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CALCULATION OF RESIDUAL NUCLEI PRODUCTION BY A BEAM OF NEGATIVELY-CHARGED PIONS INCIDENT ON A TISSUE PHANTOM*

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ABSTRACT

Monte Carlo calculations have been carried out to determine the depth dependence of the residual nuclei produced in tissue by a negatively-charged pion beam. In addition, the depth dependence of those residual nuclei which are β^+ emitters and the photon energy produced by π° decay and nuclear de-excitation are computed since these photon sources have been proposed as a possible means of monitoring the treatment volume during radiotherapy using π^- beams.

1. INTRODUCTION

There are numerous potential advantages of using negatively charged pions in cancer radiotherapy, and one of these is the possibility of monitoring the treatment volume during patient irradiation. Several methods have been proposed for mapping the spatial distributions of the absorbed dose and stopping pions. These include the monitoring of a) mesic X-rays[1]), b) γ-rays from the annihilation of positrons emitted by radioactive residual nuclei[2]), c) low-energy ($\sim$ few MeV) nuclear de-excitation γ-rays[3]), d) high-energy ($\sim$ 100 MeV) γ-rays from radioactive pion capture[4,5]), e) high-energy ($\sim$ 70 MeV) photons from π° decay[6], and (f) neutrons[7]. The expected sensitivity, accuracy, and spatial resolution of possible monitoring techniques have been discussed by Sperinde *et al.*[7]).

In the present work the residual nuclei produced in tissue by a π^- beam is estimated by means of calculation. In particular, the depth dependence of those radioactive residual nuclei that are positron emitters is obtained. Also, the depth dependence of the photon energy from nuclear de-excitation and from π° decay are computed and compared with the absorbed dose variation with tissue depth. The calculations were made using the HETC code[8]).

The method of calculation is described in Section II, and the results are presented and discussed in Section III.

2. METHOD OF CALCULATION

The π^- beam is taken to be incident uniformly over a circular area 2.5 cm in radius and normal to the tissue slab. The momentum distribution of the beam is such that the number of π^- captures per unit depth is approximately constant between 12.5 and 17.5 cm. Monte Carlo calculations using the code HETC have previously been made for this beam to obtain the absorbed dose, LET spectra, and cell survival[9]). The magnetic tapes containing the transport data generated by the HETC code in these previous calculations[9]) have been further analyzed to obtain the results here on residual nuclei production and photon-energy production. A detailed description of the methods used by HETC to simulate the pion-nucleon cascade is given in ref. 9, and the references given therein, and will not be discussed here.

3. RESULTS AND DISCUSSION

Figure 1 shows the residual nuclei produced (over all radii) by all non-elastic nuclear interactions for three depth intervals: in the dose-plateau region (0-10 cm), in the π^- stopping region (12.5-17.5 cm), and beyond the stopping region (20-30 cm). These values include the production from pion interactions in flight, from π^- capture, and from nuclear-interactions by all secondary particles, including neutrons down to thermal energies.

It is noted from fig. 1 that the relative production of various nuclides is similar at all depths. The relative production in the capture region is similar to the production previously calculated[10]) for π^- capture by tissue nuclei without the effect of nuclear interactions by secondary particles included, with the main exceptions that the ^{14}C [produced predominantly from $^{14}N(n,p)^{14}C$ reactions by thermal and near-thermal neutrons] production is much higher here and the ^{16}O production [from $(n,n'\gamma)$ reactions] is higher here.

Those residual nuclei which are positron emitters are identified in fig. 1. As found in the experiment of Taylor *et al.*[2]) the main β^+ contributors are ^{15}O, ^{13}N, and ^{11}C. The other β^+ emitters (^{14}O, ^{12}N, ^{10}C, and ^{8}B) amount to only $\approx$ 3% of the total (over all radius and depth) production of nuclei that decay by β^+ emission. About 1.8% of the incident pions produced a β^+ emitting nuclide in the π^- capture region.

