutron energy distributions consist of a peak due to the ^{7}Li(p,n$_{0,1}$)^{7}Be reaction close to the energy of the incoming proton ($Q = -1.644$ MeV) and a broad and roughly even distribution down to zero energy. Each of these components generally contains about half the neutron intensity. The peak contains contributions from reactions to the ground state of ^{7}Be (n$_0$) and to the first excited state at 0.429 MeV (n$_1$).The tail in the neutron energy distribution comes from break-up reactions and is reasonably well described using a phase-space distribution[12].

Figures 1 and 2 show typical energy distributions[13] obtained at iThemba LABS (see below). The incoming proton beam energies in these examples are 65.93 and 99.35 MeV, respectively. The Li target thickness is 6 mm. The width of the QMN peak steams from the energy loss in the Li target and the energy difference between ground and first excited state in ^{7}Be, in total amounting to ∼3 MeV. In the shown case the measured width is, however, larger due to limited time-of-flight resolution in the detection system. The mono-energetic energy distribution may be determined from the difference between the 0° (solid line) and the 16° (dotted line) distributions[13] since the ^{7}Li(p,n)^{7}Be reaction shows a strong angular dependence, while the break-up reactions responsible for the low-energy tail show a more isotropic behaviour.

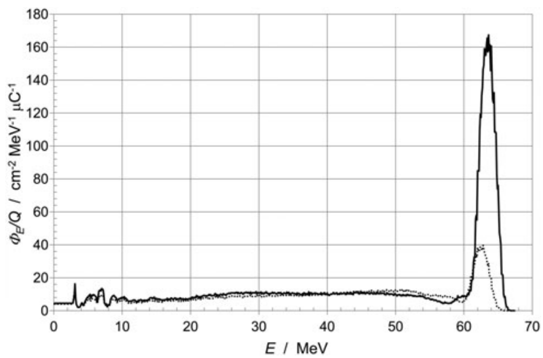

Figure 1. Energy distribution for neutrons from the ^{7}Li(p,n) reaction from 65.93-MeV protons impinging on a 6-mm thick Li target measured at 0° (solid line) and 16° (dotted line).

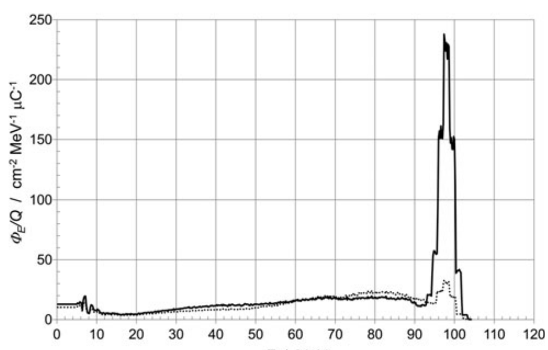

Figure 2. Energy distribution for neutrons from the ^{7}Li(p,n) reaction from 99.35-MeV protons impinging on a 6-mm thick Li target measured at 0° (solid line) and 16° (dotted line).

Since the proton sources in this and all other facilities described below are pulsed, time-of-flight techniques can also be used in active systems to partly suppress the slower neutrons in the low-energy tail.

An overview on quasi-monoenergetic high-energy neutron standards >20 MeV is given by Harano and Nolte[14]. A detailed version of the work reported here has recently been published by EURADOS[13].

OVERVIEW OF QMN FACILITIES

iThemba LABS, South Africa

The iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) facility, Faure, near Cape Town offers neutron beams with peak energies up to about 200 MeV. Detailed information on the quasi-monoenergetic fields is given by Mosconi *et al.* and references therein[15]. Five beams at neutron peak energies of ~35, 65, 97, 147 and 197 MeV at 0° and 16° have been characterised. The beam metrology is traceable to national standards via the fluence and energy distributions made by PTB, Germany.

