ABOUT THE RADIATION ENVIRONMENT AND SHIELDING OF THE HEAVY ION ACCELERATORS

L.G.Beskrovnaia, M.M.Komochkov

Joint Institute for Nuclear Research, 141980 Dubna, Russia

INTRODUCTION

The aim of this work is to develop the semiempirical method of the radiation environment and shielding prediction in wide range of energy and mass numbers of accelerated ions (nuclei) on base of works having been published early /1-5/ in the light of contemporary information. The algorithm is based on some approximations, one of which permits to use accumulated information about parameters of radiation fields formed in proton-nuclei reactions. The major components of radiation field of proton and ion accelerators are neutrons and photons, as it is known. Therefore, only these components are considered. Energy range of the proposed algorithm is between Coulomb barrier and 10 GeV/nucleon.

RADIATION ENVIRONMENT ESTIMATION

The main quantities of radiation environment are neutron yield Y and radionuclides activity, Q, which depend on mass number of nucleus-projectile A_c, its atomic number and energy per mass unit E_c and also on flux of nuclei-projectiles (ions) F. With the aim of radiation environment prediction, it is suggested to use the following expression as a basis of neutron yield, Y_{ns}, estimation from stopping-length (thick) target :

$$Y_{ns} = \frac{L}{A_t}\sum_j \int_{R_{jth}}^{R_j} F_j \sigma_j dR \qquad (1)$$

where R_j are the ranges of incident and secondary ions, R_{jth} is the range of ion j with the energy of the threshold of neutron production, A_t is the mass number of nucleus-target, L is Avogadro number, σ_j is the neutron production cross section in nucleus (j) with nucleus - target (t) interaction. At the ions energy more than 60 MeV/nucleon Y_{ns} was calculated by semiempirical formula

$$Y_{ns} = N\left(\sigma_{ns}\eta_{ns} / \sigma_p \eta_p\right) \qquad (2)$$

where N is the number of protons equivalents /1/, σ_{ns} and σ_p are the cross sections nucleus - nucleus and proton - nucleus inelastic interactions, respectively, η_{ns} and η_p are the numbers of inelastic interactions of nuclei and protons incident on target, respectively. The function f takes into account fragmentation of nucleus-projectiles.

$$f = 1 + 0.19\,\eta_{ns}\sqrt{A_c} \qquad (3)$$

Figure 1 shows the neutron yield from stopping-length target; the results have been obtained by (1),(2) and experiments which have been compiled in /5/. Radiation environment can be estimated by Y_{ns} in the first approximation /5/. It is worth while to consider residual activity at ion accelerators consisted of two components: induced by ions (or nuclei) Q_{ns} and neutrons Q_{nns}. The activity Q_{ns} can be represented as

$$Q_{ns} = N\frac{\eta_{ns}}{\eta_p} f Q_p \qquad (4)$$

where Q_p is the activity induced by protons with energy $E_p = E_c\ A_c$ /6/. The activity Q_{nns} can be represented as

$$Q_{nns} = Y_{ns}Q_{np} / Y_P = N\sigma_{ns}\eta_{ns} f Q_{np} / \sigma_p \eta_p \qquad (5)$$

where Q_{np} is the activity induced by neutrons at proton accelerator with the energy $E_p = E_c\ A_c$. On the data /6/ base it may expect that

$$Q_{ns} / Q_p = D_{ns} / D_p \qquad (6)$$

$$Q_{ns} / Q_{np} = D_{nns} / D_{np} \qquad (7)$$

where D_{ns} and D_p are the γ -radiation dose rates conditioned by Q_{ns} and Q_p respectively, D_{nns} and D_{np} are the γ - radiation dose rate conditioned by Q_{nns} and Q_{np} respectively. The results of measurements and calculations are compared in the table.

Table. The ratio of γ - dose rates measured /7/ and calculated with formulas (4)-(7) for Cu target irradiated by protons, ^{4}He and ^{12}C with energy 3.65 GeV/nucleon at other equal conditions.

Quantity	Measured	Calculated
$D_{^4He} / D_p$	3.4 ± 0.9	3.2 $^{a)}$ (4.8)$^{b)}$
$D_{^{12}C} / D_p$	8.8 ± 2.4	6.1$^{a)}$ (14)$^{b)}$

a) Calculated with expressions (4) and (6); b) Calculated with expressions (5) and (7).
The formulas (4)-(7) gives possibility to estimate dose rates near of the ions accelerator.