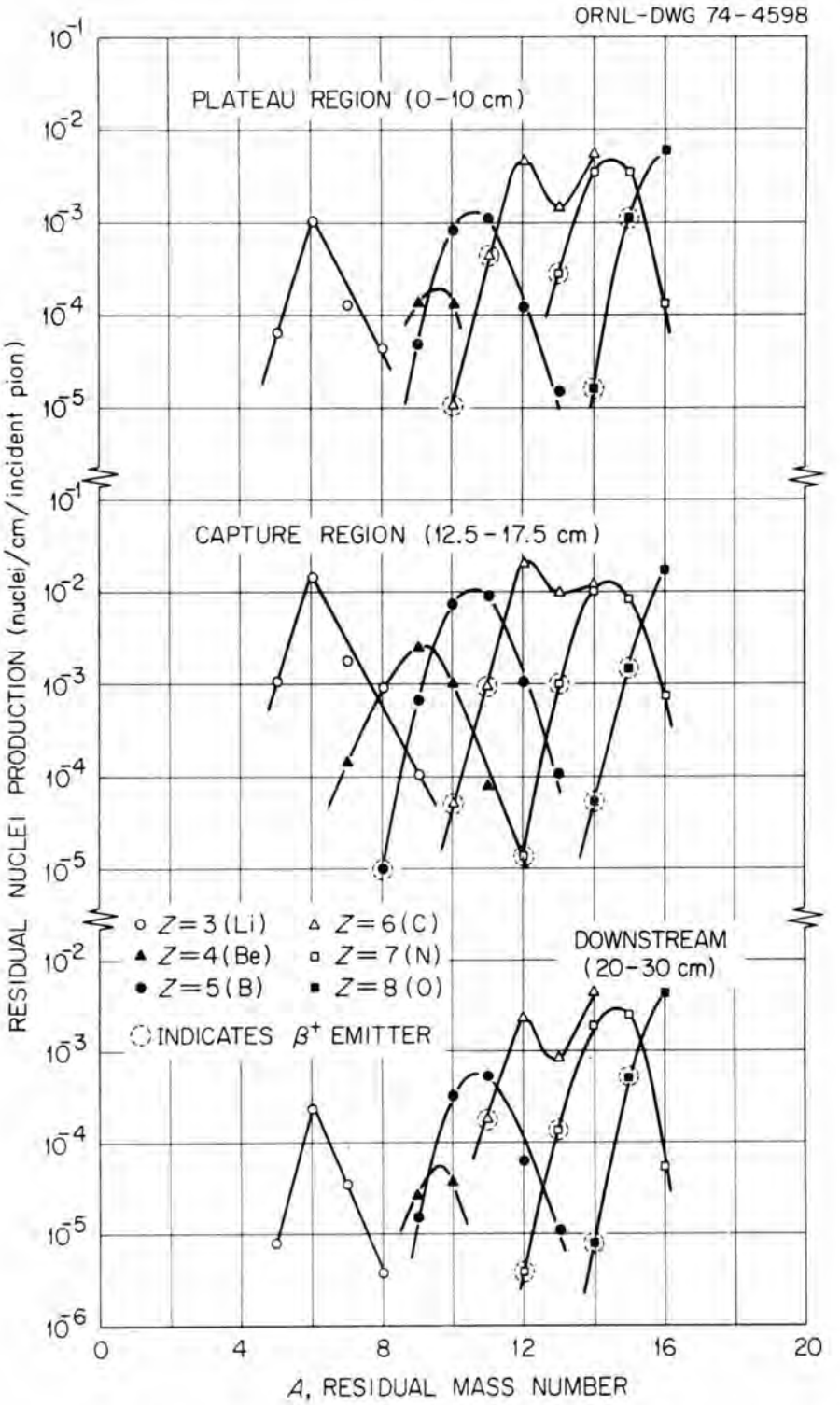

Fig. 1. Residual nuclei (number of nuclei produced per incident pion per unit depth interval) versus mass number. The curves connect those nuclei having the same charge number.

