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ORNL SUMMER SHIELDING SESSION
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NEUTRON DATA FOR WATER SHIELDING

H. Feshbach

Date Issued: DEC 16 1949

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This report is one of a series on shielding and represents part of the work of a summer group working principally at Oak Ridge National Laboratory. Participants are drawn from Nuclear Development Associates (Navy contract), NEPA, Bureau of Ships and Bureau of Aeronautics (Navy Department), AEC, RAND, General Electric, Argonne and Oak Ridge National Laboratory.

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NEUTRON DATA FOR WATER SHIELDING

H. Feshbach

Oxygen

Total Cross-section

The enclosed figure I includes the most recent measurements by Barschall et al (P. R. 75, 1124, 1949) and by the group under the leadership of J. Williams of the University of Minnesota. Barshall's measurements cover the neutron energy range 20 - 600 k.e.v. in intervals of 20 k.e.v, with a resolving power of 20 k.e.v. Williams measurements cover the range .5 Mev to 1.5 Mev. The resonances exhibited here are scattering resonances, the activation cross-section should be a fraction of a millibarn. The level spacing and width agree with theoretical predictions as computed from the formula $\Gamma_n = 2\,kD^*/K$ where Γ_n = neutron width, k = neutron wave number, K = 1.3×10^{13} cm^{-1}, D* = level spacing. The predictions for the average (i.e. averaged over resonances) behavior of the total cross-section, σ_t, with energy are given for two nuclear radii 4.3×10^{-13} and 3.3×10^{-13} cm. Neutron transmission experiments at 25 Mev (Sherr) yielding σ_t of 1.6 barns suggest a nuclear radius, R, of 4.3×10^{-13} cm. It is seen from the figure that keeping this value of R will yield fairly good agreement with experiment. If anything, a radius somewhat larger than 4.3×10^{-13} cm might be in order.

We would now like to extrapolate this data to higher and lower values of the energy. Below 20 k.e.v. it is rather probable that the cross-section is constant and equal to about 3.8 barns. Above 1.5 Mev, the most extensive experiments are those of Nuckolls et al (P.R. 70, 805, 1946); some measurements with D-D neutrons have been made by Aoki and Zinn et al. Nuckoll's et al results

are taken over widely spaced energy values ($\Delta E \sim .5$ Mev) so that some resonances will very probably be missed. Indeed the double level found by Williams at 1.1 and 1.3 Mev appear in Nuckolls' data as a single peak.

In figure II we have plotted Williams' data from neutron energy 1 Mev to 1.5 Mev, together with the points mentioned in the preceding paragraph. The dotted curve represents a guess as to the actual structure of σ_{tot}. The resonance at $\sqrt{E} = 1.5$ Mev$^{\frac{1}{2}}$ was inserted on the basis that there should be at least one resonance between resonances at 1.1 and 1.3 Mev and the resonance indicated by Nuckolls' data at 4 Mev. Another resonance was introduced at $\sim$ 5.5 Mev so that again the proper number of levels of O^{17} appear and that the average over resonances in that region agrees with the theoretical predictions. Because of the low value of 1 barn obtained by Nuckolls at 6 Mev, it was felt that there must be several resonances beyond 6 Mev. Recall that σ_{tot} at 25 Mev is 1.6 barns. However, it is to be expected that the widths of the resonances and the distances between should soon be comparable. A simple statistical theory which is more appropriate for heavier nuclei than Oxygen predicts that this will occur at 4.5 Mev. It thus seems likely that fairly soon after 6 Mev, that successive resonances will blend together to give a smooth curve which is just that given by the theoretical average. It should be emphasized that the dotted curve represents a crude estimate; the theoretical average should however be fairly close to the truth everywhere.

Inelastic Scattering

Excited levels are reported by Lauritsen and Hornyak, and Lauritsen at 6.0, 6.15, 7.0, 10.5, 10.8, 11.2, 11.94, 13.08, and 13.2 Mev. Weak levels are reported at (8.6), (9.7) and (12.5) Mev. In the calculations below, the levels at 6. and 6.15 Mev are grouped together at 6 Mev (level #1), another at 7 (level #2), levels (10.5) (10.8), (11.2) are placed at 11 Mev (level #3) and (12.94), (13.08), (13.2) at 13 Mev (level #4). The weak levels were omitted.

