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NEUTRON PRODUCTION FROM HEAVY ION INTERACTION:* SOME VERY EMPIRICAL CONSIDERATIONS†

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ABSTRACT

In the last few years there has been increasing interest in the use of heavy ion accelerators for research in nuclear physics, radiobiology, medicine and space science. Neutrons of energy up to that of the primary accelerated heavy ion may be produced by interaction with matter. The knowledge of the yield and energy spectrum of these neutrons is of fundamental importance in all the fields of application of heavy ions. Very little is known from the theoretical as well as experimental point of view about the production of these neutrons. In the present report we summarize in a rather empirical way the theory associated with neutron production and we report the scarce experimental results accumulated up to now.

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1. INTRODUCTION

The use of high energy heavy ion beams is opening new horizons in nuclear physics research.(1-4) There is also increasing interest in studying the biological effects of heavy ions on living organisms and in their promising application in radiotherapy.(4,5) Accelerators in operation up to 1971 were able to accelerate ions as heavy as A^{40} up to energies of about 10 MeV/n.‡ (6) Recent modifications of the Berkeley linear accelerator Super HILAC will allow acceleration of any type of ion up to uranium at energies up to 8.5 MeV/n.(4) Also, at the LBL, the Bevalac -- a linkage between the SuperHILAC and the Bevatron -- is already able to accelerate ions up to A^{40}, up to 2 GeV/n, and, in the future, ions up to U to about the same energy.(7) In several other countries present proton or electron accelerators are being modified for the acceleration of heavy ions, and new heavy ion accelerators are in operation or in construction.(7)

When heavy ions interact with nuclei, high energy neutrons are produced even at ion energies of a few MeV/n. Neutrons are produced mainly by the following processes:

a. Intranuclear cascade. The emitted neutrons are concentrated in the forward direction.

b. Evaporation of the superheavy complex nucleus formed by the fusion of two interacting ions. The neutrons are emitted isotropically in the center of mass system. However, due to the momentum of the compound nucleus, a peaking toward the forward direction is expected.

c. Fission of the compound nucleus with consequent emission of fission neutrons. The same consideration is applied here as for (b) concerning the emission angle.

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‡In the heavy ion research field the energy of the accelerated ion can be expressed either as total energy of the ion (in MeV) or as the ratio of the total energy to the number of nucleons of the ion (symbolized by MeV/n or MeV/amu).

d. Stripping of the projectile: these reactions take place mainly with deuteron beams because of the small internal binding energy of the proton and neutron. The neutrons are emitted mainly in the forward direction of the bombarding beam.

Processes (b) and (c) appear to be the main sources of neutrons production for ions heavier than about 10 amu; both processes take place, in a first approximation theory, through the formation of a heavy compound nucleus. In the following paragraph we will empirically calculate the threshold energy of the bombarding ions to form a complex nucleus, the cross sections for this process, and offer some hints about the energy spectrum and angular distribution of the produced neutrons. Finally we will summarize the very few experimental results accumulated up to date. The knowledge of the yield, energy spectrum, and angular distribution of the neutrons produced in these interactions is of much importance in several fields. In nuclear physics it may lead to a better understanding of the evaporation process and of angular momentum effects in the heavy nuclei reactions. In cosmic ray studies, it will provide useful information about the development of the cascade in the atmosphere. When heavy ion beams are used in radiobiology and radiotherapy, the neutrons produced in the interaction with tissue will contribute to the whole body and exit doses of biological samples or patients; it is very important to evaluate this contribution. Last, but not least, the evaluation of the neutron yield and spectra is of paramount importance in health physics for providing suitable shielding around the new accelerators.

2. ENERGY THRESHOLDS

a. The Coulomb barrier.

For two charged particles to coalesce and form a compound nucleus, the energy of the moving particle has to be at least as high as the Coulomb barrier produced by their charges.

This barrier energy is expressed by

$$E_c(\text{in MeV}) = \frac{Z_1 Z_2 e^2}{(R_1+R_2)\times 1.6\times10^{-6}} = 0.96 \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} \quad (1)$$

where Z_1, R_1, A_1 and Z_2, R_2, A_2 are respectively the atomic number, radius and atomic mass of the projectile and target nuclei; e is the electron charge; the radius of the nucleus is given by the expression $R = 1.5\times10^{-13}\ A^{1/3}$.

