INDUCED RADIOACTIVITY OF THICK COPPER AND LEAD TARGETS IRRADIATED BY PROTONS, ^{4}HE AND ^{12}C NUCLEI WITH ENERGY 3.65 GEV/NUCLEON

A. A. Astapov and V. P. Bamblevski, Department of Radiation Safety and Radiation Research,
Joint Institute for Nuclear Research, Dubna 141980, Russia

The induced γ-radioactivity brings the main contribution to the exposure dose for the personnel of a high-energy accelerator. At the machines accelerating the heavy particles to the energies of ≥1 GeV/nucleon, this contribution amounts up to 50% of the dose.

The present study deals with the levels of induced radioactivity in dependence on the target material, sort of particles being accelerated, and time t elapsed since the end of irradiation. Recommendations are given to evaluate the rate per an incident nucleus $d_A(t)$ of a dose caused by the induced radioactivity of a thick target, from the dose rate $d_P(t)$ of protons with the same ratio of energy on nucleon.

I. EXPERIMENTAL PROCEDURE

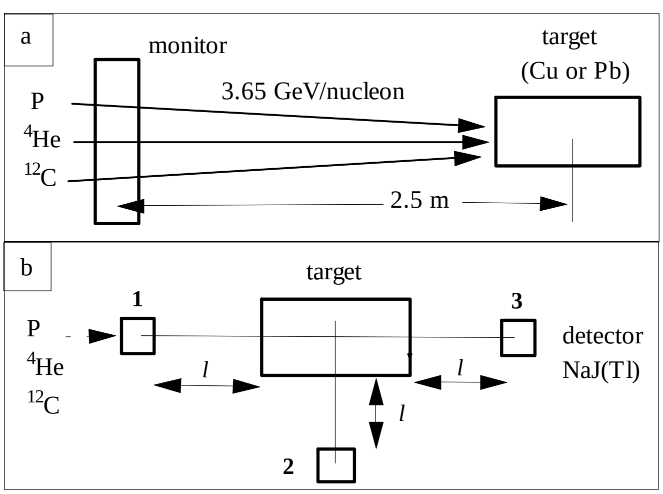
The copper target of ∅100×130 mm^2 dimensions is irradiated with beams of protons, ^{4}He and ^{12}C nuclei and the lead target of ∅100×170 mm^2 -- with protons and ^{12}C nuclei of energy 3.65 GeV/nucleon during 4 hours approximately.

The experimental conditions and monitoring are the same as those described in [1]. The irradiation control is performed with an ionization chamber. The total number of incident nuclei $Gu_m(u_c)$, where u_m and u_c are, respectively, the indices of the projectile nucleus and target nucleus, is determined using the reactions of activation: ^{27}Al(u_c,x)^{18}Fe and ^{27}Al(u_c,x)^{24}Na. The values of the reaction cross sections are taken from paper [1]. The number $Gu_m(u_c)$ determined with the detector agrees with that one obtained with the chamber within the measurement error (the chamber miscounts have been corrected). The following values of $Gu_m(u_c)$ are determined:

G_{Cu}(P)=(5.0±0.4)·10^{13}[P] G_{Pb}(P)=(13.7±0.7)·10^{13}[P]
G_{Cu}(^{4}He)=(1.0±0.1)·10^{13}[^{4}He]
G_{Cu}(^{12}C)=(4.1±0.4)·10^{10}[^{12}C] G_{Pb}(^{12}C)=(4.2±0.2)·10^{11}[^{12}C].

The exposure dose rate was measured with the use of scintillator, detector with NaJ(Tl) crystal of ∅63×63 mm^2 dimensions, and the multi-channel amplitude analyzer. Figure 1 illustrates the experiment configuration.

Figure 1. Geometry: (a) - target irradiation; (b) - dose rate measurement from the: 1- beam inlet, 2- side, 3- beam outlet.