E_n(Mev)	σ_{in} (barns)	E_1	f_1	E_2	f_2	E_3	f_3	E_f	f_4
6.0	0								
6.1	.04	.1	1.0						
7.0	.18	1.0	1.0						
8.0	.30	2.0	.81	1.0	.19				
9.0	.36	3.0	.74	2.0	.26				
10.0	.39	4.0	.73	3.0	.27				
11.0	.41	5.0	.71	4.0	.29				
12.0	.45	6.0	.61	5.0	.25	1.0	.14		
13.10	.49	7.0	.55	6.0	.23	2.0	.22		
14.0	.54	8.0	.49	7.0	.20	3.0	.23	1.0	.08

Here E_i is the energy of the emitted neutron after exciting the i th level; f_i is the fractional number of inelastically scattered neutrons having energy E_i. The results for σ_{in} are considerably below the cross-section for formation of the compound nucleus because of the strong competition of the elastic process. However, other levels as yet unknown may exist giving rise to the conclusion that one must regard the results tabulated above as lower limits to σ_{in}.

Hydrogen

The experimental data on hydrogen has been recently analyzed by Jackson and Blatt (in press). We have leaned rather heavily upon their results in the discussion below.

Angular Distribution: Spherically symmetrical in center of mass system. The most recent measurement is by Barschall and Taschek (P.R. 75, 1819, 1949) employing 14 Mev neutrons from the $H^3 + d$ reaction.

Energy Dependence: The total cross-section is given by $\sigma = \frac{1}{4}\sigma_s + 3/4\,\sigma_t$ where σ_s and σ_t are the singlet and triplet cross-sections respectively.

Triplet cross-section:

$$\sigma_t = \frac{4\pi}{\left[k^2 + (-\alpha_t + \frac{1}{2} r_t k^2 - P r_t^3 k^4 + \ldots)^2\right]} \qquad (1)$$

$$\alpha_t = \frac{1}{5.3 \times 10^{-13}} = .189 \times 10^{13} \text{ cm.}^{-1}$$

$$r_t = 1.56 \times 10^{-13} \text{ cm.}$$

$$0 \leq P \leq 0.1$$

$$k^2 = 1.21 \times 10^{24} E_{Lab} \text{ (Mev)}$$

It is clear that up to rather high energies well above that in which we are interested the terms in k^4 in the denominator of (1) are unimportant.

Therefore

$$\sigma_t \cong \frac{4\pi}{k^2(1 - r_t\alpha_t) + \alpha_t^2}$$

Numerical values are tabulated in table below.

<u>singlet cross-section</u>:

$$\sigma_s = \frac{4\pi}{k^2 + (-\alpha_s + \frac{1}{2} r_s k^2 - Pr_s^3 k^4)^2} \qquad (2)$$

$$\alpha_s = -\frac{1}{23.8 \times 10^{-13}} = -.042\ 10^{13}\ \text{cm}^{-1}$$

r_s = experimental data not sufficiently accurate to determine

For this study take $r_s = 2 \times 10^{-13}$ cm. Again $0 \leq P \leq .1$. The term in P is unimportant. The term in k^4 for energy range of interest < 10 Mev is of the order at most of 10% total at the upper energy, and smaller below. The term in α_s is unimportant for $k^2 < .5 \times 10^{24}$ (E_{lab} = .4 Mev). Thus

$$\sigma_s \cong \frac{4\pi}{k^2(1 - \alpha_s r_s) + \frac{1}{4} r_s^2 k^4}$$

For $r_s = 2 \times 10^{-13}$, $\frac{1}{4}\sigma_s \cong \frac{2.65}{k^2}$ barns.

Numerical Table (Using (1) and (2)) From Jackson and Blatt

$k^2(10^{24})$	E(Mev)	$3/4\ \sigma_t$	$1/4\ \sigma_s$ ($r_s = 2 \times 10^{-13}$)	Total
.5	.415	2.39 b	4.50 b	6.89 b
1.0	.829	2.20	2.57	4.77
1.5	1.244	2.03	1.80	3.83
2.0	1.658	1.88	1.38	3.26
3.0	2.488	1.64	.95	2.59
4.0	3.317	1.45	.72	2.17
5.0	4.146	1.30	.58	1.88
6.0	4.975	1.17	.48	1.65
7.0	5.804	1.07	.41	1.48
8.0	6.634	.98	.36	1.34
10.0	8.292	.84	.29	1.13

Added Remarks

Nothing has been said about the transport cross-sections or the angular distribution in oxygen, since no measurements are available. Theoretical average results may be obtained from curves given elsewhere (in another shielding session report by Feshbach). Use $R = 4.3 \times 10^{-13}$ cm and $X = 0.95\sqrt{E}$ (E in Mev) to obtain the required results. For $x \ll 1$, and therefore $E \ll 1$ Mev, σ transport $= \sigma$ total.

