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Abstract

The fragment separator at the future GSI facility has to be regarded as a strong source of neutron radiation. The shielding design of the instrument requires knowledge of the produced neutron fields. In this paper the neutron fields of the present fragment separator were characterized by the use of thermoluminescence dosimetry applied during an irradiation period of uranium-beams impinging on a thin Be-target with a mean energy of 0.8 GeV/u. In addition time of flight measurements of neutrons were performed in Cave B of GSI. Neutron spectra produced by carbon and uranium beams at 1 GeV/u (thick iron target, 10x10x20 cm^3) for the angular range from 0° to 90° relative to the incident ion beam were measured with a BaF_2 scintillator detection system. Conclusions for the shielding design of the planned superconducting fragment separator are drawn on the basis of the measured dose distributions at the present fragment separator.

1. Introduction

The production of rare isotopes by fragmentation or fission of heavy ions like ^{238}U in inverse kinematics is accompanied by the production of high energy neutron radiation. Typical beam parameters for the present GSI facility are energies around 1 GeV/u and mean intensities of $5 \cdot 10^7$ Ions/sec for a ^{238}U-beam. The incoming ion beam hits a Be target, where approximately 20 % of the beam interacts. In the fragment separator (FRS) the produced isotope of interest will be selected. The major part of the incoming beam and of the fragments is deposited in the first dipole element of the fragment separator. Consequently the most significant neutron production occurs in the target and near the first dipole of the FRS. In Fig. 1 the arrangement of the whole FRS is shown beginning at the target to the experimental area at the end. Areas with major production of neutron radiation are also marked. These areas are the target area, the first dipole, the energy degrader as a secondary target and finally the experiment itself.

The first part of this paper covers the measurement of the neutron dose during a beam period in July/August 2002. An experiment with a ^{238}U-beam was performed at the FRS with primary ion energies between 100 and 1000 MeV/u. The measurements were done by means of thermoluminescence dosemeters (TLD, see e.g. [1,2]). The TLD elements used here consist of pairs of TLD600/700 (^{6}LiF/^{7}LiF pairs) which are sensitive to gamma, ion and neutron radiation. The specific characteristic of neutron dosimetry at high energy accelerators is the wide range of neutron energies which have to be considered from thermal energies (0.025 eV) up to 10^9 eV. About 30 dosemeters were positioned along the FRS.

For a complete reconstruction of the dose pattern near the FRS not only the dose distribution along the FRS, but also the lateral dose gradient has to be taken into account. Therefore in addition to the TLD measurements model calculations were applied. For this analysis only the computational model for the planning of SIS 18 at GSI from 1986 was available. The model comprises the neutron production from a neon beam slowed down in a thick iron target [3,4,5]. The beam energy in the model was 2 GeV per nucleon. For the spatial dose assessment the angular distribution of the neutron production relative to the incident beam was used. A distribution derived from the superposition of 20 single source distributions was used to fit the measured dose values. The single source terms were equally spaced along the FRS. An optimization procedure was applied to determine the single source strengths.

For the shielding design of an accelerator facility or an experimental area for heavy ions it is not sufficient to know the total neutron production only, also the knowledge about their energy and angular distribution is important. Therefore energy and angular distribution measurements of the produced neutron radiation were performed.
The second part of this paper is the summary of first results of time of flight measurements of neutrons produced by a ^{12}C-beam and a ^{238}U-beam. The ions at 1 GeV/u were completely stopped in an iron target (10 cm x 10 cm x 20 cm). Therefore this experiment represents a thick target approximation. The time of flight method (TOF) was chosen to derive the neutron energy distribution. A BaF_2-detector was used in combination with a thin plastic scintillator as a start detector and a further PE-detector as a veto detector for charged particles. A comparison for the overall production of neutrons for these two types of ions will be given including a discussion about the problems on scaling the neutron production from one ion type to another.

Finally the estimation for the shielding design of the future Super-FRS will be drawn on the basis of the measurements presented here.