II. SIMULATION TECHNIQUE

The designed technique considers the general rules for generation of the secondary hadrons, fragments of projectile nuclei, and residual target nuclei in the nucleus-nucleus interactions. To a certain extent, the dependence of the radionuclide production on the charge and mass numbers is similar to that one on the projectile energy E_0 in the proton-nucleus and nucleus-nucleus collisions. So, the problem of d_A calculation splits, schematically, into two stages.

At first, the direct Monte-Carlo simulation is made of the induced radioactivity generation of a given target bombarded with protons of the same energy E_0 per nucleon. The key results are the dose rates ^0d_P and ^Sd_P of induced γ–radiation, caused by the primary protons and secondary hadrons correspondingly.

At the second stage, using the ^0d_P and ^Sd_P values and considering the peculiarities of particle production in the inelastic nucleus-nucleus collisions, the dose rates are obtained of the induced γ–radiation that arise from the primary nuclei ^0d_A, their fragments ^fd_A and secondary hadrons ^Sd_A. Such a division of the total value d_A into three components ^0d_A, ^fd_A, and ^Sd_A is reasoned by the complicated A-dependence for the specific target configuration. In the case of a thin target, the ^0d_A brings the main contribution to the d_A but in the case of a thick target and light projectile nuclei (A<12), almost the linear dependence on A is observed.

The ^0d_A, ^fd_A, and ^Sd_A calculating technique is as follows.

1) According [2], the cross section σ_A of a radionuclide generation in a nucleus-nucleus collision is related to that one σ_P for a proton-nucleus interaction up to a factor of 2:

$$\sigma_A = N\,\sigma_P,$$

where

$$N = A^{0.25} + (A\text{-}1)^{0.6}\, 0.078\, (\ln A_T - 1.85)$$

and A_T is the atomic weight of the target nucleus.

Under the equal volume density of the inelastic nuclear interactions, the difference of the residual nucleus productions results from the different relative probabilities of their yield. So, the ${}^{0}d_A$ is expressed as

$$+ \quad {}^{0}d_A(r) = N\, {}^{0}d_P(r), \qquad (1)$$

where r is the radius-vector of a space point at which the γ-field functional is being defined.

2) Considering an incident A-nucleus as A of unbound nucleons, the dose rate ${}^{S}d_A$ caused by the secondary hadrons can be written down as

$$ {}^{S}d_A \quad (r) \quad = \quad A \quad {}^{S}d_P \quad (r). $$
(2)

3) Under the nuclei inelastic interaction, the high-energy components of the internuclear cascade are generated not only at the fast stages of the process but also during the slow decay of the spectator fragments of an incident nucleus. The projectile decay by the competing mechanisms like the multifragmentation, evaporation, fission, leads to the appearance of the multicharged particles over the whole allowable mass range. The yield of the particles-fragments with energies close to E_0, that differ from neutrons and protons, is negligible. The dose rate of the γ-radioactivity induced by the spectator nucleons is evaluated according the relationship

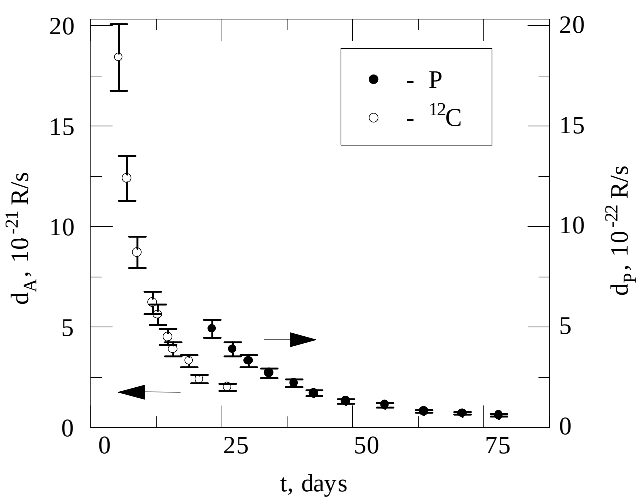
$${}^{f}d_A(r) = F(A,A_T)\, {}^{0}d_A\ (r) = F(A,A_T)\, N\, {}^{0}d_P(r), \qquad (3)$$

where $F(A,A_T)$ is the fragmentation parameter determined as the average number of protons and neutrons-spectators, that are generated in an individual interaction of a projectile A-nucleus with a target A_T-nucleus.