In Table 1 we report some Coulomb barriers for typical beams and targets as calculated with the expression (1). Some penetration of the potential barrier is expected at projectile energies slightly below these values because of quantum mechanical effects, but the cross section for such "tunneling" drops off rapidly. Also, somewhat different values would be obtained if a different nuclear radius constant were assumed. However, these variations are not very significant for the present empirical approach.

b. Q value.

We assume that from the reaction of two nuclei, a compound nucleus is formed whose mass and charge are the sum of the masses and charges of the reacting nuclei. When the atomic mass (or the mass excess) of the possible compound nucleus is known, the Q value of the reaction can be easily calculated.

$$Q = \Delta M_i + \Delta M_e - \Delta M_c \quad (2)$$

where ΔM_i, ΔM_e, and ΔM_c are the excess masses of the accelerated ion, target nucleus, and compound nucleus respectively.

In Table II we report values of Q for some typical ions and targets. The correction due to the momentum conservation in endoergic reaction (Q negative) is not considered.

In Table III we show for different types of ions and targets the sum of the Coulomb barrier and Q value when it is negative, i.e., in endoergic reactions where energy has to be provided for forming the compound nucleus. For exoergic reactions we list only the Coulomb barrier. This gives a rough value of the minimum energy required for a reaction between the ion and target, i.e., the minimum energy of the bombarding particle for neutron production.

3. THE CROSS SECTION

Most of the cross section of nuclear reactions goes into the compound nucleus formation; according to the Bohr assumption, the two colliding nuclei form some sort of highly excited long lived compound system which then decays through several different channels. Of these channels we are interested in those which give rise to the production of neutrons (evaporation, fission, spallation). If one indicates with $\sigma_c(E_0)$ the cross section for compound nucleus formation for bombardment of a target with a nucleus of energy E_0, we are interested in finding the value of the function $P(E,x)$ which expresses the probability that a compound nucleus excited to an energy E will evaporate exactly x neutrons. One can then write

$$\sigma_{i,xn} = \sigma_c(E_0)P(E,x) \tag{3}$$

where $\sigma_{i,xn}$ is the cross section for producing x neutrons. A possible expression for P derived from statistical models is reported in (10).

Experimental and theoretical studies for proving the validity of this expression and finding general expressions of σ_c and P with heavy ions at high energies are among the purposes of present day nuclear physics. The classical expression for σ_c is[8]

$$\sigma_c = \sigma_G\left(1 - \frac{A_1 + A_2}{A_2} \frac{E_c}{T}\right), \tag{4}$$

where A_1 and A_2 are the mass numbers of the projectile and target nucleus respectively, T is the kinetic energy of the projectile, E_c is the Coulomb barrier expressed by (1), and $\sigma_G = \pi r_0^2 (A^{1/3} + A^{1/3})^2$ is the geometric cross section for compound-nucleus formation, r_0, the radius parameter of nuclear matter, may have values between 1.3×10^{-13} cm and 1.5×10^{-13}cm. This expression is rather approximate and does not take into consideration quantum mechanical correction; also there are discrepancies about the value to be used for r_0. However, it can be used for empirical calculation at energies up to about 10 times above the Coulomb barrier,[8] using for r_0 the value 1.4×10^{-13}.

We indicate on Table IV some values of the σ_C for reaction of alpha particles with some heavy ions.[9] In Fig. 1 we show a typical shape of the P(E,x) function.[9]

E. Hubbard et al.[8] have measured total yields of neutrons of energy up to a few MeV (detected after slow down in a solution of $MnSO_4$ about 50 cm long) produced by C^{12}, N^{14}, and Ne^{20} ions accelerated up to about 10 MeV/n on thin and thick targets of Be, Al, Ni, Cu, Ag, Ta, Au, and U. In Fig. 2 we reproduce their results.

Contrary to what happens when light bombarding ions such as deuterons are used where the total yield increases sharply with the mass number of the thick target (where the beam is practically totally absorbed), the total yield of heavy ions shows a much smaller increase. It is practically constant for targets from Cu to Pb. This may be because the Coulomb barrier strongly affects the compound nucleus cross section. In addition, the yield increases with the increasing of the energy of the bombarding ion.

We should remember that these measurements cover only a part of the neutron energy spectrum. As we will see in the next paragraph, neutrons of energy much higher than the energy per nucleons of the projectile are produced.

