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V.E.Aleinikov,[1] A.P.Cherevatenko, F.B.Clapier,[2]
V.I.Tsovbun

NEUTRON RADIATION FIELD DUE TO 6.6 MeV/amu ^{58}Ni IONS BOMBARDING A THICK Cu TARGET

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[1] MFA USSR
[2] Institut de Physique Nucleaire, Orsay, France

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INTRODUCTION

As has been pointed out by A.Rindi[1], more theoretical and experimental results are needed to evaluate the radiation hazard due to neutrons, produced in bombardments of thick targets with intermediate energy heavy ions. The relevant measurements performed at several laboratories provide new data compared with those reviewed by H.W.Patterson and R.H.Thomas[2]. They are mainly experimental results obtained at low energies ranging between the Coulomb barrier and 20 MeV/amu. The measured parameter is the dose equivalent rate in mrem/h per unit flux. As has been noted previously [3], the dose equivalent was determined for a series of ions at a fixed angle, as has been done at Darmstadt [4] and at Oak Ridge [5], or at different angles for a specific ion: ^{12}C (ref. [6]) or ^{238}U (ref. [4]).

Recently the angular and energy distributions of the fluence and the dose equivalent of neutrons produced in a thick carbon target bombarded by 4.2 MeV/amu ^{48}Ti ions were measured in Dubna [7].

This experiment was designed to obtain a more detailed information about the shape of neutron spectra, about the angular dependence of the equivalent dose as well as the quality factor. Such kind of data would be very useful in testing some predictions made over the last few years [3,8].

In the present paper we make an attempt to test the prediction of the formula [3] describing the angular distributions and its valudity for a larger number of angles. That formula derived from the data cited above was reasonably accurate for light and very heavy ions with energies up to 15 MeV/amu but was incapable of predicting the angular distribution of neutrons near the target bombarded by 86 MeV/amu ^{12}C ions, which has been obtained by J.W.N.Tuyn [9] and is in good agreement with the cascade calculation performed by H.W.Bertini [10].

EXPERIMENT

Measurements were carried out on an external ion beam from the JINR cyclotron U-400[11]. The experimental lay-out is shown in fig.1. Detectors (D) were placed at a distance of one meter from the target at laboratory angles from 0° to 135° at 15° intervals. The choice of the 1m distance enabled us to interpose

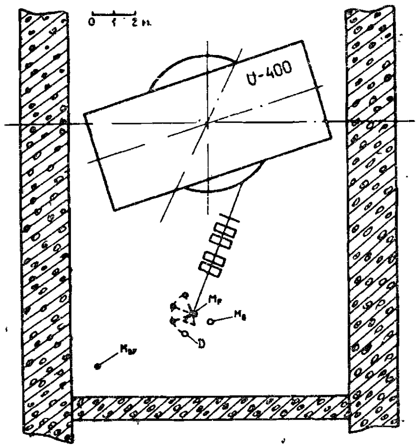

Fig. 1. Plan of the experimental hall and the arrangement of detectors.

a shadowing cone between the target and the measuring detector in order to take into account the contribution from the two-component neutron background due to secondary particles formed as a result of internal beam losses and to neutrons scattered after interaction with the floor and walls of the hall and with the iron of the main magnet. The shadowing matter was a 5% boronloaded paraffin cone 40 cm in length. For carbon detectors the distance was reduced to 0.5 m because of the low fluxes expected for high energy neutrons. The energy of ions in beam was (6.6±0.2)MeV/amu*. The ion beam with an intensity of (1–5) x x 10^{11} ions/s was monitored with a Faraday cup with a 3 mm thick copper bottom acting as a thick target.

To avoid discrepancies in measurements due to variations in the beam extraction steadines the irradiation conditions were controlled by multi-monitoring. The principal monitor, M_F, was a Faraday cup with a better than 5% accuracy. The beam extraction constancy was controlled by two auxiliary monitors. The monitor M_B, a LiI(Eu) thermal neutron detector located inside a 10-inch polyethylene sphere, was placed at a distance of 1 meter from the target at 90°. The M_{BF} monitor, a BF_3 device in the moderator was placed far from the target in order to control the overall neutron flux level from all sources of radiation. All the detectors were calibrated and referenced using a Pu–Be neutron source.

