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Fast-Neutron Production via Break-Up of Deuterons and Fast-Neutron Dosimetry

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A neutron field is produced by bombarding a lead brick with 500 and 800 AMeV deuterons. The incoming deuterons break up into protons and neutrons mainly due to Coulomb interaction with the high-Z target nuclei. The resulting charged products are deflected by a strong dipole magnet behind the target. The spectrum of the remaining neutrons in forward direction is measured from 0.1 MeV to 1.5 GeV with the time-of-flight method.

Two neutron dosimeters are tested in the neutron field described above: The extended-range rem-counter WENDI-2 from Thermo-Electron® Corporation reveals a fluence response of 778 pSv cm^2 and 947 pSv cm^2 for neutrons of energy 482 MeV and 789 MeV, respectively. A thermo-luminescence based extended range neutron dosimeter developed at GSI exhibits a fluence response of 623 pSv cm^2 and 634 pSv cm^2, respectively. A conventional version of the passive neutron dosimeter yields dose values which are lower by a factor of 5 demonstrating the advantage of the extended-range neutron dose equivalent meters.

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1. Introduction

Neutrons constitute a major component in the radiation field outside the shielding of particle accelerators. While the neutrons percolate through shielding walls the spectrum is shifted towards lower energies. Nevertheless, when the energy of the primary beam particles approaches several tens of GeV per atomic mass unit, one has to expect a certain leakage of GeV neutrons. The *Gesellschaft für Schwerionenforschung* in Darmstadt (GSI) is preparing for a new *Facility for Antiproton and Ion Research* (FAIR). A large synchrotron for ions from protons up to Uranium-238 will allow beam intensities up to 10^{12} particles per second at energies of several ten GeV per atomic mass unit. Thus, appropriate instrumentation will be needed in the future to survey the radiation levels over a substantial number of beam lines and experimental laboratory buildings.

Recently neutron dose equivalent meters have been developed which show an enhanced response to neutrons above 20 MeV. The response function of these instruments is determined and optimized mainly with the help of Monte-Carlo simulations. Experimental data is very limited, especially for neutron energies above 200 MeV. Here we report on the production and characterization of a quasi-mono-energetic neutron field via break-up of deuterons with energy of 500 and 800 AMeV[*]. In these neutron fields two different neutron dosimeters are tested, both optimized for high energetic neutrons: First, the active counter WENDI-2 from Thermo-Electron® Corporation and second, a passive neutron dosimeter based on the thermo-luminescent technique built at GSI.

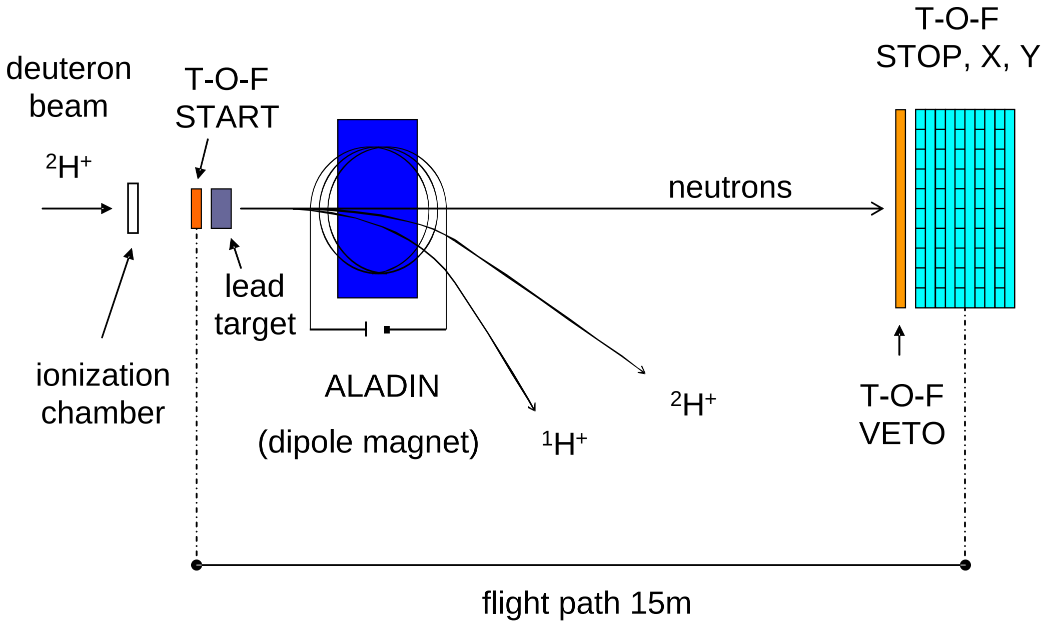

Fig. 1: Scheme of the experimental set-up for time-of-flight neutron spectrometry.