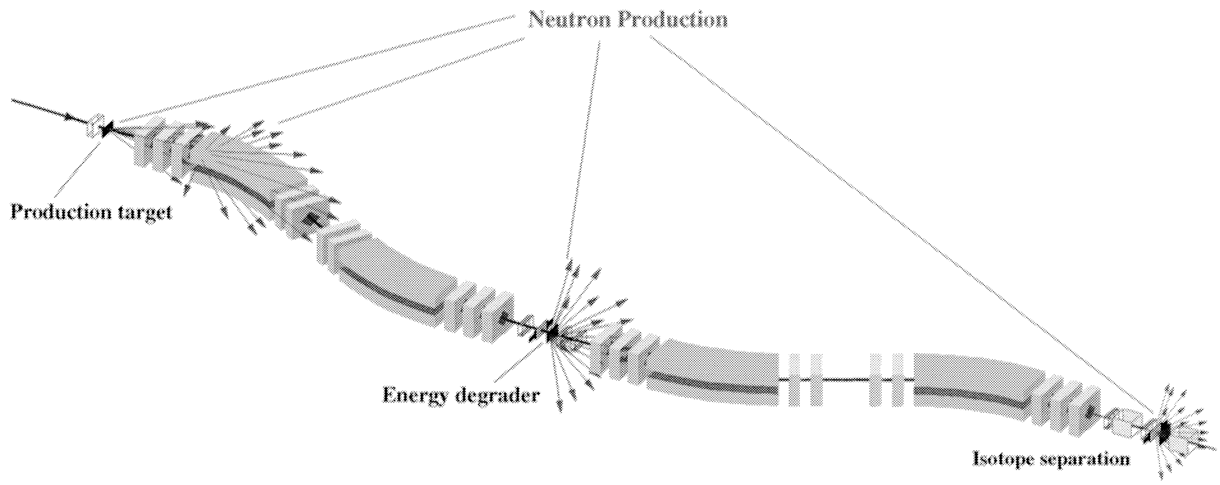

Fig. 1: View of the GSI Fragment Separator (FRS) with the production target, the energy degrader and the experimental area at the end. Also indicated are the positions where substantial neutron production rates are expected. The major part of the neutrons will be produced in the first dipole.

2. Thermoluminescence Dosimetry for Neutron Radiation

At accelerators with short extraction pulses it is advantageous to measure the radiation with passive detectors in order to avoid pile-up problems. For the dosimetry of gamma and neutron radiation it is common to use TLD as passive dosemeters. In this paper the dosimetry is concentrated on neutron radiation which is the substantial component of the total dose.

The following method was used for neutron dosimetry by means of TLD:

1. Measurement of the total dose for all radiation types, that means gamma radiation, neutron radiation and in particular ion radiation with a ^{6}LiF system (TLD 600). With this system an additional channel for the neutron detection is used by the exothermic reaction: $n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$ (+ 4.78 MeV)
2. Measurement of all radiation types with a ^{7}LiF system (TLD 700) with the exception of the neutron detection by the exothermic reaction of the TLD 600 system (see 1.).
3. Subtraction of the reading of dosemeter 2 from the reading of dosemeter 1.

The irradiated TL elements were evaluated by a Harshaw TLD Reader system (type 8800 Card Reader). Because of the strong energy dependence of the exothermic reaction (1), one has to compensate for the inverse dependence of the reaction cross section on the neutron velocity. Therefore the TLD-elements are positioned in the centre of a polyethylene sphere. With this setup one can approximate the energy dependence of the whole detection system to the dose quantity to be regarded in this case, the ambient dose equivalent H*(10) for neutron energies from thermal up to about 10 MeV. The dose measurements are performed near the target area of the FRS and therefore very energetic neutrons (up to 1 GeV) must be regarded. The detection system must be adjusted to these neutrons. The response of the system was improved by the introduction of an additional layer in the PE-sphere. This additional layer consists of lead. The impinging high energy neutrons can cause spallation reactions in this layer and the nuclei emit neutrons. The conversion of a high energy neutron in neutrons with lower energies in a spallation reaction is suitable to increase the response of the dosemeter to these high energy neutrons (see Fig. 2).
The response of the TL-detection system was computed as a function of the neutron energy in the range from 1 MeV to 1 GeV with the MC-simulation programme FLUKA [6]. For the

calculations the deposited energy in the ^{6}LiF and ^{7}LiF element was scored. The difference of the deposited energy gives the response to neutrons detected by the exothermic reaction. The response is given in units of the response to neutrons from an AmBe-source.