Also omitted is the (n, α) reaction on O^{16}. It exists. The Q value is - 2.31 Mev, and there is a resonance in the 3 to 4 Mev region. No cross-sections

have been measured, but even at resonance it cannot be much more than 0.1 barn.

The data in this report was used in a Monte Carlo calculation for a water shield (report by Nelson and Kahn in summer series). Some still more recent Minnesota data on oxygen are given in a trip report by Ergen.

The hydrogen reference to Jackson and Blatt has subsequently appeared in Phys. Rev. 76, 18 (1949).

HF:lg
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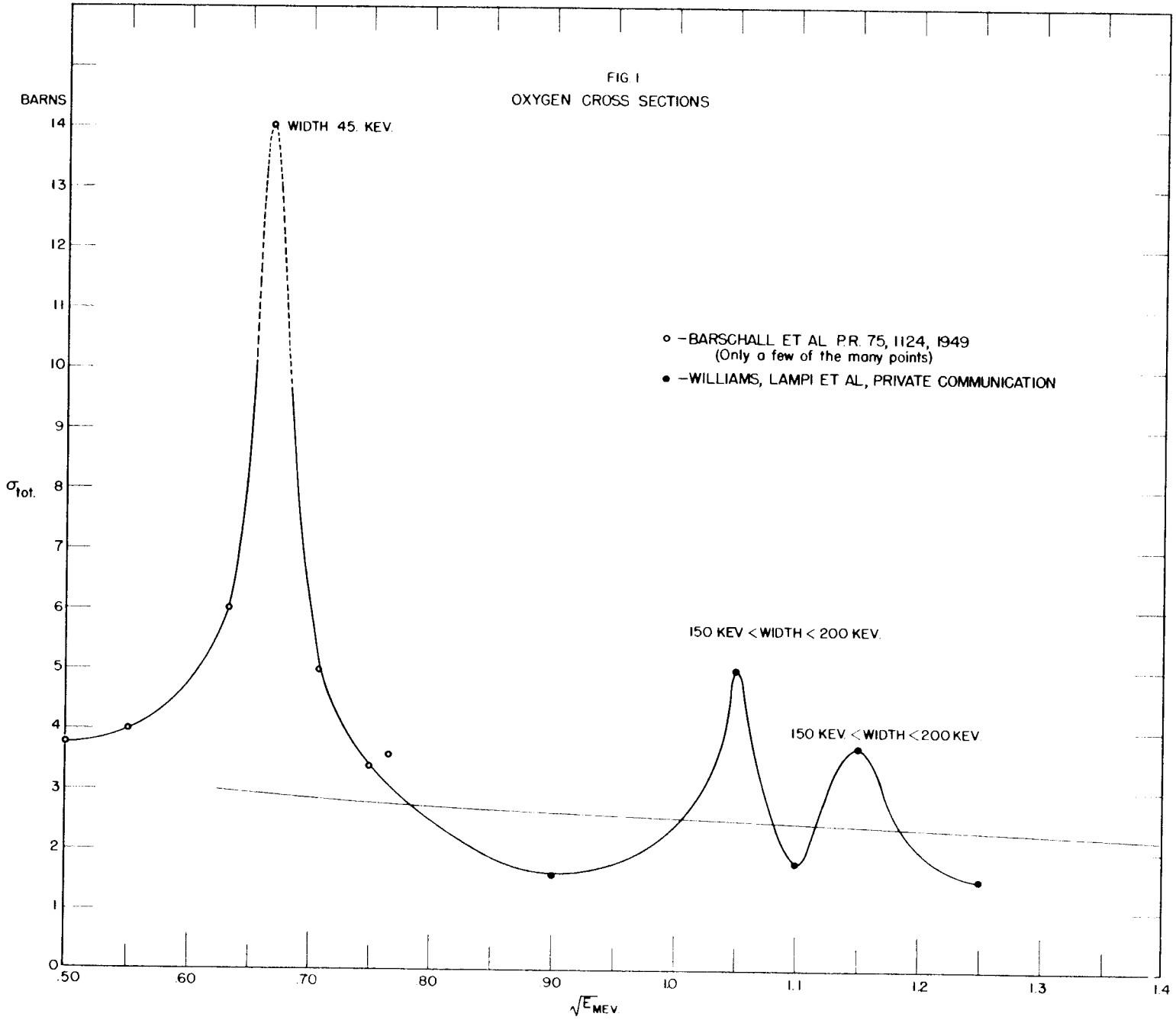
FIG. 1