The resulting value is

$$d_A(r) = {}^{0}d_A\ (r) + {}^{S}d_A(r) + {}^{f}d_A(r). \qquad (4)$$

Figure 2. Dose rates at position #1, l=13 cm, lead target.



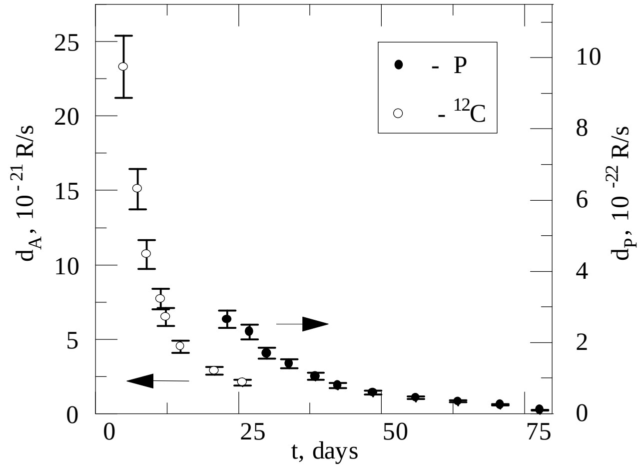


Figure 3. Dose rates at position #2, l=13 cm, lead target.

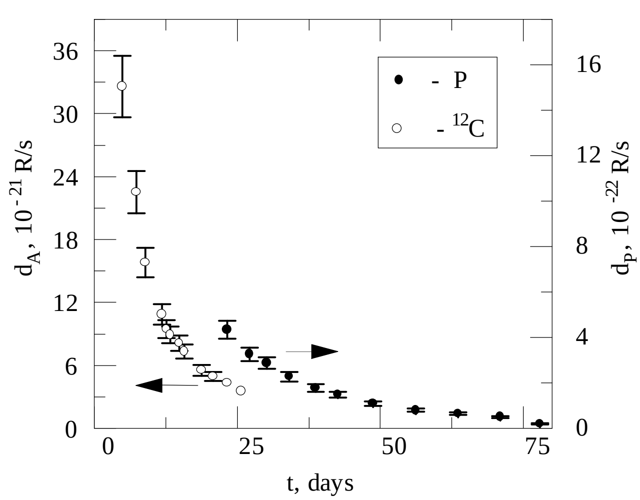
III. RESULTS AND DISCUSSION

Experimental results presented at figures 2-4 are the time-dependent exposure dose rates by the induced radioactivity of the lead target irradiated with protons and ^{12}C nuclei at l=13 cm and various configurations (see table 1 for the dose rate d_{12C}/d_P ratios). The indicated error is the monitoring inaccuracy that does not exceed 10%. The additive error of the γ-irradiation dose rate has the systematic nature and is less than 15%.

Table 1. Ratio of dose rates d_A/d_P caused by the induced radioactivity of the targets bombarded with nuclei and protons.

target	A	data	geometry 1	geometry 2	geometry 3
Cu	^{4}He	exp.	3.4±0.9	-	3.4±0.9
Cu	^{4}He	calc.	3.2	-	4.0
Cu	^{12}C	exp.	7.9±2.0	-	9.6±2.4
Cu	^{12}C	calc.	9.3	-	12.7
Pb	^{12}C	exp.	5.0±1.3	10.3±2.6	10.4±2.6

Figure 4. Dose rates at position #3, l=13 cm, lead target.