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[*] AMeV: kinetic particle energy given per number of particle nucleons

2. Neutron spectrometry

Deuterons with a kinetic energy of 500 and 800 AMeV are delivered from the GSI synchrotron in the experimental area *Cave C* where the *Large Area Neutron Detector* (LAND) is situated. Deuterons hit a 5 cm thick lead target and break up mainly via Coulomb interaction producing a field of mainly neutrons and protons. The protons and other charged particles are separated from the neutrons by a large dipole magnet. The neutrons with energies higher than 100 MeV are detected by LAND. The neutron yield below 100 MeV has been assessed to be smaller than 20 % in terms of fluence and smaller than 30 % in terms of dose. Fig. 1 shows a scheme of the experimental set-up

LAND is a large time-of-flight detector wall built at GSI by a collaboration of different nuclear physics institutes. A detailed description of LAND can be found in [1]. Briefly, LAND is a multi-layer array of passive iron converters and active BC 408 plastic scintillators. The signals from 200 different scintillator paddles are processed (anti-coincidence to a veto detector for charged particles) and stored for later evaluation. The energy of the detected neutrons is derived from their time of flight over a 15 m long path. The spatial resolution perpendicular to the beam axis is 10 cm times 10 cm. The detection efficiency is higher than 90 % for neutrons above 500 MeV. The differential neutron yield as measured with LAND is shown in Fig. 2. The neutron spectrum resulting from 500 and 800 AMeV deuterons can be approximated by a Gaussian function with maximum at 482 and 789 MeV and full width at half maximum (FHWM) of 119 MeV and 203 MeV. The total neutron yield is 5.06 and 6.42 neutrons per 100 primary deuterons, respectively.

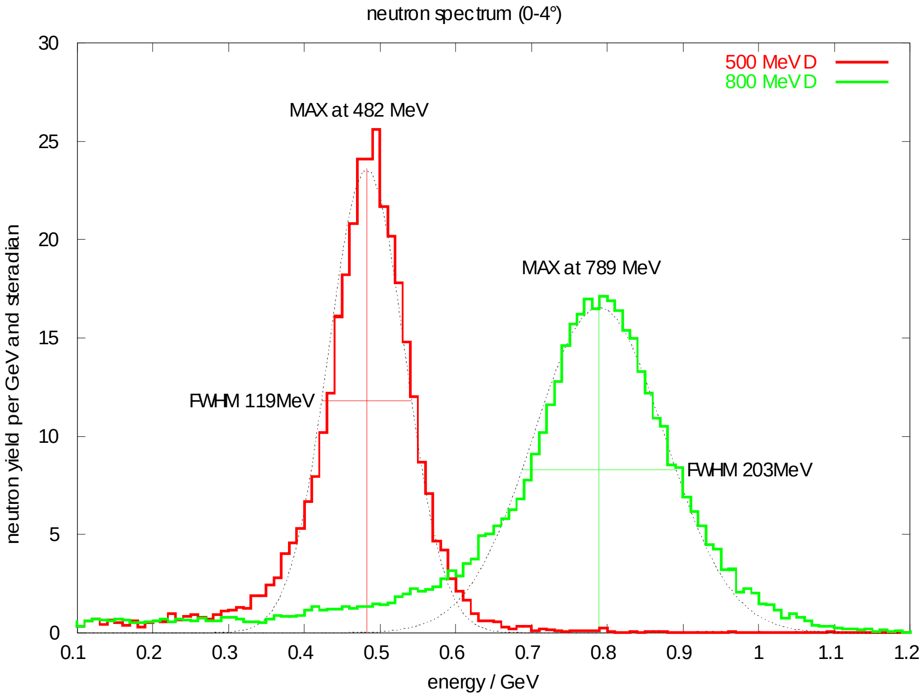

Fig. 2: Neutron yield per primary deuteron as measure with LAND covering a polar angle from 0° to 4° as seen from the production target..