It should be mentioned that in the calculations the Fermi-Teller Z-law[11]) is used to determine the type of nucleus capturing the pion; i.e., the probability of final capture by a nucleus of charge Z (excluding hydrogen) is taken to be proportional to Z times the atom density of Z-type nuclei. Deviations from the Z-law have been observed (e.g., ref. 12), and the use of some other method for determining the capture probabilities could, of course, have some effect on the residual nuclei production in the capture region.

Figure 2 shows the depth dependence of β^+ emitting nuclei produced within the radius of the incident beam (R = 2.5 cm) and produced over all radii (R = ∞). Also shown for comparison is the depth dependence of the absorbed dose (from ref. 9) normalized to the R = ∞ nuclei production in the 0-2 cm depth interval. The depth dependence of the β^+ emitting nuclei follows only very approximately the depth dependence of the absorbed dose. Furthermore, because of the increasing radial spread of the incident pions and secondary particles with increasing depth, the depth dependence of the production of β^+ emitting nuclei within a radius of 2.5 cm is quite different from the depth variation of the laterally-integrated production. The local minimum in the production for R = 2.5 cm near a depth of 10 cm is about a factor of 2 less than at the entrance. Taylor *et al.*[2]) have measured the β^+ activity as a function of depth for a π^- beam different from that considered here (and for beam diameter and detector size that are unspecified in their paper), and find a corresponding decrease of about a factor of 5. Taylor *et al.*[2]) attribute this large decrease in the β^+ activity in the dose-plateau region as resulting from the energy dependence of the cross sections for pion

