# The Total Neutron Cross Sections of Gold, Chlorine, and Phosphorus*

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The total neutron cross sections of gold, chlorine, and phosphorus have been measured over the energy range 100 to 700 kev using the mono-energetic neutrons from the $H^3(p,n)He^3$ reaction with an energy resolution of about 40 kev. Pronounced resonances were found in phosphorus, slight indications of resonances were found in chlorine, and no resonances were found in gold.

## INTRODUCTION

PREVIOUS measurements[1] of the total cross section of phosphorus for fast neutrons have yielded only scanty information in the energy range available to us. The total cross section for chlorine has not been reported previously, while that for gold appeared in abstract form[2] during our investigation.

## APPARATUS

A radiofrequency ion source has recently been installed in our small electrostatic generator, which together with suitable auxiliary focusing voltages yields a 15-$\mu$a resolved beam of protons in the energy range 500 to 1600 kev. The generator voltage is kept constant to within 1 to 2 kv by the use of a corona stabilizing circuit whose error signal is derived from a pair of insulated slits located at the output end of the analyzing magnet.

In order to measure the ion beam energy, work was initiated on a torsion balance with which the magnetic field of the analyzing magnet could be measured. Development work was under way at the time of these experiments, and the necessary stability and reproducibility of the torsion balance was achieved. However, since the completion of this work would have required more time than could reasonably be allotted to these experiments, it was decided to rely on the existing generating voltmeter. A careful investigation of the stability and reproducibility of the generating voltmeter revealed that after certain difficulties in the grounding of the rotor were eliminated, the only remaining variable was the temperature expansion of the generator column. When this was reduced as far as possible by the use of water cooling coils on the pressure tank, the reproducibility of the generating votmeter was generally about 2 kv. Thus, while the voltmeter left much to be desired, it was adequate for the present experiments and was then calibrated, using the $F(p;\alpha,\gamma)$ resonance at 873.5 kev, the $Al(p,\gamma)$ resonance at 993.3 kev, and the $H^3(p,n)$ threshold at 1.019 Mev.[3,4] In addition, the $H^3(p,n)$ threshold was checked after each 100-kev interval throughout the cross-section measurements.

The tritium targets were prepared by absorbing tritium gas at 1-mm Hg pressure into a zirconium film evaporated onto a wolfram backing.[5] Some difficulty was encountered in making uniform zirconium-tritium targets, as evidenced by the presence of fluctuations in the neutron counting rate of about two or three times the statistical fluctuations. To remove this source of trouble two pairs of crossed electrostatic deflecting plates were installed just after the output slits of the analyzing magnet. A 60-cycle per second ac voltage was applied across one pair of plates, and a 400-cycle per second ac voltage was applied across the other pair of plates in order to spread out the beam over the diaphragms near the target.

The target area was suitably diaphragmed to allow suppression of the secondary electrons from the target and thus permit the use of a beam current integrator in order to monitor the neutron yield. A conventional condenser and neon-glow tube was used in conjunction with a scale of 256 scalar for measuring the total charge accumulated on the target during each run.

The neutrons were detected by a conventional enriched $B^{10}F_3$ slow neutron counter[6] surrounded by paraffin with an outer layer of cadmium. The outside dimension of the counter with paraffin was 4 inches, and its effective length was 6 inches. Two checks of the stability of the neutron detector and its associated circuitry, using a 10 millicurie Ra-Be source, showed that electronic jitter and voltage drifts did not influence the counting rate more than one percent.

Finally, there was present in all the measurements a time dependent background of neutrons coming mainly from the region of the analyzing magnet chamber. This was reduced considerably by interposing a stack of five gallon cans filled with a saturated water solution of borax. In addition, the counting rate of these background neutrons was determined at frequent intervals while taking the data, and an attempt was made to correct the desired neutron counting rate for this source of neutrons. Since the amount of these background neutrons was never more than five percent, it is felt

* Assisted by the Joint Program of the U. S. Office of Naval Research the U. S. Atomic Energy Commission.
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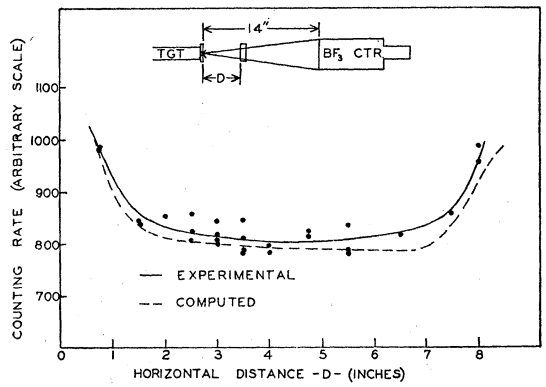


FIG. 1. Counting rate of neutron counter *versus* the distance of the gold scatterer from the target along the target-detector axis. The solid line is the average of the experimental points. The dashed curve was computed using the following parameters: counting rate without scatterer—1317, shadow cone background —130, cross section at 1.13 Mev—8.00 barns, counter diameter —4.00 inches, target-detector distance—16 inches.

that this source of fluctuation is adequately accounted for.