DETECTION AND MEASUREMENT TECHNIQUE

To measure neutron spectra we used a ^{6}LiI(Eu) crystal placed at the centre of moderating polyethylene spheres with different diameters of 3, 5, 10 and 12 inches /12/ and a threshold (20 MeV) activation carbon detector. The unfolding procedure has been described previously /13/. The cross sections of the $^{12}C(n, 2n)^{11}C$ reaction near threshold have been taken from /14/.

* *The energy measurements have kindly been performed by Dr. U. K. Utenkov.*

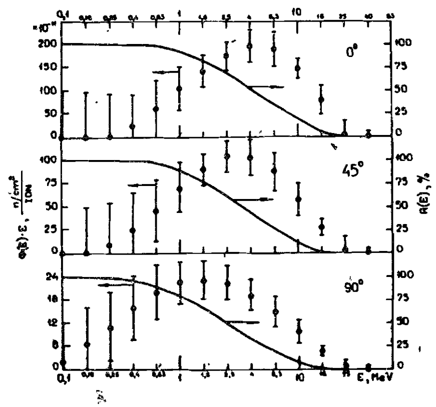

Fig. 2. Differential ϕ(E)·E, and integral, R(E), dose distributions as functions of neutron energy, measured at angles of 0°, 45° and 90° at a distance of 1 m from the target.

By measuring absorbed dose and the quality factor we have determined the corresponding dose equivalent. For this purpose a tissue equivalent ionization chamber model REM-2 /15,16/ operating in unsaturated regime /16/ was used. The systematic accuracy of this REM-2 instrument was considered to be better than 25% /15,16/.

The 10-inch sphere was used for all angles and the complete set of the detectors was used at 0°, 45° and 90°. The readings were obtained by subtraction of the results of measurements with the shadowing cone from those without it. In the case of using a carbon detector the shadowing cone was not placed.

RESULTS

The energy distributions of neutrons corresponding to the spectra measured at 0°, 45° and 90° are plotted as ϕ(E)·E in figure 2. The part of neutron plix with an energy above 20 MeV in the total flux varied from 0.3% to 1% for different angles within an accuracy of factor 2. The dose equivalent due to neutrons with energies below E_{min} = 100 keV is smaller than 2% in all cases.

In table 1 we give the quality factors and dose equivalent rates per unit flux measured with the REM-2 chamber for three angles of interest, compared with the same dose data plus fluence per ion (100 keV ≤ E ≤ 25 MeV) obtained using the Bonner sphere technique. The total neutron yield is estimated to be (1.6± ±0.4)x10^{-3} n/ion. The integral dose distribution as a function of neutron energy has been calculated. The percentage ratio of the equivalent dose of neutrons with energies above a given E to the total equivalent dose is expressed as

$$R(E) = \int_{E}^{E_{max}} \frac{dH(E)}{dE} \times dE \Big/ \int_{E_{min}}^{E_{max}} \frac{dH(E)}{dE} \times dE,$$

where H(E) is the energy distribution of equivalent dose and E_{min} = 100 keV. The R(E) dependence is shown in fig.2.

Table 1

Quality factors and dose equivalent rates per unit flux measured with the REM-2 chamber and the dose equivalent rated and neutron flux (E ≥ 100 keV) measured using the Bonner spheres. All values are given for a distance of 1 meter

Angle	Rem-2		Bonner spheres	
	Q.F.	mrem·s / h·ion	mrem·s / h·ion	n / cm^2·ion
0°	5.2±1	$(7.2\pm1.4)\times10^{-10}$	$(6.9\pm2.4)\times10^{-10}$	$(5.4\pm1.4)\times10^{-9}$
45°	5.1±0.4	$(3.6\pm0.4)\times10^{-10}$	$(3.6\pm0.9)\times10^{-10}$	$(2.9\pm0.8)\times10^{-9}$
90°	5.4±2.7	$(1.0\pm0.6)\times10^{-10}$	$(0.84\pm0.21)\times10^{-10}$	$(0.8\pm0.12)\times10^{-9}$

DISCUSSION

In considering the ratios R(E) one can see that, as expected, the higher energy components are more essential at 0°, and that there is a little difference at 45° and 90° angles. In all distributions (fig.2) neutrons with E >2.5 MeV represent more than 50% of rem-dose and those with E >14 MeV less than 9%. This indicates that devices which have neutron response functions near dose equivalent shape for neutrpn energies of 0.1-14 MeV are suitable for use as dosemeters for any angle of neutron emission.

