NEUTRON PRODUCTION BY HEAVY ION INTERACTION FOR NUMATRON SHIELDING DESIGN

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For shielding design of the high energy heavy ion accelerator, NUMATRON, it is indispensable to get the information on the neutron production by heavy ion interaction. The measured total neutron yields for proton, deuteron and alpha particle reactions have summarized for a variety of target materials in ref. 1 and their results are shown in fig. 1. Figure 1 shows that the neutron yield from proton reactions increases with the proton energy and the target atomic mass, while the increase of the yield with the target atomic mass is much less apparent for deuteron and alpha particle reactions. Ref. 1 also includes the neutron production by ^{12}C-, ^{14}N-, ^{20}Ne-ion bombardment of energy 10.4 MeV/u as shown in fig. 2. These results indicate the following facts:

i) The neutron yield increases with the target atomic mass, but is practically constant for targets from Cu to Pb.
ii) The yield increases with increasing the ion energy, but does not increase with increasing the ion atomic mass, for the same energy per nucleon of the ion.

For higher energy region, Santoro[2] has calculated the neutron energy spectrum $d^2\sigma/dEd\Omega$ from Fe bombarded by 900-MeV ^{12}C ion (75 MeV/u) and Gabriel et al.[3] from C bombarded by 1.2 GeV ^{12}C ion (100 MeV/u). The total neutron yield for a thin target, ΔY is obtained from

$$\Delta Y = \iint_{4\pi} \frac{d^2\sigma}{dEd\Omega} dE d\Omega \frac{N_0}{A} \quad \text{cm}^2/\text{g per incident ion,} \quad (1)$$

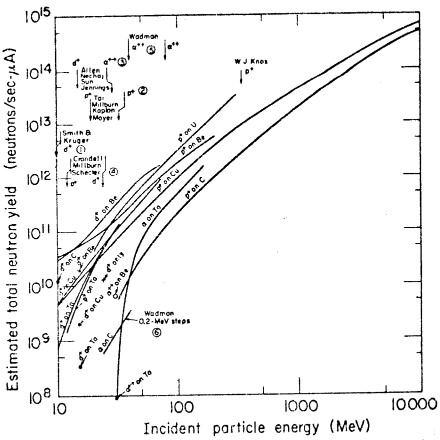

Fig. 1 Plot of neutron yields vs incident particle energy for several combinations of targets and ions. (1) Smith and Kruger, $MnSO_4$, (2) Tai, Millburn, Kaplan, and Moyer, $MnSO_4$, (3) Allen, Nechaj, Sun, and Jennings, $^{32}S(n,p)^{32}P$, (4) Crandell, Millburn, and Schechter, $MnSO_4$, (5) Wadman (40 and 80-MeV α^{++} on Ta), $^{58}Ni(n,p)^{58}Co$, (6) Wadman (23.2- to 40.8-MeV α on C). Moderated BF_3 curve shape accurate; yield valve probably high. (From ref. 1)

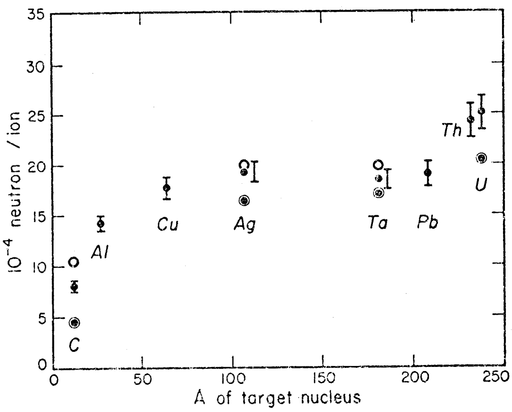

Fig. 2 Neutron yields from thick-target bombardments by heavy ions of approximately 10 MeV per nucleon. The points are ● for 122-MeV ^{12}C, O for 141-MeV ^{14}N, and △ for 201-MeV ^{20}Ne. (From ref. 1)

where N_0 = Avogadro's number
A = target atomic mass.
The values of ΔY calculated from eq.(1) are shown as a function of ion energy in fig. 3. The value of ΔY for 10-MeV/u energy was estimated by dividing the neutron yield for thick targets in fig. 2 into one range thickness. Then the total neutron yield for a thick target, Y is given by

$$Y = \int_0^R \Delta Y \, dt \quad n/p \,, \qquad (2)$$

where R = range of bombarding ion in g/cm^2.

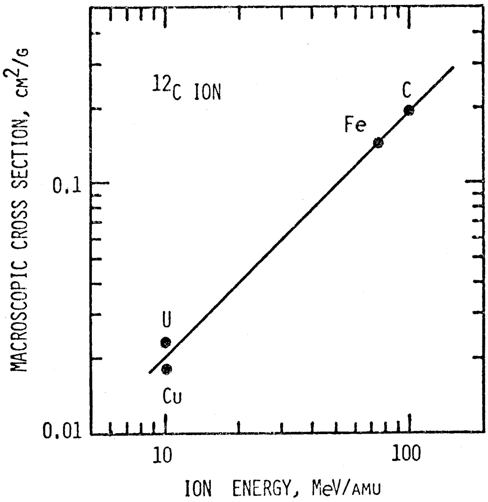

Fig. 3. A rough estimation of the total neutron yield for thin target by ^{12}C ion bombardment

For the case of 900-MeV ^{12}C on Fe, the yield Y is 0.23 and for 1.2 GeV ^{12}C on C, Y is 0.39 from eq.(2). The NUMATRON intends to have the highest final energy of 1.47 GeV/u for ^{12}C, ^{14}N and ^{20}Ne ion beams among of heavy ions. Since there is no data on neutron production due to 1.47 GeV/u heavy ion interaction, it must be estimated from the data due to proton reaction. The estimated neutron yields are as follows;

Target	1.47-GeV/u proton	1.47-GeV/u ^{12}C
Cu	11.4	~28
U	~40	40~98

References

1) H.W. Patterson and R. H. Thomas, Accelerator Health Physics, Academic Press, 1973, p. 128 - 148.
2) Cited in A. Rindi, LBL-4212 (1975).
3) T. A. Gabriel et al., ORNL-TM-4334 (1973).