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THE EFFECTIVE (n,2n) CROSS SECTION FOR U^{238}

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THE EFFECTIVE (n,2n) CROSS SECTION FOR U²³⁸

SUMMARY

Neptunium -237 is currently produced in the Hanford reactors at a rate of approximately .003 gms/MWD¹ via the following reactions:

- a) $U^{238} (n,2n) U^{237} \xrightarrow{\beta} Np^{237}$
- b) $U^{235} (n,\gamma) U^{236} (n,\gamma) U^{237} \xrightarrow{\beta} Np^{237}$.

In order to calculate the buildup of Np²³⁷ via reaction (a), which accounts for the greater share of the formation of Np²³⁷, the n,2n cross section for U²³⁸ must be known. An old value quoted by Arnold² of 5.2 millifermis³ for an "effective" 2200 m/s value is not large enough to account for the observed Np²³⁷ yield⁴ by about a factor of two. Recent n,2n cross section measurements for U²³⁸ permit a newer calculation and the result is 11.2 mF, effective 2200 m/s value.

1. HW-57744 REV, "Increasing Palm Availability," R. E. Tomlinson, October 13, 1958. (Secret).
2. ORNL-2104, "Effect of Recycle of Uranium Through Reactor and Gaseous Diffusion Plant on Buildup of Important Transmutation Products in Irradiated Power Reactor Fuels," E. D. Arnold, September 11, 1956. (Confidential).
3. 1 fermi (F) = 10^{-24} cm² = 1 barn.
4. B. Judson, Private communication.

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DISCUSSION

Recent measurements of the n,2n cross section in U^{238} by Knight et.al. at Los Alamos⁵ show that the n,2n cross section has a sharp threshold at 6 Mev (as predicted by the masses of U^{238} , U^{237} , and n). The cross section peaks at 10 Mev with a value of 1.5 F. Beyond 10 Mev it drops off rapidly to 300 mF at ~ 16 Mev. The fraction of fast neutrons with energies in excess of 6 Mev is small ($\sim 1.2\%$). However, sufficient fast neutrons above the n,2n threshold interact within a fuel element with U^{238} to produce significant amounts of U^{237} .

The n,2n cross section has been integrated over the fast neutron flux spectrum $N(E)$ measured by Cranberg et al⁶

$$\frac{\int_0^{\infty} \bar{\sigma}_{n,2n}(E) N(E) dE}{\int_0^{\infty} N(E) dE}$$

to give $\bar{\sigma}_{n,2n} = .0146$ fermis.

A similar integration of the U^{238} fission cross section yields .307 fermis⁷.

Since we have a convenient measure of a fast neutron reaction in U^{238} , namely the fast effect, in terms of the volume-averaged thermal flux within a fuel element, it is simple to obtain an effective n,2n cross section also expressed in terms of the thermal flux.

The fast fissions in a fuel element per primary neutron is

$$\frac{\text{fast fissions rate in slug}}{\text{primary neutrons from } U^{238} \text{ fission/sec}} = \frac{P_c \bar{\sigma}_f / \bar{\sigma}_t}{1 - P_c (\nu_8 \bar{\sigma}_f + \bar{\sigma}_e)} \quad (1)$$

where P_c is the collision probability of a fast neutron in the uranium and is a function of slug size and shape, $\bar{\sigma}_f$, $\bar{\sigma}_t$, and $\bar{\sigma}_e$ are the fission, total and elastic scattering cross sections for U^{238} averaged over the fission spectrum, and ν_8 is the number of neutrons per fission in U^{238} . A similar expression can be written for the n,2n reaction.

5. Knight, Smith, Nobles, and Warren, Bull. Am. Phys. Soc. Ser II, 2, 198 (195). See also BNL-325, 2nd edition.
6. Cranberg, Frye, Nereson and Rosen, Phys. Rev. 103, 663 (1956).
7. HW-52834 REV., "Lattice Parameters Derived From Neutron Distributions," R. Nilson, February 18, 1958 (Confidential).
8. Glasstone and Edlund, "The Elements of Nuclear Reactor Theory".

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$$\frac{\text{n,2n reactions rate in slug}}{\text{primary neutrons from } U^{235} \text{ fission/sec.}} = \frac{P_c \bar{\sigma}_{n,2n} / \bar{\sigma}_t}{1 - P_c \left(\frac{\nu_8 \bar{\sigma}_f + \bar{\sigma}_e}{\bar{\sigma}_t} \right)} \quad (2)$$

The expression $\frac{\nu_8 \bar{\sigma}_f + \bar{\sigma}_e}{\bar{\sigma}_t}$ is usually written Z.

The expression for δ , the fast to thermal fission rate in the slug is ⁷

$$\delta = \frac{(P_c \bar{\sigma}_f / \bar{\sigma}_t) \nu_5}{1 - P_c Z} \quad (3)$$

The primary neutron birth rate i.e., neutrons born per thermal fission per sec in U^{235} is simply

$$\nu_5 \times \text{thermal fission rate,} \quad (4)$$

where ν_5 is the number of neutrons per U^{235} fission.

Combining 1, 2, 3, and 4 above we obtain

$$\text{n,2n reaction rate} = \frac{\bar{\sigma}_{n,2n}}{\bar{\sigma}_f} \delta \times \text{thermal fission rate.} \quad (5)$$

Using the values obtained from $\bar{\sigma}_{n,2n}$ and $\bar{\sigma}_f$ we get the result:

$$\underline{\underline{\text{n,2n reaction rate} = .0477 \delta \times \text{thermal fission rate.}}} \quad (6)$$

The thermal fission rate per unit volume in the slug is

$$\Sigma_{fu} \bar{\phi}_{th},$$

where Σ_{fu} is the macroscopic fission cross section of the uranium and the $\bar{\phi}_{th}$ is the volume-averaged thermal neutron flux in the slug. Hence, the n,2n reaction rate per unit volume is

$$.0477 \delta \Sigma_{fu} \bar{\phi}_{th}.$$

and the effective 2200 m/s n,2n cross section is

$$.0477 \delta \sigma_{fu}.$$

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The value of δ for Hanford I & E slugs is $.056^7$ and σ_{fu} (2200 m/s) = 4.18 F.

Thus

$$\sigma_{n,2n \text{ eff}} = 11.2 \text{ mF} \quad \text{for 2200 m/s neutrons in an I \& E slug.}$$

The reason the above effective cross section depends on slug geometry and size through the parameter δ is that only while the fast neutrons are inside the slug in which they were born can they react with ^{238}U via the high threshold n,2n reaction. If the neutron returns to the slug from the moderator it will be well below the n,2n threshold.

The effective cross section apparently also depends on the enrichment of the uranium through σ_{fu} . This can better be looked at as an increase in the fast flux inside the slug, since the higher the enrichment, the higher the ^{235}U fission rate for a given thermal flux and consequently the faster fast neutrons are made available in the slug to react. However, the Np^{237} production rate will not be increased by enriching the slugs since for a fixed pile power with enriched uranium as with natural uranium, the average flux in the fuel must decrease by the same amount that σ_{fu} is increased.

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