In an attempt to determine a less complicated procedure for dose rate measurements the readings of the 10-in and 12-in spheres are compared with the total dose equivalent (see table 2). One can see that with a 12-in sphere alone there is a possibility of obtaining realistic estimates of radiation dose induced by similar heavy ions of close energies with a better that 10% accuracy, if the background is carefully controlled.

Table 2

Comparison of the conversion factors for the 10 and 12-in spheres. (Counts per second per mrem/h)

Angle	0°	45°	90°
10-in sphere	1.27	1.05	1.29
12-in sphere	1.03	0.97	0.90

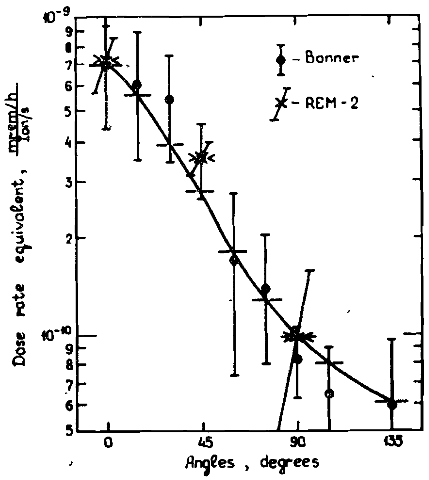

Fig.3. The angular distribution of the dose equivalent compared with the parametrization: -- parametrization of the Bonner spectrometer data; >< parametrization of the Rem-2 data.

The analytic formula for the angular distribution[3] has the following from

$$f(\theta,\gamma) = \frac{1}{4\pi}\cdot\frac{1}{\log(1+1/\gamma)}\cdot\frac{1}{\gamma+\sin^2\theta/2},$$

where θ is the angle in degrees and γ is an anisotropy fit parameter determined by the value of $f(0°)/f(90°) = 1 + 1/\gamma$.

According to our results, the γ factors determined from the dose rates obtained using the Bonner spheres and the REM-2 chamber are equal to 0.083 and 0.080 respectively. In fig.3, the calculated $f(\theta,\gamma)$ function is shown together with the experimental angular distributions relative to 0°. One can notice that the distribution measured using the REM-2 chamber is the same as that derived from $f(\theta,\gamma)$ and that agreement with the Bonner distribution is quite satisfactory. Thus the validity of the formula for derivation of $f(\theta,\gamma)$, which was earlier tested for the ions ranging from ^{12}U to ^{20}Ne and for ^{238}U, has now been confirmed for medium-mass ions also for energies below 10 MeV/amu. Consequently the dose angular distributions can be plotted on the basis of measurements at 0° and 90° in the indicated region of ion energies. However some restrictions may arise, for example, in the case where the target nucleus is much lighter than the projectile.

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Алейников В.Е. и др. E16-85-32
Поле нейтронов вблизи толстой медной мишени, бомбардируемой ионами ^{58}Ni с энергией 6,6 МэВ/нуклон

По показаниям детектора тепловых нейтронов, помещенного в шаровые полиэтиленовые замедлители, получены угловые распределения мощности эквивалентной дозы и энергетические распределения нейтронов. С помощью рекомбинационной тканеэквивалентной камеры REM-2 получены значения фактора качества для нескольких углов вылета излучения. Получено удовлетворительное согласие результатов измерений и эмпирической параметризации углового распределения мощности эквивалентной дозы нейтронов. Выход нейтронов составил $/1,6 \pm 0,4/\cdot 10^{-3}$ нейтронов на ион.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ

Препринт Объединенного института ядерных исследований. Дубна 1985

Aleinikov V.E. et al. E16-85-32
Neutron Radiation Field Due to 6.6 MeV/amu ^{58}Ni Ions Bombarding a Thick Cu Target

The angular distribution of the dose equivalent rate and neutron spectra were obtained using the Bonner sphere spectrometry. The quality factor was measured by a tissue equivalent Rem-2 chamber at several angles. The agreement between the results of measurements and an empirical parametrization of angular distribution is satisfactory. The total yield is estimated to be $(1.6 \pm 0.4)\cdot 10^{-3}$ neutrons per heavy ion.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1985