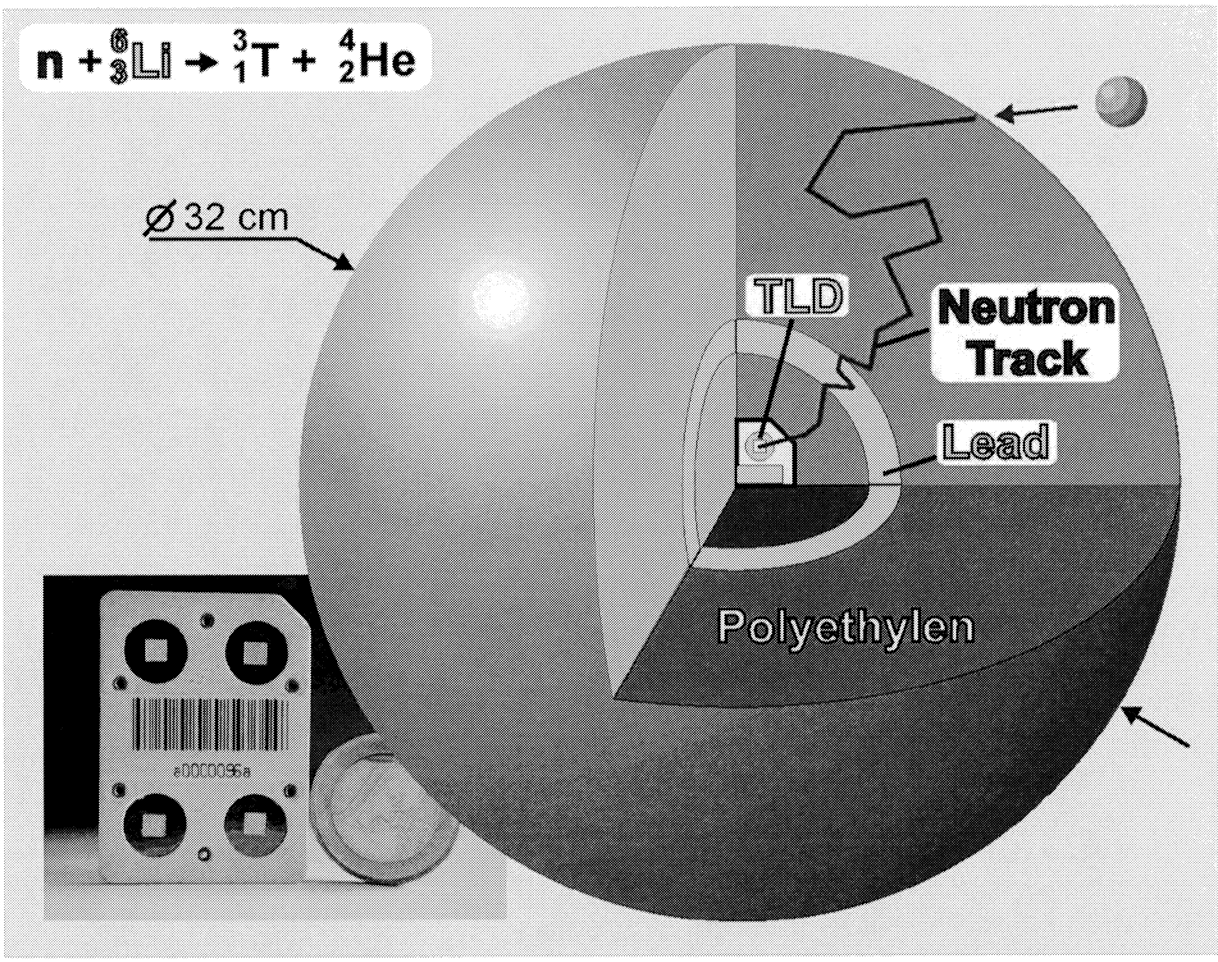

Fig. 2: TL detection system consisting of a TL chip (two pairs of TLD600/700, left) and a PE sphere for the energy compensation of the ^{6}Li(n,t)α reaction up to about 10 MeV; PE sphere with an additional lead layer for an increased response to neutrons of 20 MeV or higher (see also Fig. 3).

The responses for the two types of spheres are shown in Fig. 3. Also shown is the ambient dose equivalent H*(10) due to the ICRP 74 [7] (from 1 MeV to 200 MeV) and the results of Sannikov et al. [8] (from 200 MeV to 1 GeV). For the detection system with the bare PE-sphere the response decreases for neutron energies above 10 MeV and for 1 GeV the response is one order of magnitude lower in comparison with the combined PE-Pb sphere. The ambient dose equivalent has a local maximum at about 25 MeV and none of the systems is suitable to follow this curve in this energy range.

For energies between 50 and 500 MeV the PE/Pb detection system has a response closer to the ambient dose equivalent. For the whole neutron energy range from 1 MeV to 1 GeV one can estimate that the calibration of the PE/Pb-sphere with neutrons from an AmBe-source could underestimate the dose value by about 50 %.