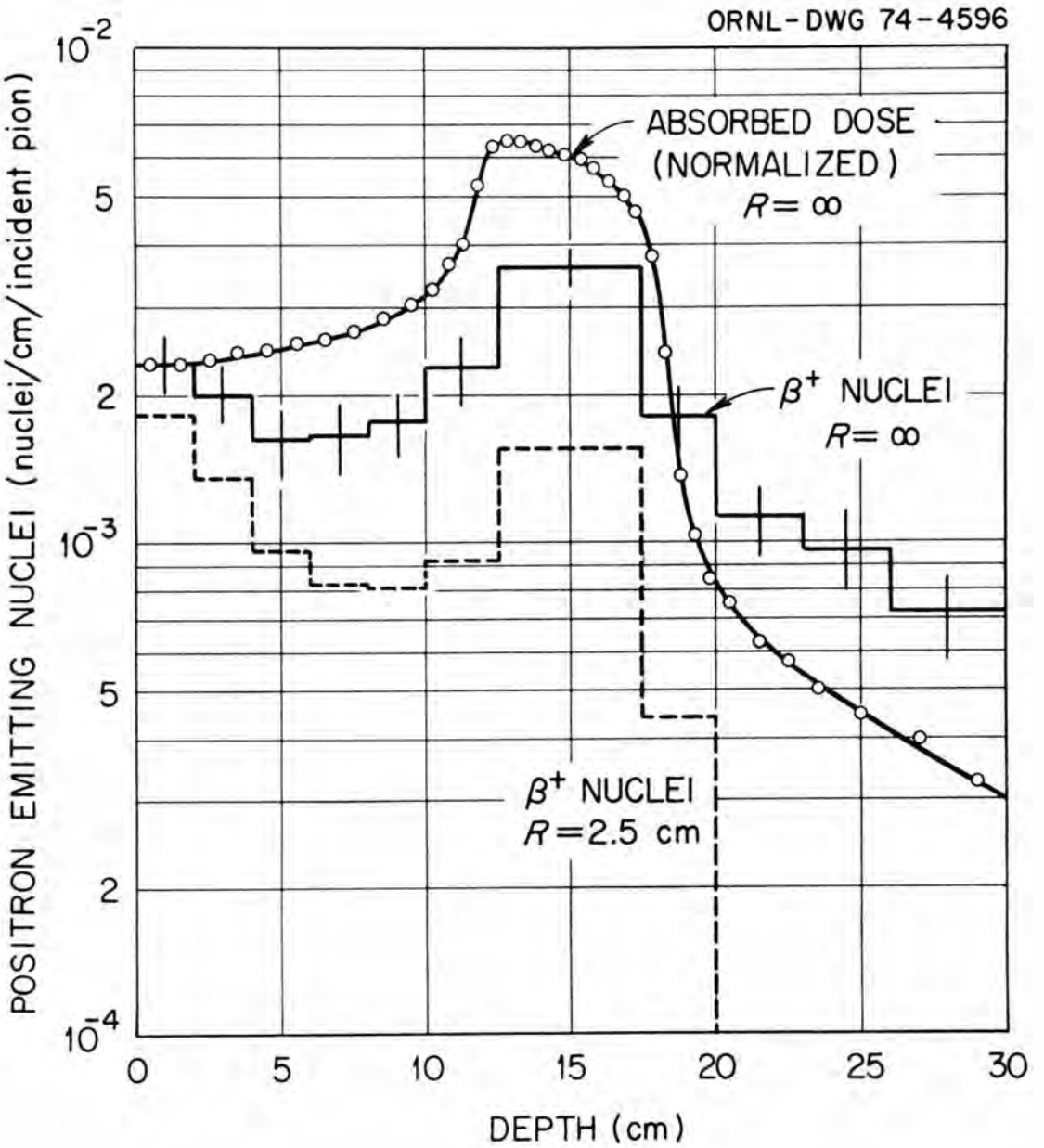

Fig. 2. Depth dependence of β^+-emitting nuclei and absorbed dose.

interactions in the plateau region. However, it would seem that this effect could in large part arise from geometric effects--i.e., if the area of the incident beam is such that multiple scattering causes a substantial fraction of the incident pions to scatter out of the incident beam area and if the cross sectional area of the detector is of the same order or smaller than the area of the beam, then a rather large decrease in the β^+ activity in the plateau region would be expected.

Figure 3 shows the laterally integrated depth dependence of the absorbed dose, π^- captures, photon energy production from nuclear de-excitation, photon energy production from the decay of neutral pions, and the production of β^+ emitting nuclei. All of these distributions are normalized to unity at a depth of 15 cm. Absolute normalization can be obtained as follows: the relative absorbed dose distribution in fig. 3 times 1.72×10^{-7} gives the absorbed dose in rad/cm /incident pion, the relative π^- capture distribution times 1.34×10^{-1} gives the number of π^- captures/cm/incident pion, the relative de-excitation photon energy times 8.23×10^{-1} gives the energy production in MeV/cm/incident pion, the relative π° energy distribution times 5.59×10^{-1} gives the energy production in MeV/cm/incident pion, and the relative β^+-nuclei distribution times 3.60×10^{-3} gives the number of β^+-emitting nuclei produced per cm per incident pion (same as in fig. 2). In computing the π^- capture probabilities for each type of nuclide in the tissue, π^- capture by hydrogen is not considered. Therefore, the photons from the decay of neutral pions produced by π^- charge exchange with hydrogen nuclei [a reaction which occurs for 0.12% of the captures in water[7])] are not included in the energy production from π° decay in fig. 3. The π° energy