3. Fast-neutron dosimetry

The instrumentation used to survey radiation controlled areas is normally calibrated to the operational quantity *H*(10)* named ambient dose equivalent. The ambient dose equivalent from neutrons is highly depending on neutron energy. The official function to convert neutron fluence in neutron dose equivalent is given in [2] covering neutron energies from thermal to 200 MeV (see blue line in Fig. 3). For higher energies conversion coefficients have been calculated ([3],[4], see red and green lines in Fig. 3) but not officially approved, yet. As a result it is not clear which should be the desired value for the dose response of a neutron dose meter. Sannikov and Savitskaya [3] report a conversion factor of 420 and 580 pSv cm^2 for 500 and 800 MeV neutrons, whereas Ferrari and Pellicioni account smaller values of 290 and 377 pSv cm^2 for 500 MeV and 1 GeV neutrons, respectively. Apart from that conventional *rem-counters* are not suitable for neutron energies above 100 MeV as their response function declines steeply above 10 MeV.

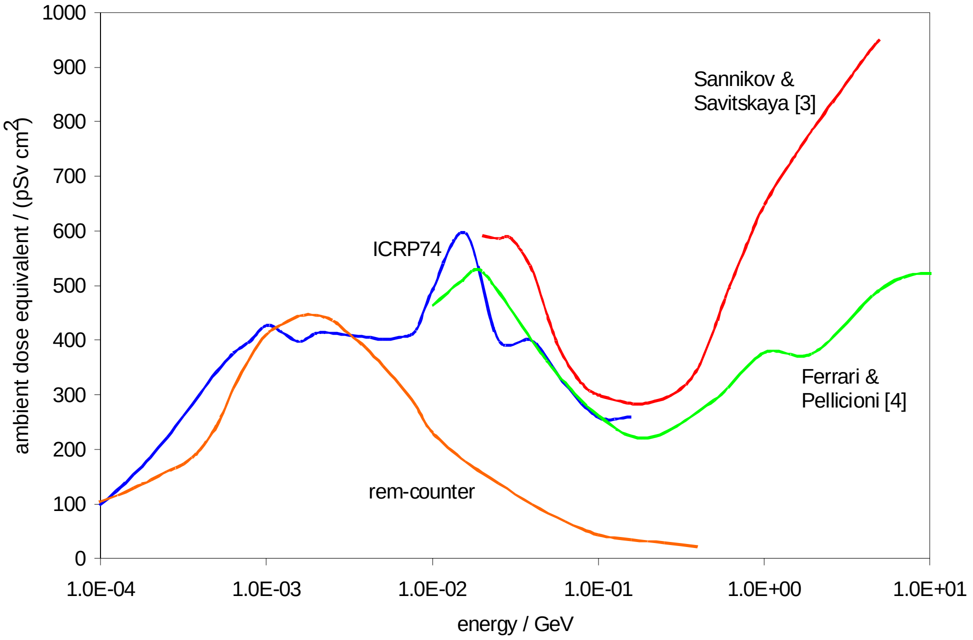

Fig. 3: Fluence to dose conversion function for neutron ambient dose equivalent (blue, red, green lines) and response function of a standard rem-counter (orange line) from 100 keV to 10 GeV.

3.1 Neutron dosimeter WENDI-2

According to the suggestions of Birattari et al. [5] the response of a standard rem-counter can be extended to higher energies by introducing a layer of heavy metal in the moderator. Fast neutrons are converted to neutrons of lower energies mainly through spallation reactions. Olsher et al. [6] developed an optimized rem-counter featuring a tungsten layer which is commercially available from Thermo-Electron® Corporation. The instrument – specified for neutron energies from thermal to 5 GeV – was named WENDI-2, an abbreviation for Wide Area

Neutron Detection Instrument, second version. A cylindrically shaped Helium-3 proportional counter is situated in the centre of the moderating (polyethylene) and converting (tungsten) cylindrical structure. The instrument is calibrated using a 37 MBq Americium-241/Beryllium source, exhibiting a calibration factor of $3.2 \cdot 10^9$ counts per Sv.