TSL, Sweden

A description of the neutron fields provided at the the Svedberg Laboratory (TSL) may be found in the paper by Prokofiev *et al.*[16]. The average energies of the peaks of the fluence distributions for the neutron beams which can be provided range from 11 to 175 MeV (see Figure 1 for an example). The peak neutron fluence rate reaches 10^6 cm^{-2} s^{-1} for proton energies <100 MeV and 10^5 cm^{-2} s^{-1} for higher energies. A special feature of the facility is the availability of collimator openings ranging from 1 to 30 cm. Thus, the beam diameters of >1 m can be reached at the largest distance.

TIARA, Japan

This facility offers QMN beams with peak energies in the range of 40–90 MeV[17]. The interval between beam pulses ranges from 45 to 90 ns, depending on the proton energy. In addition, beam pulses spaced at intervals over 1 μs can be delivered. The distance from the ^{7}Li target to the place where the measurements can be performed can be adjusted from 5 to 18 m. Neutron beam profile, neutron energy distributions and absolute neutron fluence were evaluated for the neutron fields with peak energies of 45, 60 and 75 MeV[18].

CYRIC, Japan

The AVF cyclotron used at CYRIC can provide proton beams with an energy ranging from 14 to 80 MeV[19]. The irradiation room is a narrow room whose size is 1.8 m (W)×10 m (L)×5 m (H). The size of the neutron beam is ~84 mm (horizontal)×84 mm (vertical) at that point. The available fluence rate of the neutron beam is ~10^6 cm^{-2} s^{-1} μA^{-1} at the sample position, located at ~1.2 m downstream of the production target. The flux of the neutron beam per solid angle can be varied from about a few hundred sr^{-1} s^{-1} to 3·10^{10} sr^{-1} s^{-1}.

RCNP, Japan

A QMN field for the energy range of 100–400 MeV is available at the RCNP cyclotron facility of Osaka University. Protons accelerated up to 65 MeV using an AVF cyclotron can be boosted up to 400 MeV in the ring cyclotron. Protons passing through the 10-mm thick ^{7}Li target are swept out by the swinger magnet to the beam dump. Since the target can be moved to different positions within the swinger magnet neutron beam angles of up to 30° can be delivered. The experimental tunnel has a length of ~100 m, which enables precise measurements of energy distributions by the time-of-flight method[20]. The potential as a high-energy neutron reference field has been investigated for proton beams with energies of 140, 250, 350 and 392 MeV. The highest number of neutrons per solid angle per electric charge reaches 1.0·10^{10} sr^{-1} μC^{-1} for 140 MeV to 392 MeV protons.

NPI, Czech Republic

The Nuclear Physics Institute (NPI) at Řež, Czech Republic, provides neutron beams with peak energies up to 36 MeV. Standards beams in MeV are 18, 21.6, 24.8, 27.6, 30.3, 32.9 and 35.6, respectively[21]. As at the other facilities, the neutron beam is produced from an ^{7}Li target. However, this facility differs in that the proton beam is not bent towards a beam dump but stopped in a carbon disc directly behind the lithium target. This arrangement allows placing target samples at distances as close as 48 mm from the lithium target. Therefore, a neutron fluence rate of ~10^9 cm^{-2} s^{-1} in the QMN peak at 30 MeV, can be achieved.

NFS, France

A new facility that will offer both a white neutron energy spectrum and a QMN spectrum is currently under construction at GANIL in Caen, France. The facility is called Neutrons For Science (NFS) and is expected to deliver its first beams late 2014.

The neutron production targets at NFS will be located in a converter cave. The beams are delivered to an experimental area which is separated by a 3-m thick concrete wall from the converter cave. A bending magnet placed between the converter and the collimator entrance will remove protons from the neutron beam. A conical channel through the wall defines the neutron beam. The experimental area (25 m × 6 m) will allow performing time-of-flight measurements by using experimental set-ups at distances from 5 up to 25 m from the neutron production point.

