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NEUTRON AND FISSION YIELDS FROM HIGH-ENERGY DEUTERONS
IN INFINITE U^{238} TARGETS

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FROM: Eugene Canfield

SUBJECT: Neutron and Fission Yields from High-Energy Deuterons in
Infinite U^{238} Targets

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INTRODUCTION

In 1953-54 there was considerable interest in the MTA concept wherein high-energy deuterons were to impinge on large U^{238} targets. Reawakened interest and the availability of newer cross sections and calculational models warrant a re-examination of earlier work.

A qualitative description of events when large U^{238} targets are bombarded by deuterons in the few hundred MeV range illustrates the problem. Many deuterons lose all their energy by ionization before interacting with a nucleus (for $E_d \leq 350$ MeV, most of them do!) The nuclear interactions that do occur include three types: 1) both nucleons interact strongly with the U^{238} , 2) one nucleon interacts, the other "strips" and proceeds with half the initial energy, and 3) "near misses" cause nuclear or electric field interactions which breakup the deuteron but only slightly perturb the U^{238} nucleus. Processes (1) and (2) lead to highly excited nuclei after the possible ejection of cascade or "knock-on" nucleons. The cascade and stripper nucleons lead to further interactions. The excited nuclei

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lose energy by boiling off nucleons, fissions, and γ emission. The neutrons from evaporation or fission may be of sufficient energy to cause further fissions.

An up-to-date and extensive survey of the experimental and theoretical cross sections and probabilities for many of the above processes is contained in a book by Earl K. Hyde, "The Nuclear Properties of the Heavy Elements," Vol. III (Fission Phenomena), Prentice-Hall 1964 (hereinafter called HYDE).

In view of the data unknown or unavailable at the time, we shall review and largely redo the results of a 1953 paper by C. C. Olds, LRL-69, "Neutron Production from High Energy Charged Particle Bombardment of Infinite Uranium Targets" (hereinafter called OLDS).

Finally, results of these calculations, those of OLDS, and certain experimental bulk measurements are given.

REVIEW OF LRL-69

In LRL-69 (1953) OLDS treated deuterons ($200 \lesssim E_d \lesssim 700$ MeV) in infinite U^{238} targets. He considered the deuteron as two nucleons forming a loosely bound sphere of diameter $d = 2.2 \cdot 10^{-13}$ cm impinging on a large sphere (U^{238}) of radius, $R = 1.5A^{1/3} \cdot 10^{-13}$ cm $= 9.3 \cdot 10^{-13}$ cm. Using energy dependent nuclear transparencies and simple geometrical considerations he divided the cross section for attenuation of deuterons in U^{238} into 3 parts:

$$\sigma_d = \sigma_1 + \sigma_2 + \sigma_3$$

$\sigma_1 = \sigma$ for both nucleons interacting with the nucleus,

$\sigma_2 = \sigma$ for one nucleon interacting, the other continuing as a free particle

$\sigma_3 = \sigma$ for a breakup into two free particles due to nuclear or electric field interactions without inducing a nuclear reaction.

He defined

$\sigma_1 = \sigma_1 + \sigma_2 =$ nuclear interaction cross section,

$\sigma_s = \frac{1}{2}\sigma_2 + \sigma_3 =$ the stripping cross section; the σ for producing a neutron or proton of energy $\frac{1}{2} E_d$.

In lieu of a detailed cascade model, OLDS assumed one cascade nucleon was ejected in each high-energy interaction. His ratio of cascade neutrons to protons was $\frac{A - Z}{Z} = \frac{146}{92} = 1.59$. The energy of the cascade nucleon was estimated

from correlations with certain bulk measurements for protons on U^{238} . The struck nucleus was treated as a degenerate Fermi gas of neutrons and protons which lost its excitation energy by neutron evaporation (the Coulomb barrier prevented proton evaporation) before fission or gamma emission. All secondary nucleons were followed until degraded below U^{238} fission threshold. A final graph gave the total yield of neutrons resulting from all reactions initiated by a deuteron of given incident energy in traversing one range in U^{238} . Fissions and captures were not reported. His calculated deuteron cross sections and the yields read from his graph are listed in Table I.

Table I. LRL-69 cross sections and neutron yields for deuterons in infinite U^{238} targets. Energies in MeV, σ in barns.