3.2 Passive thermo-luminescent neutron dosimeter

The passive neutron dosimeter consists of a 12 inch polyethylene sphere and a card carrying two crystals of each TLD600 and TLD700 thermo-luminescent material. TLD600 contains lithium-fluoride enriched in Li-6 thus being sensitive to neutrons via the (n,t) reaction. On the contrary, TLD700 contains practically no Li-6 and consequently is not sensitive to low energetic neutrons. The neutron dose is calculated from the difference of the signals in both crystal types. The advantages of the passive neutron dosimeter compared to rem-counters are the following: It does not show pile-up effects in highly pulsed fields and can operate for several months without the need of electricity or maintenance. Furthermore, the passive system is not sensitive to gamma rays and charged particles due to the subtraction of the TLD700 signal from the TLD600 one. The draw-backs are: no information on the time profile of the dose rate is provided and the detection limit is in the order of 100 µSv.

Applying the concept of a heavy metal converter from the extended range rem-counters a modified version of the passive dosimeter has been developed. The response function of the device has been calculated using Monte-Carlo methods [7]. Both passive dosimeters are calibrated with a Americium-241/Beryllium source before using them in the fast-neutron field. The standard passive dosimeter will be referred to as STLD and the modified version as STLD(X) from here on.

3.3 Results

The response of the neutron dosimeters described above is tested in the fast neutron field characterized in Sec. 2. The detectors are exposed in a distance of 5.36 m to the production target, where a neutron fluence of 21.9 cm^{-2} and 34.8 cm^{-2} is produced by 10^6 deuterons of 500 and 800 AMeV, respectively. For the passive dosimeter between $3 \cdot 10^{11}$ and $1.5 \cdot 10^{12}$ deuterons are applied to each card. The response of the active detector WENDI-2 can be derived from correlating the instrument counts with the single deuteron counts of the time-of-flight start detector. The resulting fluence responses for the three devices are shown in Tab. 1. The highest fluence responses are observed for the WENDI-2 instrument. The values are between a factor of 1.6 and 2.7 *higher* than the conversion factors found in [3] and [4]. For the modified passive dosimeter STLD(X) one obtains values which are *higher* by a factor of 1.1 to 2.1. The standard passive dosimeter STLD, which is mainly sensitive to neutrons with energy smaller than 20 MeV, shows response values which are by a factor of 2.4 to 5.2 *lower* than the conversion factors found in [3] and [4]. Furthermore, the response of the STLD is smaller by more than a factor of 5 than the response of the STLD(X), which is an indication that the dose contribution of low energy neutrons is comparatively small for both neutron fields under investigation.

Tab. 1: Fluence responses of the neutron dose equivalent meters. The devices have been calibrated to an Am-241/Be neutron source (h(10)=391 pSv cm^2). All values are given in pSv cm^2 (standard deviation in parentheses).*

Neutron Energy	WENDI-2	STLD(X)	STLD
482 (119) MeV	778 (39)	623 (32)	121 (15)
789 (203) MeV	947 (47)	634 (56)	112 (32)

4. Conclusion

A quasi-mono-energetic field of high energetic neutrons can efficiently be produced by break-up of deuterons and subsequent deflection of the residual charged particles. From 500 and 800 AMeV deuterons breaking up in a 5 cm thick lead brick, one obtains neutron yields in the range of 5 to 6 % (energy > 100 MeV). The resulting neutron spectra show distinct peaks close to the energy per nucleon of the primary deuterons with a full width at half maximum of approximately 25 % of the energy in the maximum.

The neutron dose equivalent meter WENDI-2 overestimates the doses resulting from the neutron field described here by a factor of 1.6 to 2.7. The response of the passive dosimeter STLD(X) is lower than the one of the WENDI-2, but still higher than the conversion factors published in [3] and [4]. The observed over-response might originate from neutrons with energies below 100 MeV. However, their dose fraction was assessed to be smaller than 30 % and therefore can not account for the large varieties between the observed responses and the published conversion factors.

With rising energy (> 1 GeV) one may expect an even more pronounced difference between the active and the passive dosimeter types. While active instruments count an increasing number of events caused by charged particles, the passive dosimeters STLD and STLD(X) are not affected because of the TLD600/700 subtraction process.

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