4. THE ENERGY SPECTRUM AND ANGULAR DISTRIBUTION

If one assumes that a nucleus excited to energy E^* will de-excite only by neutron emission, as long as this is energetically possible, an approximate expression for the neutron spectrum has the form[10]

$$N(E)dE = KE\, e^{-\frac{E}{T}}\, dE$$

where T is the nuclear temperature taken to be constant. If T may be taken equal to that typical of a Fermi gas of particle,[11] then

$$T = (10\, E^*/A)^{1/2}$$

where A is the mass of the compound nucleus. Some authors[12] assume that, for the evaporation process, the constant K is proportional to $\frac{1}{T^2}$. However, in heavy ion interactions there is a competition of neutrons emitted by fission. Simon[13] has studied the fission competition in the neutron emission for the case of O^{16} ions of 164 MeV (10.25 MeV/n) interacting with an Au target.

In Fig. 3 we show the yield as a function of the energy reported by Simon.

Evaporation neutrons are emitted isotropically in the center of mass system of the two interacting particles, and, for light particles like p or d, their energy spectrum is peaked toward energies much lower (a few MeV) than the excitation energy. However, in the heavy ion interaction, a high momentum transfer takes place from the projectile to the target; the neutron emission is not any more isotropic but strongly forward peaked, and the neutron energy spectrum may be displaced toward higher energies. However, very little theoretical and experimental data have been accumulated up to date. R. T. Santoro[14] has performed calculations for interaction of 900 MeV C^{12} ions on Fe, taking into consideration the neutrons produced by cascade and evaporation of the projectile and target nuclei. Figure 4 shows a rather personal plot from the hystograms calculated by Santoro; it evidences the forward peaking of the total n emission and the extension of the emitted neutron energies to rather high values.

5. SOME EXPERIMENTAL RESULTS

L. Stephens and A. Miller[15] have summarized some of the data of total neutron yields from different targets and projectiles. However, their data are limited to projectiles up to He^4 and the yields are limited to neutrons up to a few MeV (as measured in $MnSO_4$ or with moderated BF_3 counters.) Figures 5,6, and 7 were drawn using part of their data. Figure 5 shows that the neutron yield from proton reactions increases with the energy of the p and the atomic mass of the target. The increase of yield with the atomic mass of the target is much less apparent for deuteron and alpha particle projectiles.

Figure 2 shows the results of Hubbard et al.[8] where the yield is shown to be independent from the target mass, at least up to the mass of Pb. From these results and especially from those of Stephens et al., it appears that for the same total energy of the projectile, the neutron yield does not seem to increase with increasing the projectile mass. The author has performed some rough measurements with heavy ions at the Berkeley SuperHILAC and these results are summarized in Table IV.

6. CONCLUSIONS

Not enough theoretical and experimental results have been accumulated up to now about neutron production from ion interaction, even at low energies and low atomic number, to allow extrapolation to different ions and energies. We urge experimenters to explore it in detail in the near future because of its importance in the various fields cited in the introduction.

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Table I. Coulomb barriers for some projectile and target nuclei (in MeV and (MeV/n))