E_d	σ_d	σ_1	σ_2	σ_3	σ_1	σ_s	Yield
200	4.26	1.43	1.67	1.15	3.10	1.98	4.6
300	4.26	1.37	1.70	1.19	3.07	2.04	12
400	4.26	1.33	1.72	1.21	3.06	2.07	22
500	4.26	1.22	1.75	1.29	2.97	2.16	33
600	4.26	1.00	1.79	1.46	2.79	2.35	44

PRESENT CALCULATIONS

High Energy Cross Sections and Ranges

The deuteron cross sections given in Table I can be modified in light of more recent experiments. Millburn, Birnbaum, Crandall, Schecter, PR 95 1268 (1954) give cross sections for 160 MeV deuterons on U. In the notation of Table I, they give

$$\begin{aligned}\sigma_d &= 3.31 \pm 0.15 && \text{(total attenuation)} \\ \sigma_s &= 1.75 \pm 0.25 && \text{(production of stripped particle)}\end{aligned}$$

Schecter and Heckrotte PR 94 1086 (1954) correct an earlier paper (PR 90 633 (1953)) to give $\sigma_s = 1.4 \pm 0.2$ for $E_d = 190$ MeV. These values are appreciably smaller than those used by OLDS. His σ_3 is most suspect; it contains a large term

$$\pi [(R + a)^2 - (R + a/2)^2] = 0.76 \text{ barns}$$

for near misses in which the deuteron breaks up. If σ_3 is reduced by about 0.45 b to give $\sigma_d = 3.31$, the cross sections are consistent with the above experiments.

Table II. The cross sections of Table I when σ_3 is reduced.

E_d	σ_d	σ_1	σ_2	σ_3	σ_1	σ_B
200	3.81	1.43	1.67	0.71	3.10	1.55
300	3.81	1.37	1.70	0.74	3.07	1.59
400	3.81	1.33	1.72	0.76	3.05	1.62
500	3.81	1.22	1.75	0.84	2.97	1.72
600	3.81	1.00	1.79	1.02	2.79	1.92

In HYDE, pp. 436 and 439, two papers are quoted which give $\frac{\sigma_F}{\sigma_{IN}} \approx 0.75 - 0.85$ for protons on U^{238} from one to a few hundred MeV. Also quoted is $\sigma_F = 2.49$ b for 190 MeV deuterons (this is nearly constant for $100 \leq E_d \leq 190$). We will assume then that $\frac{2.49}{3.10} = 80\%$ of inelastic events lead to fissions, 20% to captures, for all energies down to about 10 MeV.

UCRL-2426 Vol. II (Rev.) 1957, High Energy Particle Data, gives range-energy curves for deuterons and protons in H, C, Cu, and Pb. Log-log extrapolations of Range vs Z indicate U Ranges (in gm/cm^2) = 1.03 Pb Ranges. We make the somewhat optimistic approximation that particles traverse their entire range without energy loss, then stop abruptly. Then the probability of a nuclear interaction before the charged particle dies an ionization death is just

$$P_1 = 1 - \exp \left(- \frac{6024 \sigma R}{238} \right) = 1 - \exp (-\tau)$$

For deuterons, $\sigma = \sigma_d$ of Table II. For protons of energy E, assume $\sigma = \frac{1}{2}(\sigma_1 + \sigma_2)$ for a deuteron of energy 2E, calculate P_1 , and treat the proton as equivalent to P_1 neutrons of energy E. Assume protons with $E < 50$ ionize to death.

Table III. Probabilities of nuclear interaction before ionization death for deuterons and protons in U^{238} .

E_d	$R \left(\frac{gm}{cm^2} \right)$	σ	τ	P_1	E_p	$R \left(\frac{gm}{cm^2} \right)$	σ	τ	P_1
100	10	(3.81)	0.096	0.092	50	5.00	(1.57)	0.020	0.020
200	33.4	3.81	0.322	0.275	100	16.7	1.55	0.065	0.063
300	66.0	3.81	0.636	0.471	150	33.0	1.535	0.128	0.120
400	107	3.81	1.032	0.644	200	53.5	1.525	0.206	0.186
500	155	3.81	1.495	0.776	250	77.5	1.485	0.291	0.252
600	210	3.81	2.025	0.863	300	105	1.395	0.371	0.310
Deuterons					Protons				

Cascade Events

Metropolis etal. PR 110 185 (1958) give Monte Carlo results for proton initiated cascades. Their results, in graphical and chart form, are somewhat incomplete, but from them one can get (approximately) the data in Table IV.

Table IV. Results gleaned from Metropolis, etal.

E	P ₀	P ₁	P ₂	P ₃	$\bar{N}$	E*	$\bar{T}$
<50	1	0	0	0	0	E + 7	--
50	0.5	0.5	0	0	0.5	50	7
100	0.302	0.534	0.121	0.043	0.91	70	33.7
150	0.136	0.525	0.263	0.076	1.28	86	48.5
200	0.067	0.403	0.395	0.135	1.60	94	63.6
250	0.044	0.363	0.398	0.195	1.74	100	83.2

E = incident nucleon energy. (Data is derived for incident protons. We assume it valid for neutrons as well),

P_n = probability of n particle cascade (n = 0,1,2,3),

$\bar{N} = \sum_n n P_n$ = average number of cascade particles,

E* = average excitation energy of residual nucleus,

$\bar{T} = \frac{1}{\bar{N}} [E - E^* - 7(\bar{N} - 1)]$ = avg. E of cascade particles, assuming 7 MeV binding energy per nucleon.