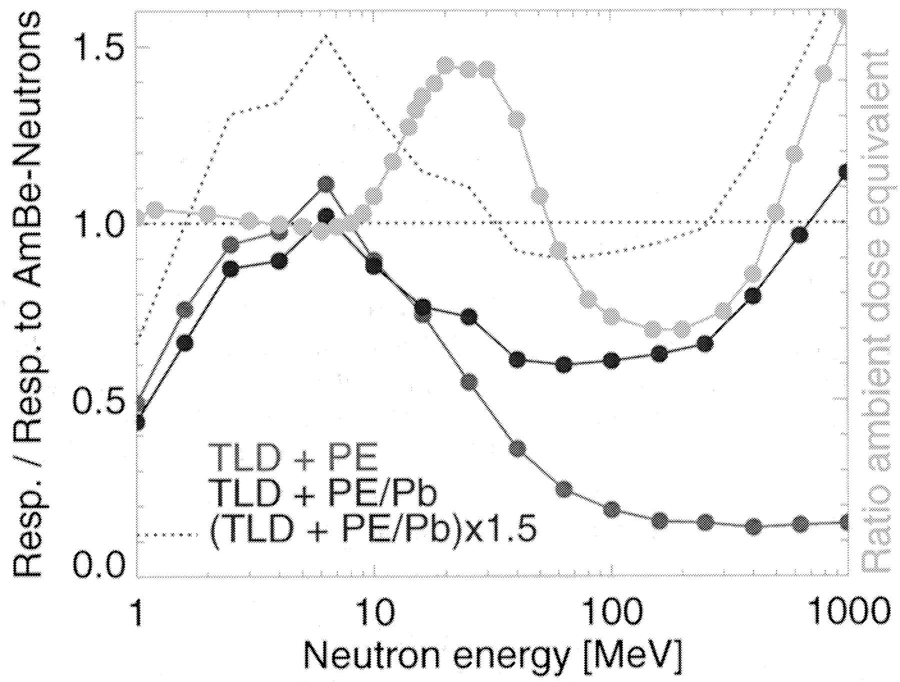

Fig. 3: Relative response of the used TL detection systems, as simulated with the MC-code FLUKA. The conversion factor for the ambient dose equivalent H*(10) is also shown here. All values are related to the corresponding quantity of neutrons from an AmBe-source.

Model Calculations for the Estimation of the Shielding Design

The neutron dose rate can be modelled by the use of so called line-of-sight calculations. In these models, applicable for simple geometries only, one uses the distance from the reference point to the point like neutron radiation source and the attenuation length in the shielding. Further important quantities are the angular dependent source strength of the neutrons, the effective (or mean) neutron energies and the attenuation parameter which depends on the effective neutron energy and the used absorption material. One of the first formulations of such models was introduced by B.J. Moyer [9].

The following formulation for the quantities of the line-of-sight model was used here:

1. A source term for the neutron production which considers the angular dependence of the yield of the neutron production $dN(\vartheta)/d\Omega$,
2. an effective dose conversion factor $C_{Neff}(\vartheta)$, which enables the computation of the dose value from the neutron fluence with an effective neutron energy,
3. the geometrical factors like the inverse square law for the distance to the source and the attenuation in the shield by the application of an exponential law with an attenuation factor $\Lambda(\vartheta)$ which considers the decreasing mean neutron energy with the increasing angle ϑ,
4. consideration of the build-up effect in the shielding by the factor B (typical values are 7.5 or 8 for concrete).

$$H(\vartheta) = F \cdot I \cdot \frac{1}{r^2} \cdot \frac{dN(\vartheta)}{d\Omega} \cdot C_{N_{eff}}(\vartheta) \cdot B \cdot e^{-\left[\frac{\rho \cdot d}{\Lambda(\vartheta)}\right]}$$

The primary beam intensity is I and the fraction interacting with the target is considered by the factor F. Only the first part of the formula is used to derive the dose pattern near the FRS. The factor B•exp[-ρ•d/Λ] is set to one, because the absorber thickness d is negligible and the build-up factor is equated with one.

For the analysis only the neutron dose distribution caused by a Ne beam with 2 GeV/u, impinging in a thick iron target, has been used. The model was developed for the safety report for the construction of SIS18 in 1986 [3]. The model is based on experimental data and on results from Monte Carlo calculations [3,4,5]. The parameters dN/dΩ, C_{neff} and Λ are taken from ref. [3] for the entire range of angles from 0° to 180°. The neutron production yield ranges from 70/sr in forward direction to 6.7E-3/sr in backward direction which means that four orders of magnitude difference in the neutron production must be expected for these directions.