The new Spiral 2 LINAG (LINear Accelerator of Ganil) will deliver pulsed proton and deuteron beams up to 33 and 40 MeV, respectively, at a maximum intensity of 5 mA in pulses that are shorter than 1 ns. However, the ion beam intensity on the neutron production targets will be voluntarily limited to 50 μA. The reduced intensity means reduced wall thickness for radiation protection and reduced activation of the converter. It will also mean a manageable power distribution on the neutron production targets. Furthermore, the LINAG beam frequency (88 MHz) is not optimised for time-of-flight measurements. In order to avoid wrap around effects, the neutron beam frequency must be reduced to <1 MHz. Therefore, a fast beam-chopper downstream of the RFQ will select 1 over N bursts, with $N > 100$ corresponding to a maximum ion-beam intensity of 50 μA delivered onto the neutron production target of NFS.

DISCUSSION AND CONCLUSIONS

Reliable radiation protection monitoring of workplaces at high-energy radiation fields in medical facilities, research accelerator environments, on-board aircraft and in space requires numerical simulations of an instrument's fluence response and its benchmarking to high-energy neutrons >20 MeV. These benchmark measurements need careful calibration, traceability to national standards, determination of uncertainties and intercomparisons of various instrument assemblies. To this end QMN reference fields, and more generally high-LET calibration fields, with good traceability are needed.

All six currently active facilities, and a planned future NFS facility, make use of the same nuclear reaction to produce the QMN beams, the ^{7}Li(p,n)^{7}Be reaction. It is therefore to be expected that similar experiences have been made at the various facilities. Generally speaking, none of the existing facilities were originally conceived for QMN applications, but have mostly been adapted from an existing infrastructure at an accelerator laboratory. Several facilities suffer from too much background caused by scattered neutrons in a room not large enough for QMN measurements. A low background can only be achieved in a large irradiation hall provided with a raised floor, so that the neutron source and the detector under test can be located close to the centre of a large volume, as at various national metrology institute neutron irradiation facilities. Only a few have a path long enough to allow precise time-of-flight measurements. Some of the facilities report logistical problems, such as sub-optimal access to the target area and/or the experimental room, lack of a remote system for exchanging targets or insufficient space provided to the users to set up their experiment. In some cases the shielding between the target area and the experimental room is not efficient enough.

From the experience gained at the operational facilities described in this report, several conclusions regarding an optimised QMN reference field can be drawn. An ideal QMN facility should offer the following:

- QMN fields over a wide energy range (offering peak energies from ~20 MeV to several hundred MeV).
- Well-characteried neutron energy distributions.
- A low, well-characterised background.

To achieve this, several key factors are relevant:

- A stable short-pulsed proton beam of sufficient intensity.
- Adjustable time between subsequent proton pulses (pulse selection/beam kicker).
- Access to the neutron production room without a passage from the measurement area, possibly even complete remote control of target changes.
- Several neutron beam lines at various angles (from 0° up to ~25°), this can facilitate the subtraction of the non-peak fluence.
- Large measurement area/experimental hall to allow for usage of time-of-flight methods; suitable general working environment (office space, access to workshop, etc.).
- Sunken floor and raised roof to minimise ambient background.
- Provision of stable and reproducible high-quality beams.

An additional desirable feature would be the option to switch to neutron fields to simulate a workplace field, for example an atmospheric-like neutron energy fluence distribution, to allow testing and intercomparison of instruments.

Besides these listed technical aspects, accessibility is an important feature for any user and, for several reasons, this is generally difficult for all the facilities. It is noted that three out of the six operating facilities are located in Japan, and one, iThemba LABS, in South Africa. Furthermore, owing to normal routine activities during weekdays, iThemba LABS only offers QMN beams during weekends. Finally, all the four mentioned facilities normally require a nuclear physics involvement in dosimetry and metrology for measurements which is often difficult to provide.

After the shut down of the facility in Louvain-la-Neuve a few years ago, TSL in Sweden is the only European facility that offers beams with energies >40 MeV. However, a major task of TSL is the construction of a dedicated facility for proton cancer therapy, and lacking Government support, the TSL

QMN is facing being closed down in the immediate future.

There exists the need to make measurements, and to benchmark calculations, of the increasing number of high-energy neutron fields. Nevertheless, it is unfortunately likely that no QMN beams with energies >40 MeV will be available in Europe in the near future.

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