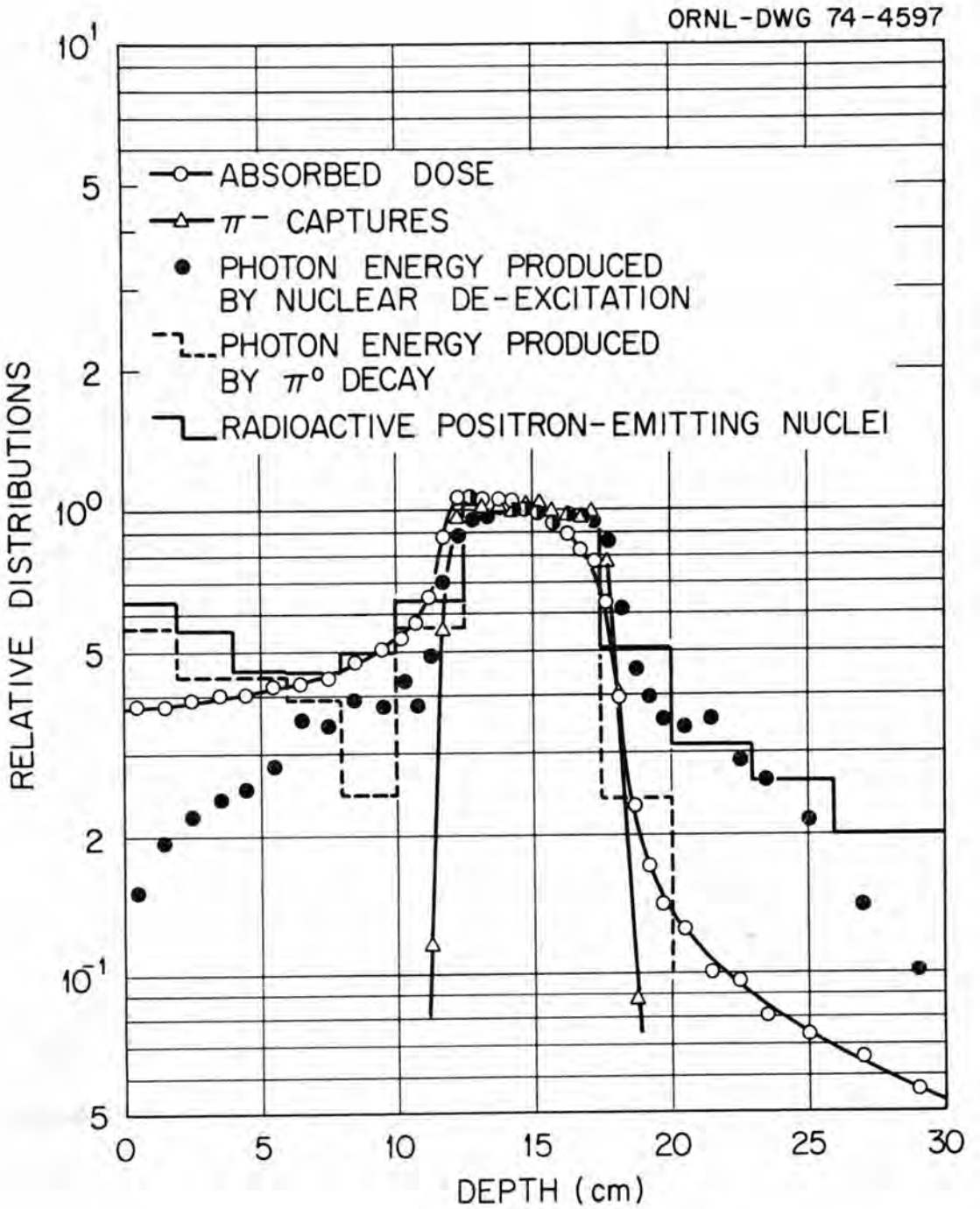

Fig. 3. Relative depth dependence of absorbed dose, π^- captures, photon energy produced by nuclear de-excitation and by π° decay, and by β^+-emitting nuclei.

production can be converted to number production by using an average energy per π° photon of approximately 70 MeV. For the de-excitation photons, the average photon energy produced per excited nucleus is about 4 MeV but because the emitted photon spectrum is rather complex (and not computed) the conversion from energy production to number production is not straightforward.

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