For the estimation of the spatial dose distribution at the FRS the described Moyer model was applied. The dose distribution was assumed to be caused by 20 equally spaced neutron sources along the FRS beam line while the angular characteristic of the neutron yield and the corresponding dose conversion factor were taken from SIS18 report [3]. At every position j there is a dose contribution from the source i with a dose value H_{ij} calculated by the above mentioned formula and neglecting the attenuation in the shielding. The sum over all sources gives the dose value at the position j:

$$H_j = \sum_{i=1}^{n} H_{ij}.$$

When the dose values for the measurement positions were computed one can apply a minimization procedure to estimate the source strength of the 20 single sources at the positions j. Here the function minimization procedure MINUIT was applied [10]. The following function was minimized.

$$\chi^2 = \sum_{j=1}^{30} \frac{(H_j - M_j)^2}{\sigma_j^2}$$

M_j is the measured dose value at position j and σ_j the error of M_j. During the minimization procedure the source strength of the single sources were determined. On the basis of these source strengths (20 parameters) one can derive the spatial dose distribution near the FRS.

Results of the TLD Measurements

During the irradiation period in July/August 2002 a ^{238}U beams were used in the FRS. The energy range of the beams was 100 MeV/u to 1000 MeV/u, the mean value was 800 MeV/u. The measured dose along the FRS was about 10 Sv near the target and 100 μSv in the experimental area. The total number of ^{238}U-ions in the FRS was 10^{14}.
Examples for dose values near the target area inside the shielding and on the roof are summarized. In a few examples spheres with bare PE moderator and those with an additional lead layer were used for an intercomparison (see Fig. 5 for the positions). The values are given in

Table 1. The difference of the reading of the TL-dose values of both types of spheres near the target of the FRS is remarkable. The sphere with lead layer gives a TL-signal which is about one order of magnitude higher than the signal of the other one. This gives an indication on the presence of very energetic neutrons because the response of both types of spheres differs by one order of magnitude e.g. for 1 GeV neutrons (see also Fig. 3).

Table 1: Examples for dose values measured for a ^{238}U-irradiation period at the present FRS (23 days in July/August 2002) with a mean beam energy of 800 MeV/u. The measurements were done near the beam line of the FRS and on the roof of the shielding of the FRS (see Fig. 4). Also given in this table are the values of the shielding thicknesses of the roof.

Pos.	Inside FRS		Roof	Concr.-Shield
	TLD [μSv]	TLD/Pb [μSv]	TLD [μSv]	[m]
1	1.6E+06	1.7E+07	9.3	3.2
2	2.1E+06	1.8E+06	80	4.0
3	2.0E+06	9.2E+06	-	4.0

For the estimation of the spatial dose distribution (two dimensional dose distribution near the FRS beam line) the above mentioned model was applied with the parameters determined by the χ^2-procedure.

Positions 1,2,3

Target **Experimental Area**

Fig. 4: Computed neutron dose distribution near the FRS of GSI. The distribution is based on TL measurements and a model calculation. The measurement positions are indicated by white circles along the FRS beam line. The measurements were performed in July/August 2002 with ^{238}U-beams with mean energy 800 MeV/u. The numbers at the isodose lines are given in the unit μSv.

The entire dose distribution was computed for a grid of points from the entrance area in front of the target to the experimental area at the end of the FRS. A picture of the entire dose distribution is shown in Fig. 4, the positions of the TLD are indicated by the white circles.

Because of the strongly forward-peaked neutron emission two neutron cones were identified near the target area. The first one is a result of the neutron production in the target, the second one is dominated by the neutron generation in the first dipole. The dose values vary from 10 μSv up to 10^7 μSv in the target area. In the experimental area a third neutron cone is produced but the dose values are 5 orders of magnitude lower than in the target area.

3. Measurement of Neutron Spectra by the Time of Flight Method for heavy Ion Beams at 1 GeV/u

For the TOF-measurements a BaF_2-detector was used in combination with a plastic start detector and a plastic veto detector. The BaF_2-detector was originally developed for the TAPS detector [11]. The detector is positioned to the target with a distance from 3.7 m to 7 m for the ^{238}U beam and from 3.7 m to 4.9 m for the ^{12}C beam. The target was an iron block with the dimensions: 20 cm x 10 cm x 10 cm. The measurements were performed between 0° and 90° (see Fig. 5).