DIFFERENTIAL DISTRIBUTION

Phenomenological model with using simple formulas for calculation of double differential cross sections of neutron production $d^2\sigma / dEd\Omega$ in order to predict of the radiation environment and shielding from neutrons has been developed in /2-5/. The basic regularities of the neutrons production in nucleus-nucleus interactions have been obtained by analysis of data /6,10,27-35/ from ref. /5/ and were used for development of the model. Analysis has been showed that there is the similarity in differential cross sections of neutron production for different collided nucleus at different energy. The neutron production cross section is presented in the form of the sum of four components:

$$d^2\sigma / dEd\Omega = \sum_{i=1}^{4} (d^2\sigma / dEd\Omega)_i \tag{8}$$

The first component of the sum describes high energy part of neutrons spectrum. The second component describes neutrons generated in single nucleon collisions of the nucleus-projectile with nucleus-target. The third component is presented as the product of nucleus-nucleus interaction inelastic cross section σ_{ns} , number N and the double differential distribution of cascade neutrons in proton-nucleus interactions. The fourth component describes the distribution of the evaporation neutrons. The description of these components is given in /5/.

The information about $d^2\sigma / dEd\Omega$ permits to determine double differential neutrons yield from thick target, that lets to estimate the radiation environment both before and outside the shield. The dose of neutrons with the energy more then E_t emitted from the thick target at the distance r, outside the shield with the thickness x can be calculated as:

$$Hr^2 = \int_{E_t}^{\infty} (d^2Y / dEd\Omega) Bh \exp(-x / \lambda) dE \tag{9}$$

The neutrons flux emitted from thick target with energy more then E_t outside the shielding for various angles can be expressed as:

$$\frac{dY}{d\Omega}(x) = \int_{E_t}^{\infty} \frac{d^2Y}{dEd\Omega} B \exp(-x / \lambda) dE \tag{10}$$

where B and λ is buildup factor and attenuation length of neutrons fluence (dose), respectively, at the ordinary concrete, h is a conversion factor from the fluence of neutrons to the dose.

Neutrons flux distribution from thick Cu target bombarded by 86 MeV/nucleon ^{12}C ions with the intensity of 10^{11} s^{-1} in the heavy concrete measured /8/ and calculated by the algorithm is presented in Fig.2. The difference of data in Fig. 2 at the concrete thickness x=0 can be explained due to detection by carbon detector of the charges-fragment nucleus-projectiles emitted from the target. Comparison of the experimental data /9/ and calculated data obtained by the expression (8) is plotted in Fig.3. This comparison was carried out for energy spectrum of neutrons emitted from the thin gold target at $\theta = 0^0$ at the interaction the gold nucleus at 800 MeV/nucleon energy with it.

CONCLUSIONS

The phenomenological model for the radiation environment and shielding prediction has been examined by the experimental data. Comparison of calculated and measured data shows the reasonable agreement. Thus, the algorithm allows to estimate quickly the radiation environment and shielding of heavy ion accelerators in the energy range from tenth MeV/nucleon to tenth GeV/nucleon with atomic mass of nucleus projectiles and nucleus-target from Helium to Uranium.

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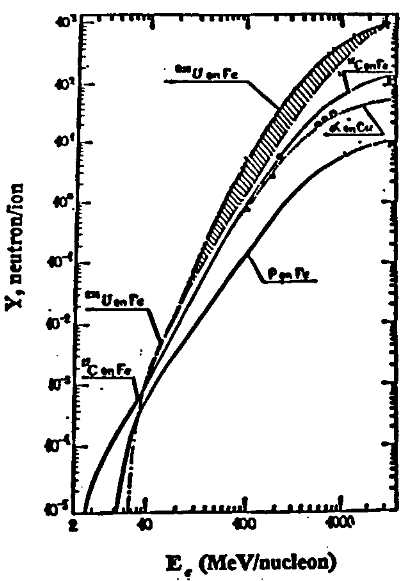

Fig.1. Total neutron yield from the thick iron or copper target per one ion with energy of E_o.

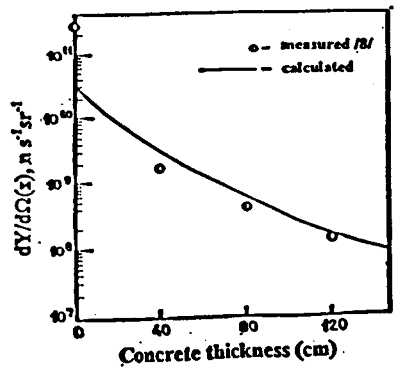

Fig.2. Neutron flux (E>20 MeV) attenuation in heavy concrete.

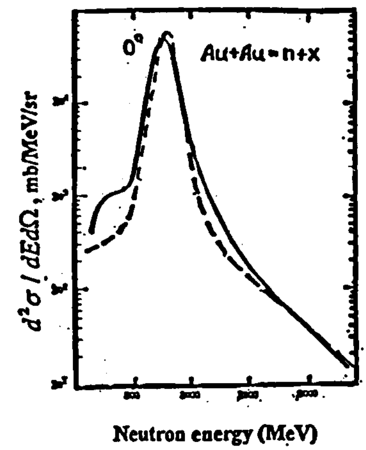

Fig.3. Measured /9/ and calculated neutron spectra produced by 800 MeV/nucleon Au on Au.