We assume that a deuteron initiated cascade (i.e., a σ_1 collision in notation of Table II) can be treated as simultaneous independent cascades caused by two nucleons. (E.g., a 300 MeV deuteron cascade gives $\bar{N} = 2(1.28) = 2.56$, $E^* = 2(86) = 1.72$, and $\bar{T} = 48.5$.) Furthermore, we always use the $\bar{N}$, E^* , $\bar{T}$ values for cascades; all cascades are average types. Metropolis also gives neutrons/proton ratios for cascade particles. For incident protons in the energy range of interest, N/P $\simeq$ 2.0; for incident neutrons, N/P $\simeq$ 4.0. We assume N/P = 3 for all cascades.

Evaporation Neutrons

The de-excitation of the nucleus following the high-energy cascade is complicated by competition between nucleon evaporation and fission. (Gamma, deuteron, etc., emission is small.) Lindner and Turkevich PR 119 1632 (1960) calculated final spallation yields from excited heavy nuclei. The simple assumption that one nucleon was evaporated for each 10 MeV of excitation gave results consistent with more sophisticated models. Dostrovsky, Rabinewitz, and Bivins, PR 111 1659 (1958) did Monte Carlo calculations of evaporations from heavy nuclei and found

that about 10% of the evaporated nucleons were protons. HYDE devotes many pages (of pp. 403-4, pp. 430-31, p. 446, and Sections 11.8 and 11.9) to the question of whether fission occurs before, during, or after evaporation of nucleons. The calculation of precise distributions of high-A spallation end products is very sensitive to this competition. Fortunately the total number of neutrons and fissions resulting is not; the assumption that fission occurs at or very near the end of the evaporation chain seems to give adequate results.

Therefore, we assume that the excited nucleus boils off one nucleon (0.9 neutrons, 0.1 protons) per 10 MeV of excitation until $E^* = 10$ MeV. The resultant "cold" nucleus then fissions 80% of the time (consistent with our previous assumption that $\alpha_F = 0.80 \alpha_{IN}$). These evaporated neutrons have average energies of about 3 MeV (10 MeV de-excitation less 6.5 - 7 MeV binding energy).

This model gives evaporated neutron yields very close to those given by OLDS from thermodynamic properties of the nucleus considered as a degenerate Fermi gas of neutrons and protons.

Multiplication of Evaporated and Fission Neutrons

These low-energy (few MeV) neutrons may be treated by fast reactor multi-group cross sections. We use the LASL 16-group set given in ANL-5800, Second Edition, pp. 568-9.

Notation:

- F = fissions,
- C = radiative captures above fission threshold,
- N_L = low-energy neutrons (below fission threshold),
- N_F = fission spectrum neutrons,
- N_E = evaporation neutrons,
- k = multiplication (or reproductive) factor per generation,
- $\bar{\nu}$ = average number of neutrons produced per fission.

For an infinite U^{238} system, one gets $k = 0.3153$, $\bar{\nu} = 2.61$. One fission spectrum neutron splits into $0.1208F + 0.0244C + 0.8548 N_L$. These fissions produce more neutrons, etc. to give a total multiplication factor

$$M.F. = 1 + k + k^2 + \dots = \frac{1}{1 - k} = 1.460$$

Therefore one fission spectrum neutron eventually results in

$$\begin{aligned} 1N_F &\Rightarrow 1.46[0.1208F + 0.0244C + 0.8548 N_L] \\ &= 0.176F + 0.036C + 1.248 N_L \end{aligned}$$

The evaporation neutron average energy of about 3 MeV is appreciably greater than the $\bar{E} \approx 2$ MeV for fission neutrons, and consequently causes more fissions. It seems reasonable to treat evaporation neutrons as sources to the highest energy group ($E \geq 3$ MeV) of the LASL 16-group set. We find that one evaporation neutron splits into $0.246F + 0.021C + 0.733 N_L$, with $\bar{\nu} = 2.77$. After multiplication, one gets

$$\begin{aligned} 1 N_E &\Rightarrow 0.246F + 0.021C + 0.733 N_L + (0.246)(2.77) N_F \\ &= 0.366F + 0.046C + 1.583 N_L \end{aligned}$$

Recapitulation of Calculations

A high-energy deuteron is injected into an infinite sea of U^{238} . Its probability for a nuclear interaction in traversing one "range" is given in Table III. These interactions are divided in the ratio of $\sigma_1:\sigma_2:\sigma_3$ of Table II to give the following events:

- 1) A cascade caused by both nucleons interacting with the nucleus (σ_1),
- 2) One stripped nucleon with half the initial energy plus a cascade caused by the other nucleon (σ_2),
- 3) Direct breakup without appreciable nuclear interaction.