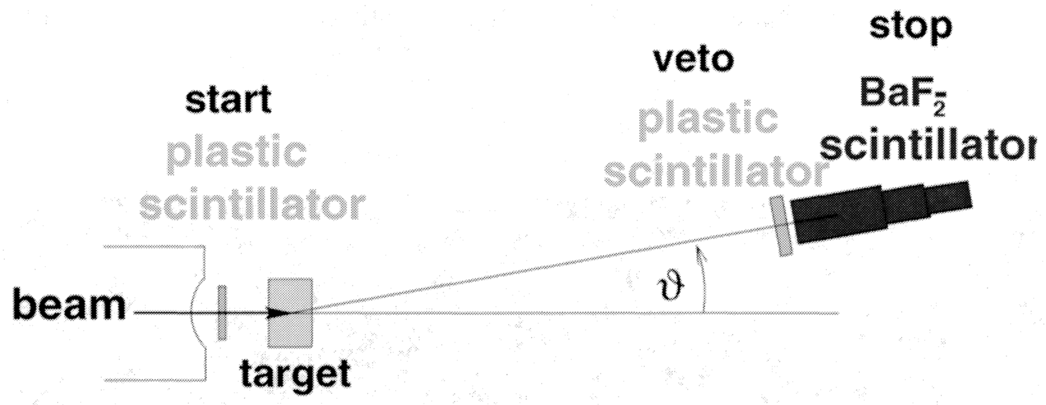

Fig. 5: Setup of the TOF-detector for the measurement of neutron spectra in thick target approximation for a ^{12}C beam and a ^{238}U beam with 1 GeV/u. The measurements were performed for the angles θ with 0°, 7.5°, 15°, 30°,50° and 90°. The used detectors are a BaF_2 scintillator for the neutron detection and plastic scintillators as start and veto detectors.

The detection threshold was about 7 MeV for the energy deposition in the BaF_2 -scintillator which corresponds to about 25 MeV for the neutron energy. The detection efficiency is about 15 % for fast neutrons with energy greater than 50 MeV and decreases rapidly towards lower energies. Further details will be described in the paper of Gunzert-Marx et al. [12].

First results for the neutron spectra

The TOF measurements were performed in Cave B of the GSI target hall. For the detector positions 6 angles of deflection were considered, namely at 0°, 7.5°, 15°, 30°, 50° and 90°. Although the beam energy was 1 GeV/u, neutrons with higher energies were measured. This can be explained by the Fermi-energy of the nucleons within the nucleus, where the momentum addition from the nucleons of the ions and the target nucleons can release neutrons with energies higher than the nominal incident energy per nucleon. Some of the measured neutron spectra are shown in Fig. 6 caused by the impinging ^{238}U beam. The released neutrons are strongly forward peaked and consequently the neutron distribution in forward direction has the highest proportion of the entire neutron spectrum. With increasing angle the number of created neutrons decreases. A further characteristic of the spectra is the decrease of the centre of the neutron energy with increasing angle.