Projectile ion / Target ion	$_1P^1$	$_2He^4$	$_3Li^7$	$_6C^{12}$	$_8O^{16}$	$_{10}Ne^{20}$	$_{18}A^{40}$	$_{36}Kr^{84}$	$_{54}Xe^{132}$
$_4Be^9$	1.25	2.09(0.5)	2.88(0.41)	5.27(0.44)	6.68(0.42)	8.01(0.4)	12.56(0.31)	21.4(0.25)	28.91(0.22)
$_6C^{12}$	1.75	2.97(0.74)	4.11(0.59)	7.55(0.63)	9.58(0.6)	11.51(0.57)	18.16(0.45)	31.1(0.37)	42.14(0.32)
$_{13}Al^{27}$	3.12	5.44(1.36)	7.62(1.08)	14.15(1.18)	18.08(1.13)	21.84(1.09)	34.99(0.87)	60.88(0.72)	83.28(0.63)
$_{26}Fe^{56}$	5.17	9.22(2.3)	13.05(1.86)	24.49(2.04)	31.47(1.97)	38.16(1.91)	62(1.55)	109.5(1.3)	151.1(1.14)
$_{29}Cu^{63}$	5.59	10 (2.5)	14.17(2.02)	26.64(2.22)	34.27(2.14)	41.59(2.08)	67.73(1.69)	119.9(1.43)	165.7(1.25)
$_{47}Ag^{107}$	7.85	14.24(3.56)	20.23(2.89)	38.47(3.2)	49.67(3.1)	60.47(3.02)	99.44(2.48)	177.97(2.12)	247.6(1.87)
$_{79}Au^{197}$	11.12	20.48(5.12)	29.43(4.2)	56.12(4.67)	72.76(4.55)	88.88(4.44)	147.7(3.69)	267.7(3.19)	375.4(2.84)
$_{82}Pb^{208}$	11.36	20.95(5.24)	30.13(4.3)	57.49(4.79)	74.57(4.66)	91.11(4.55)	151.6(3.79)	275.(3.27)	385.8(2.92)
$_{92}U^{238}$	12.27	22.69(5.67)	32.67(4.67)	62.44(5.2)	81.05(5.06)	99.11(4.95)	165.3(4.13)	300.6(3.58)	422.5(3.20)
$_{98}Cf^{250}$	12.88	23.85(5.96)	34.37(4.9)	65.7(5.47)	85.34(5.33)	104.4(5.22)	174.2(4.35)	317.1(3.77)	445.9(3.38)

Table II. Q values for compound nucleus formation (in MeV)[†]

Target ion \ Projectile ion	$_1p^1$	$_2He^4$	$_3Li^7$	$_6C^{12}$	$_8O^{16}$	$_{10}Ne^{20}$	$_{18}A^{40}$	$_{36}Kr^{84}$	$_{54}Xe^{132}$
$_4Be^9$	+ 6.59	+10.6	+26.2	+17.1	+19.8	+26.2	+24.9	+16.1	+ 7.6
$_6C^{12}$	+ 1.9	+ 7.2	+16.4	+13.9	+16.7	+19	+20.4	+ 6.4	- 5.5
$_{13}Al^{27}$	+11.6	+ 9.6	+27.6	+16.6	+14.2	+17.7	+14.6	-11.5	-39.1
$_{26}Fe^{56}$	+ 6.0	+ 6.3	+19.9	+ 5.9	+ 2.8	+ 1.8	- 9.6		
$_{29}Cu^{63}$	+ 7.7	+ 3.7	+19.9	+ 3.9			-15.7		
$_{47}Ag^{107}$	+ 8.1	+ 2.2	+17.1						
$_{79}Au^{197}$	+ 7.1	- 1.5	+ 8.8	-18.3	-39.4		-116.9(*)		
$_{82}Pb^{208}$	+ 3.8	- 8.9	- 5.6	-32.0	-46.5	-58.03	-128.6		
$_{92}U^{238}$	+ 5.3	- 5.0	+ 0.4	-23.8	-38.3				
$_{98}Cf^{250}$	+ 4.0	- 7.3							

(†) The values of ΔM used for the calculation are those reported in (16).
(*) From (9)

Table IV. Some total reaction cross sections for alpha particles on heavy targets calculated from optical-model potential.[9]

Energy of alpha particles (MeV)	Cross section in millibarns		
	Pb^{206}	Th^{232}	U^{235}
12			0.000024
14	0.036	0.0048	0.0026
16	0.79	0.148	0.091
18	8.75	1.62	0.966
20	67.7	18.0	11.7
22	249	106	76.8
24	498	312	257
26	736	561	501
30	1123	996	945
34	1413	1328	1286
38	1636	1584	1550
42	1812	1787	1759
46	1953	1950	1928

Table V. Some measurements of neutron yield at the Berkeley SuperHILAC

Protectile ion	Energy of ion (MeV)	Target	Energy of neutrons	Angle of detection	Yield ($ns^{-1}/\mu A$)
O^{18}	136 (7.56 MeV/n)	Cm+Be	> 20 MeV	0°	1.7×10^{6} (in 0.3 sr)
A^{40}	232 (5.8 MeV/n)	Pb+Be	> 20 MeV	0°	3×10^{5} (in 0.3 sr)
A^{40}	243 (6 MeV/n)	Pb+Be	> 20 MeV	0°	3×10^{5} (in 0.3 sr)
A^{40}	243 (6 MeV/n)	Pb+Be	> 20 MeV	43°	1.5×10^{4}
A^{40}	243 (6 MeV/n)	Pb+Be	from 200 keV to ~5 MeV	0°	10^{6} (in 0.3 sr)
A^{40}	285 (7.12 MeV/n)	Au+C	> 20 MeV	0°	3.5×10^{5} (in 0.3 sr)
A^{40}	285 (7.12 MeV/n)	Au+C	> 6.5 MeV	0°	1.8×10^{7} (in 0.3 sr)