OXYGEN CROSS SECTIONS



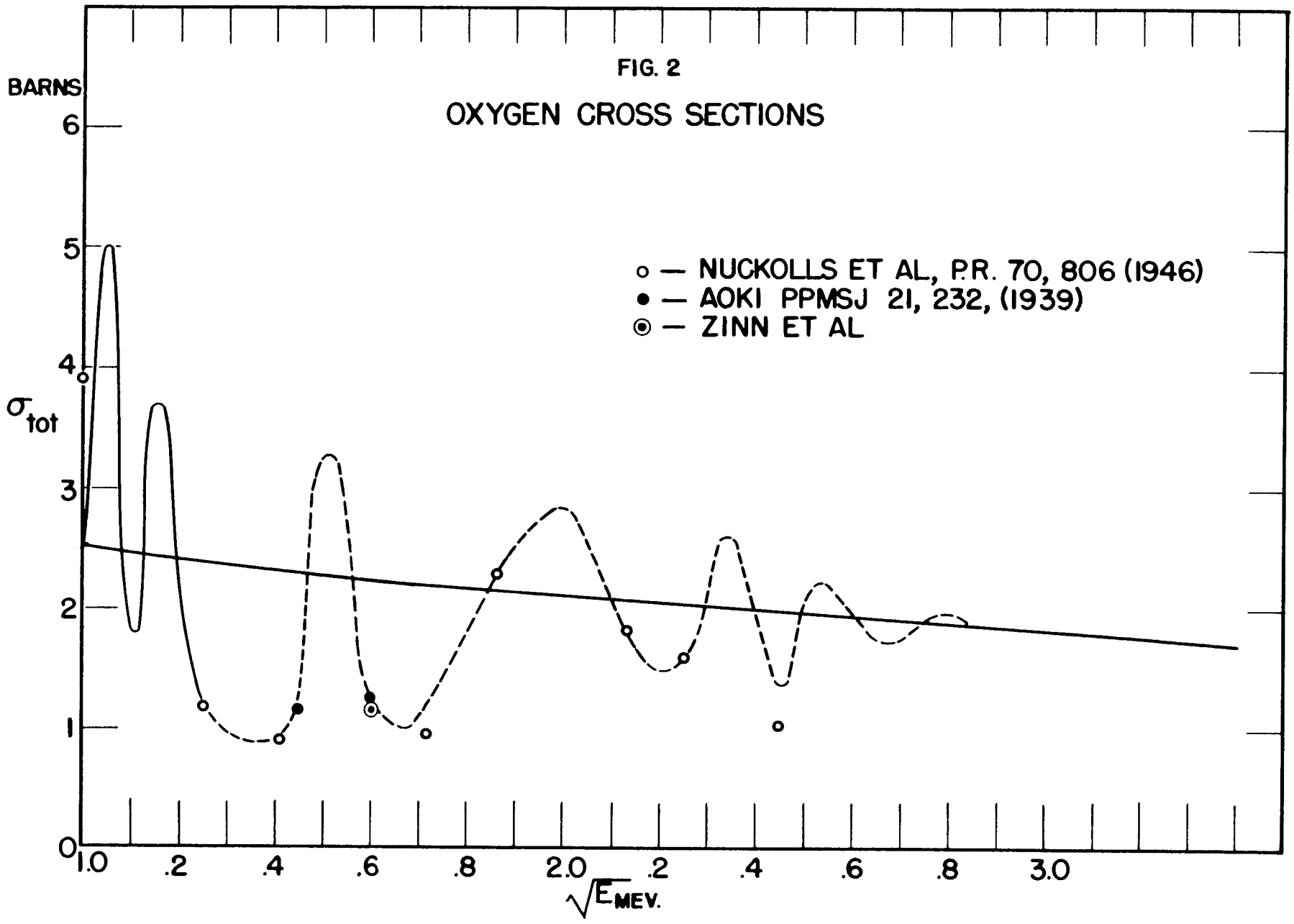


FIG. 2

OXYGEN CROSS SECTIONS