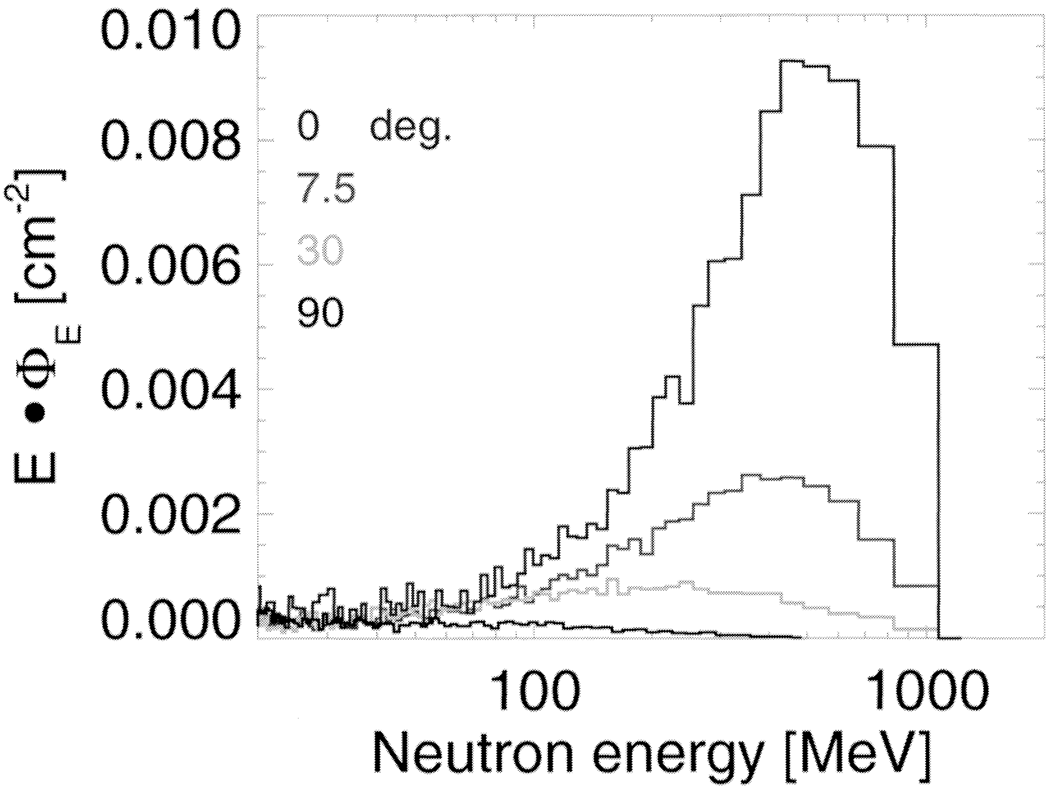

Fig. 6: Neutron spectra produced by a ^{238}U ion beam at 1 GeV/u slowed down in a thick iron target for the range of angles from 0° to 90° related to 100 cm distance to the target.

The measurements were repeated for a ^{12}C beam at the same specific energy and the same target. The result at 0° is given in Fig. 7 in combination with the neutron spectrum of the ^{238}U-beam at the same angle.

The shape of the neutron spectrum is slightly different for both cases but the number of neutrons produced in forward direction can roughly be scaled by a factor of about 3 from a ^{12}C beam to a ^{238}U beam (see Fig. 7). This scaling factor cannot be easily derived from simple scaling parameters like the number of nucleons in the projectile or the reaction cross sections. Due to the very different ranges of the ^{12}C and ^{238}U ions in the thick target (19.4 cm and 1.6 cm, respectively) the spatial distribution of the primarily produced neutrons is expected to be very different and the transport of these neutrons through the iron block plays an important role. The situation is further complicated by the contributions of secondary fragmentation products and – in case of ^{238}U – of fission processes. At the present stage of analysis one can state, however, that a simple scaling with the number of nucleons in the projectile significantly overestimates the number of produced neutrons.

The fast neutron production (neutron energies > 25 MeV) of a ^{238}U-beam at 1 GeV/u in a thick iron target is about 140 neutrons per ion. The corresponding number for a ^{12}C ion for the same energy per nucleon and the same target is about 45 neutrons per ion.