FIGURE CAPTIONS

Fig. 1. The probabilities P(E,x) that a nucleus with excitation energy E will evaporate exactly x neutrons as a function of E/T where T is the nuclear temperature. The curves are for $\overline{B}/T = 4.0$ where B is the average neutron binding energy. From[10]

Fig. 2. Total neutron yields from thick target bombarded by heavy ions of an energy of about 10 MeV/n. The points are ● for 122 MeV C^{12}, o for 141 MeV N^{14} and ◉ for 201 MeV Ne^{20}. From[8]

Fig. 3. Neutron yield at 0^o for 164 MeV O^{16} ions on a thick Au target. From[13]

Fig. 4. Spectra of neutrons emitted at different angles from bombardment of Fe with ^{12}C ions of 75 MeV/n as calculated by Santoro.[14]

Fig. 5. Total neutron yield produced by interaction of p on different targets as a function of proton energy. From[15]

Fig. 6. Total neutron yield produced by interaction of deuteron with different targets as a function of deuteron energy. From[15]

Fig. 7. Total neutron yield produced by interaction of alpha particles on different targets as a function of alpha particle energy. From[15]

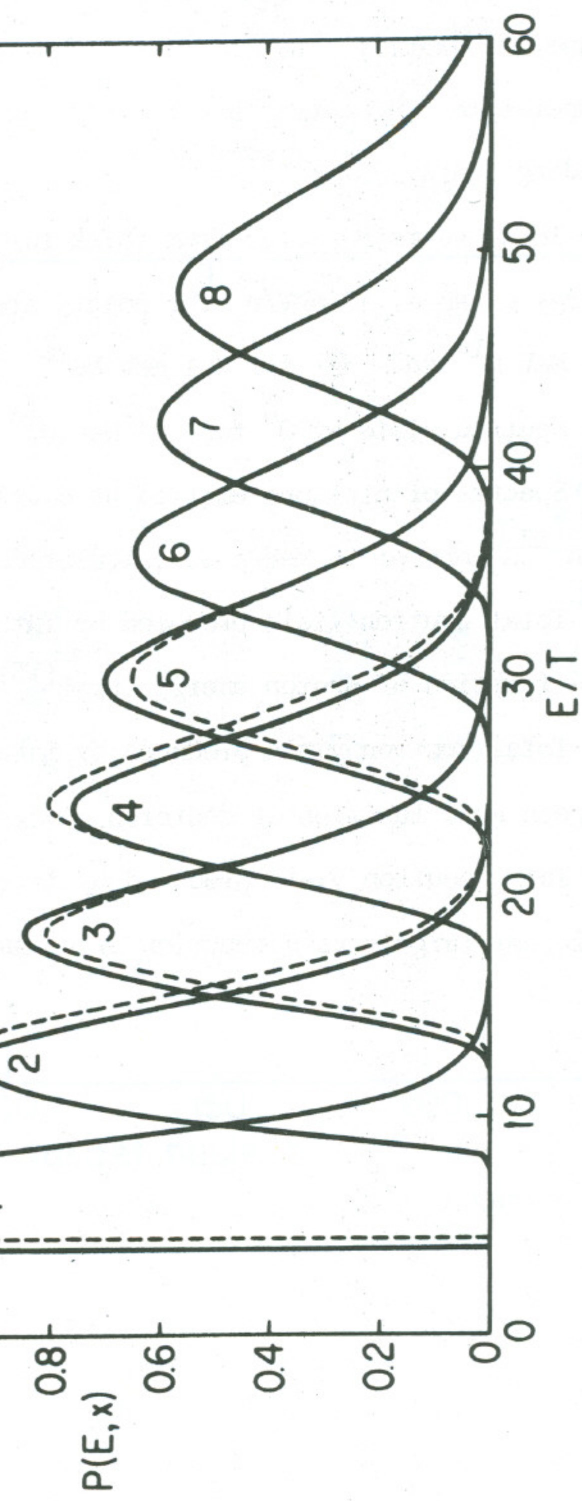

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Fig. 1

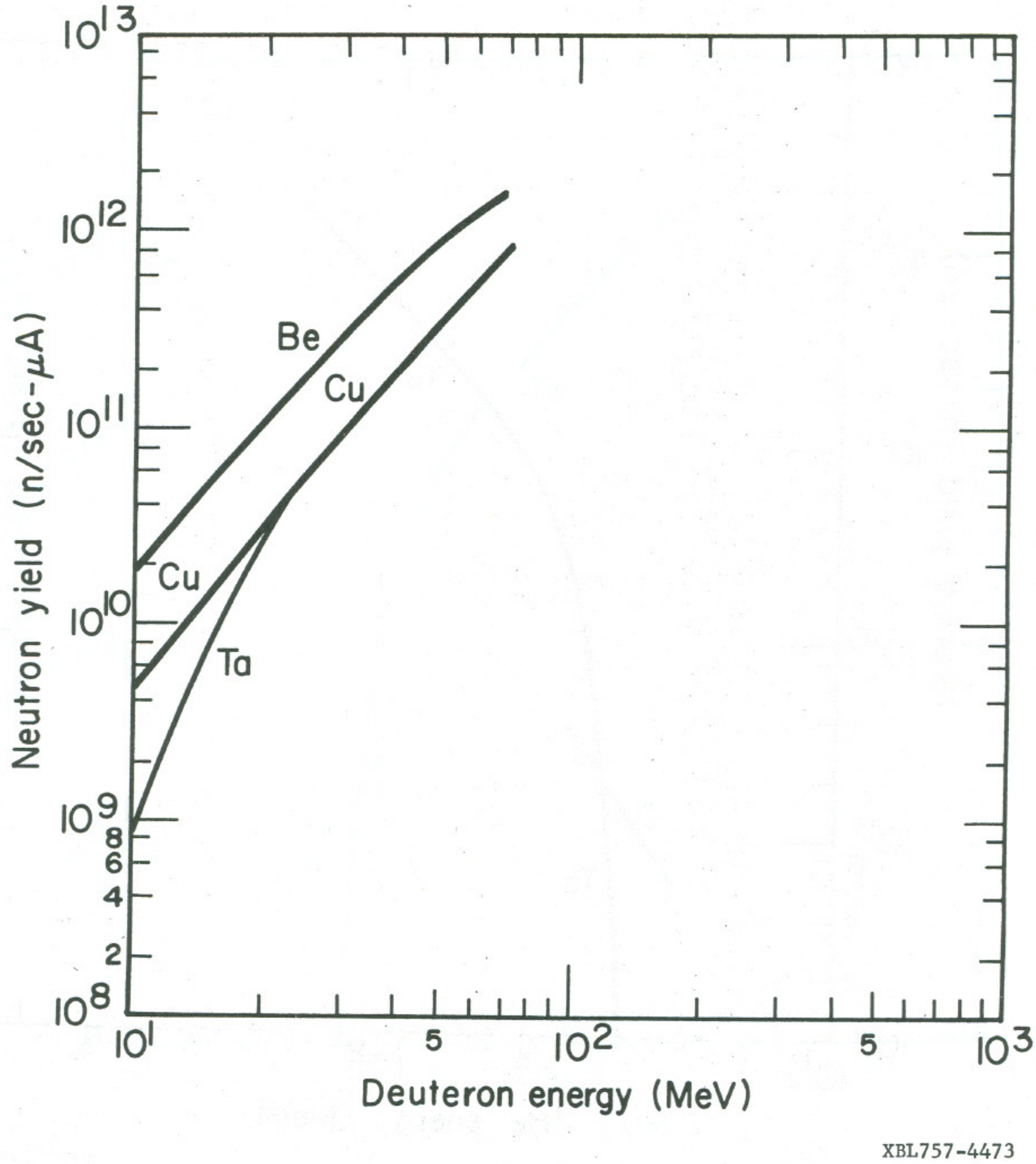
Neutron yield (n/sec-μA)
Deuteron energy (MeV)
Be
Cu
Cu
Ta
10^13
10^12
10^11
10^10
10^9
8
6
4
2
10^8
10^1
5
10^2
5
10^3
XBL757-4473

Fig. 6