Cascades (Table IV) give rise to $\bar{N}$ cascade nucleons ($0.75 \bar{N}$ are neutrons, $0.25 \bar{N}$ protons), each with energy $\bar{T}$, leaving a residual nuclear excitation E^* . (For deuterons, use $2E$, $2\bar{N}$, $2E^*$, $\bar{T}$). The stripped and cascade nucleons may give further cascades (protons are first depleted by ionization as in Table III).

The nuclear excitation is lost by evaporation of nucleons (90% neutrons), one nucleon per 10 MeV until $E^* = 10$ MeV. Then 80% of the nuclei fission. The 3 MeV evaporation neutron and fission neutron multiplications are calculated from fast reactor multigroup constants, and total events are tallied.

RESULTS AND DISCUSSIONS

The results of the calculations are shown in Table V and in the graphs.

Table V. Calculated captures, fissions, and low-energy neutrons per incident deuterons in infinite U^{238} medium.

E_d	Fissions	Captures	Neutron Yields	LRL-69 Yields	Ratio
200	1.97	0.33	6.94	4.6	1.51
300	4.66	0.76	16.9	12	1.41
400	8.45	1.41	29.9	22	1.36
500	12.07	1.99	43.0	33	1.30

These yields are considerably higher than those previously calculated by OLDS in LRL-69. Exact details of many steps in OLDS calculations were not reported, but some differences in assumptions are apparent.

1) OLDS assumed that neutrons constituted $\frac{A-Z}{Z} = 61\%$ of the cascade nucleons, and that the 39% protons ionized without further nuclear interaction. We assume that neutrons form 75% of cascade nucleons and get a small enhancement from the cascade protons which interact before ionizing. On the other hand, OLDS's larger values for σ_3 (direct breakup) introduced more high-energy neutrons and protons which caused more cascades.

2) OLDS used old U^{238} cross sections for fission neutrons which predicted that one fission neutron gave rise to 0.0963 new fissions with $\bar{\nu} = 2.5$. These give $K = 2.5(0.0963) = 0.241$ and a multiplication of $\frac{1}{1-K} = 1.32$. The newer LASL set gives $K = 2.61(0.1208) = 0.3153$ and a multiplication of $\frac{1}{1-K} = 1.460$.

3) OLDS used an effectiveness factor for evaporation neutrons which depended on the initial excitation of the nucleus. Using his factors would reduce our yields by ~15%.

The accompanying graphs show our results, those of OLDS, and some experimental results. The experimental yields are those given in LRL-69 and LRL-118 without reference. The 190 MeV point was measured in Berkeley with a 24 in. x 24 in. x 13 in. target. The 230 MeV point was measured at Chicago with presumably a similar target. These yields might be considerably larger if the targets were more nearly "infinite" instead of "semi-infinite"; i.e., if the beam could be introduced into the central region of the targets instead of impinging on the 24 in. x 24 in. side. The initial deuteron interactions take place within one range of the surface; consequently many neutrons leak without further interactions.

This effect is illustrated by the two "experimental" data on the fissions per deuteron graph. In MTA-42 (1953), radial distributions of measured fissions in 24 in. x 24 in. x 13 in. targets were used to extrapolate to results for 24 in. x 24 in. x 13 in. targets. These plotted points involve extrapolations of 30-40%. Point B was extrapolated from a normal target in which the deuteron beam impinged on the center of the 24 in. x 24 in. face. To see the effect of burying the initial deuteron interactions deeper into the target, the impact area was replaced by a lattice of 1/16 in. U^{238} foils separated by 1/8 in. air gaps. This increased the range for 190 MeV deuterons from 5/8 in. to 1-13/16 in., the normal range for 350 MeV deuterons. Their measured

fissions for 24 in. x 24 in. x 13 in. targets rose from 0.92 to 1.13 (23%); the laterally infinite results rose from 1.27 to 1.43 (17%). (These are the points B and A.) No neutron yields were reported, but it appears that substantial increases in measured fissions and neutron yields might result from extending the lateral dimensions of the targets and channeling the deuteron beam into the interior to reduce leakage out the front surface.

In conclusion, our calculated results for fissions and neutron yields in infinite targets are some 50% higher than measurements made in finite (and "semi-infinite") targets. Much (or most) of this discrepancy may be due to leakage of neutrons out the front surface.

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