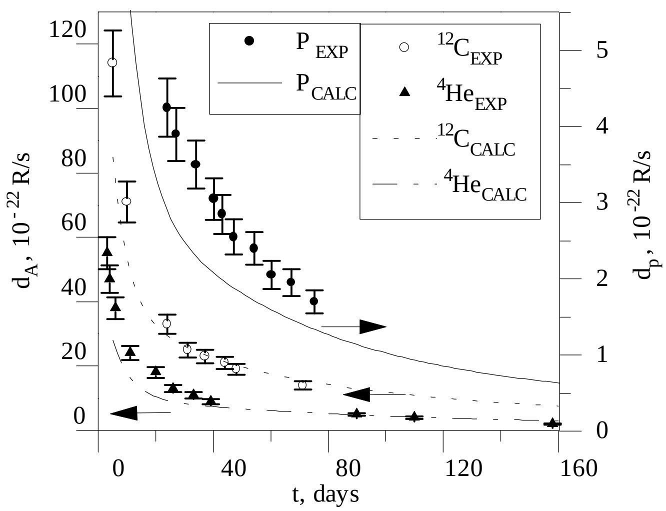


Figure 5. Dose rates at position #1, l=23 cm, copper target.

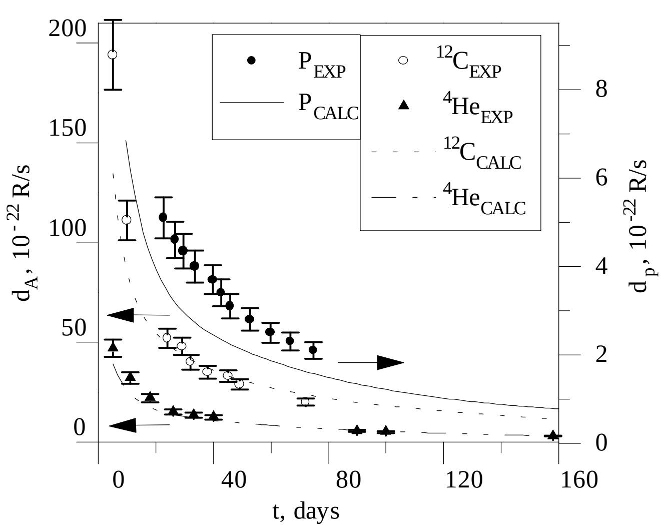
Figures 5 and 6 show the experimental data and simulation results of the exposure dose rates in dependence on time at l=23 cm and points 1 and 3 respectively for the copper target irradiated by protons and nuclei ^{4}He and ^{12}C. The calculated values d_P are obtained with Monte-Carlo method and the d_A ones - according to the formulae (1)-(4).

The proposed transitional formulae give results that differ from the experimental data not more than 25%. It is necessary to note that the calculation of d_P value (to be used later) underestimates it by 30%. Taking this into account, one may expect the satisfactory estimation of d_A values at transition on (1)-(4).

The experimental and calculated values of d_A/d_P agree even better (see table 1).

The above relationships leads to a conclusion that for the primary nuclei with $A \leq 12$, the d_A is governed by the $^S d_A$ value. For this reason, the following slightly overestimating formula is allowable when the extraction of components $^0 d_P$ and $^S d_P$ is hindered:

Figure 6. Dose rates at position #3, l=23 cm, copper target.



$$d_A(r,t) = A\, d_P(r,t). \qquad (5)$$

The presented formulae are applicable for the analysis of the long-life component of the induced radioactivity of the thick targets with diameter and thickness $\leq 2\lambda$ (λ is the inelastic interaction free path) and light nuclei ($A \leq 12$) with energy $\geq$ 1GeV/nucleon.

Due to the complexity, it is hardly attainable to realize the sufficiently justified direct simulation of the radionuclide production for nuclei. So, the obtained experimental data and derived simple relationships can be useful for the evaluation of the induced radioactivity levels at the relativistic nucleus accelerators.

IV. ACKNOWLEDGMENTS

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V. REFERENCES

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[2] M. M. Komochkov -- JINR Communication P16-83-190, 1983 (in Russian).