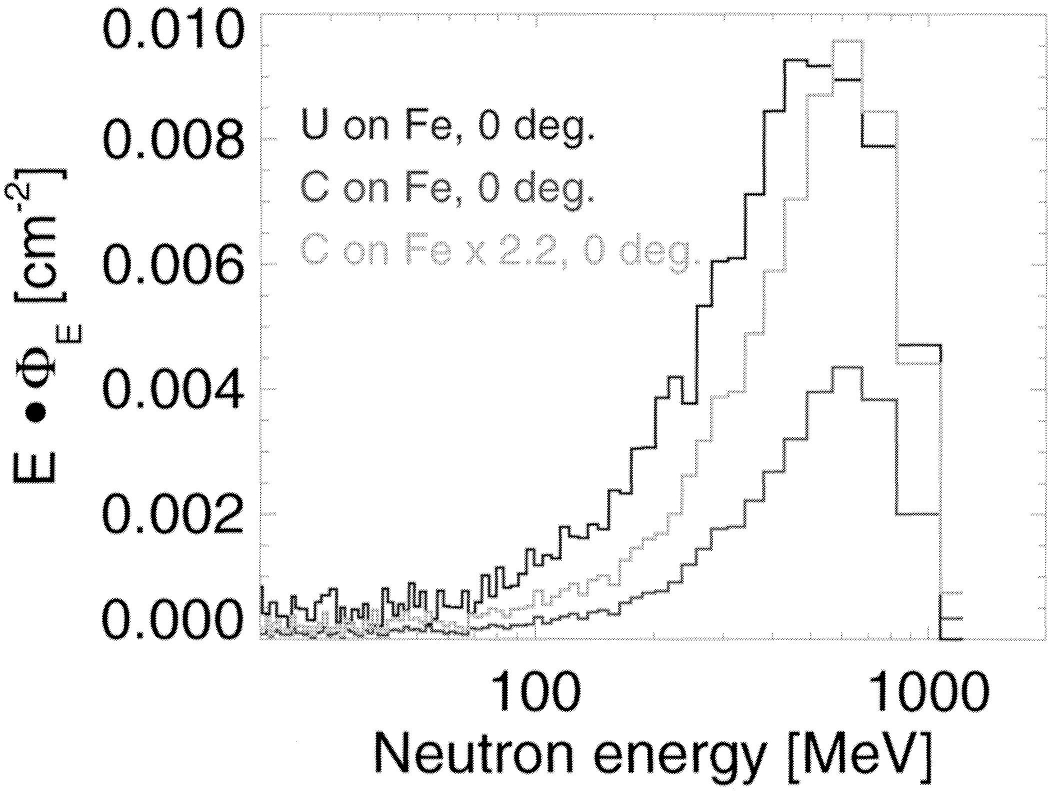

Fig. 7 :Comparison of neutron spectra in forward direction for a ^{238}U beam and a ^{12}C beam, both at 1 GeV/u. For comparison the ^{12}C ion produced neutron spectrum was scaled with a factor 2.2. The spectra are related to 100 cm distance to the target.

This comparison confirms the need to extend the knowledge about the neutron production at heavy ion accelerators in the GeV per nucleon energy range. Scaling the dose rate estimations and shielding measures from a proton accelerator facility to a heavy ion facility by the number of nucleons might lead to an overestimation of the dose rates and an over-shielding of the facility.

4. Summary and Outlook

At GSI a new accelerator facility with a Superconducting Fragment Separator (Super-FRS) is planned. For the design of the buildings containing the Super-FRS one has to consider the necessary shielding measures which are dominated by the neutron production near the target area. For a detailed estimation of the shielding one needs information not only on the entire neutron production, but also on the energy and angular distribution of the neutrons.

For the estimation of the overall neutron production and the neutron dose assessment thermoluminescence dosemeters (TLD) were used in a measurement campaign at the present FRS. The measurements showed that for an estimated number of 10^{14} ions of ^{238}U-type (or an average number of $5 \cdot 10^7$ Ions/sec for a 23 day irradiation period) one can expect a radiation exposure on the roof of the shielding of about 80 µSv. To keep the same radiation level outside the shielding for the planned Super-FRS with a ^{238}U-beam with 10^{12} Ions/ sec one can estimate the additional shielding material near the target area. To achieve the same dose (rate) level one needs an additional concrete shielding of about 4 m thickness.

The analysis of the neutron production was continued by time of flight measurements of neutrons produced in a thick target where a heavy ion beam with an energy of 1 GeV/u was stopped.

The neutron spectra measured in the angular range from 0° to 90° - relative to the beam line of the incident beam - can serve as input distributions for shielding calculations. Neutron spectra were measured for a ^{238}U-beam and a ^{12}C beam. The fast neutron production of the ^{12}C beam cannot be scaled to the ^{238}U-beam by application of the ratio of the nucleon number of the projectiles. If one calculates this ratio one can expect a scaling factor of 20, actually the ratio of 3 was observed. Therefore the shielding design cannot be done with neutron production data from light ions scaled to heavy ions on the basis of the nucleon numbers, this would lead to an over-shielding of the facility.

The future activities will concentrate on the more complete measurement of the double differential neutron production cross section in thick target approximation for a wider range of projectile types. With the obtained neutron data, shielding calculations can be performed by means of Monte Carlo transport codes like FLUKA or MCNPX [6,13].
A further application will be the development of a simple shielding model - like the Moyer formulation - for the data of the ^{12}C and U-beam at 1 GeV based on the neutron transportation through the bulk shielding by means of the above mentioned Monte Carlo programs.

Important for the neutron dosimetry at heavy ion accelerator facilities are passive dosemeters like the thermoluminescence based dosemeters whose reading is independent on the pulse structure of the impinging primary beam. The hitherto existing dosemeters are not suitable to give a precise dose assessment for the entire range of neutron energies from 0.025 eV to GeV. Inside and outside the shielding the dosemeter has to measure over 11 orders of magnitude and to fit the quantity ambient dose equivalent. Further work is needed to improve the response of the spherical multi-layer detection system.

Acknowledgement

The authors thank Dr. R. Simon for valuable discussions.

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