## EXPERIMENTAL

Before measuring the total neutron cross sections the effect of the exact location of the scatterer was investigated. Figure 1 shows that the location of the scatterer along the target-detector axis is not very critical, and that the scattering-in correction can account for the observed variation of the counting rate. As the scatterer is moved nearer to the neutron source, the counting rate rises sharply and may be accounted for by the rapid increase of the solid angle subtended by the scatterer from the target. If the scatterer is moved toward the neutron counter, a sudden increase in counting rate occurs because in our set-up the diameter of the counter is larger than the diameter of the scatterer. As the scatterer passes inside the detector cone, some neutrons pass directly into the detector without passing through the scatterer. The entire effect can be computed from the parameters given in the caption to Fig. 1. Hence, it was felt that the correction which is due to the scattering of neutrons into the detector is adequately accounted for by the following formula:

$$\sigma nd = \ln[(1-f/(N/N_0-f)], \qquad (1)$$

where $\sigma$ is the total cross section, $n$ is the number of scattering nuclei/cm$^3$, $d$ is the thickness of the scatterer, $N$ is the counting rate with the scatterer in place corrected for the paraffin shadow cone background, $N_0$ is the counting rate without the scatterer corrected for the shadow cone background, $f$ is a geometrical measure of the scattering-in correction and is given by

$$f=[(4\pi/\sigma)(d\sigma/d\omega)]\cdot[(L/r)^2A/4\pi(L-r)^2], \qquad (2)$$

where $d\sigma/d\omega$ is the differential cross section in the direction of the detector, $L$ is the target-detector distance, $r$ is the target-scatterer distance, and $A$ is the area of scatterer. The first bracket was taken equal to unity, since it is not exactly calculable but is expected to be near unity in our energy range according to the continuum theory of nuclear reactions.[7] In the geometry used the scattering-in correction $f$ usually amounted to four percent.

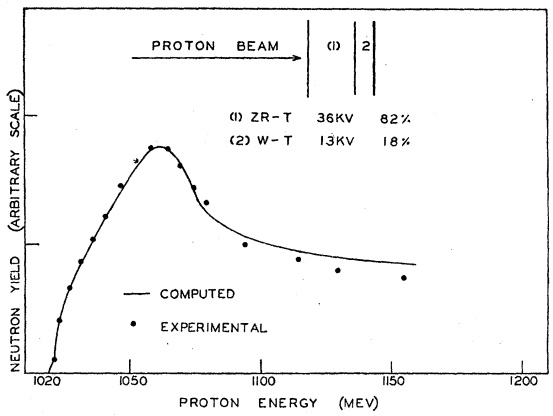


FIG. 2. Yield of neutrons in the forward direction from the $H^3(p,n)He^3$ reaction. The solid curve was computed by adding the yield predicted for a 36-kv thick target containing 82 percent of the tritium to the yield curve predicted for a 13 kv thick target containing 18 percent of the tritium but displaced in energy by 36 kv. The algebraic details are given in the Appendix.

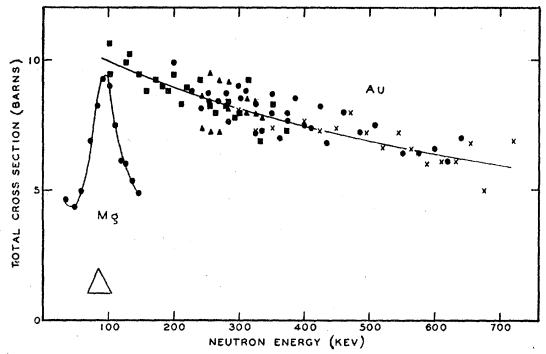


FIG. 3. Total cross section of gold for neutrons in the energy range 100–250 kev was measured with the detector 60° from the direction of the proton beam. The total cross section of magnesium was also measured in the 60° geometry.

The variation of the neutron counting rate as the scatterer was moved in a plane perpendicular to the target-detector axis was also investigated. A misalignment of about one-half inch gave a negligible change in the counting rate provided that the scatterer was aligned initially.

The energy spread of the neutrons was determined almost entirely by the thickness of the zirconium-tritium target. In order to measure this target thickness, careful measurements of the neutron yield in the forward direction were taken (see Fig. 2). In the Appendix the shape of the yield curve to be expected was calculated,

[7] Final Report of the Fast Neutron Data Project, NYO-636 (unpublished).

using several reasonable assumptions. If only one uniform target was employed, a departure of the experimental points from the calculated curve was observed in much the same fashion as that described by Bonner and Butler.[8] If, however, two different target layers were assumed to constitute the target, then much of the discrepancy was removed. In particular, if 82 percent of the tritium was assumed to be present in a 36-kv layer, and directly in back of this 18 percent of the tritium was assumed to be present in a 13-kv layer, then a unique fit was obtained within the accuracy of the assumptions involved. The second layer is thought to be due to an absorption of the tritium in the wolfram backing onto which the zirconium was evaporated. In any case the neutron energy spread is seen to be due to a 40–45 kv thick target.

As a check on this the narrow resonance in the total neutron cross section of magnesium at 85 kev reported by Fields and Walt[9] was measured with our source of neutrons. Figure 3 shows the observed neutron energy

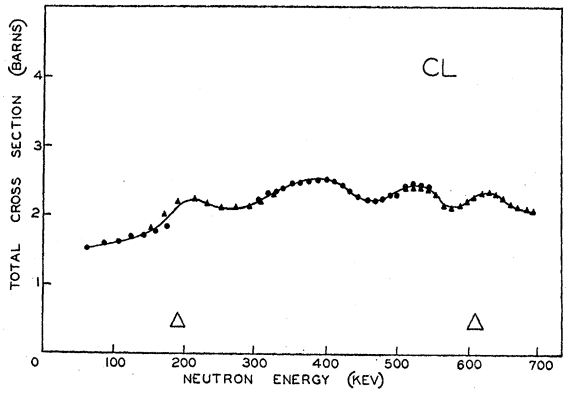


FIG. 4. Total cross section of chlorine for neutrons in the energy range 100–700 kev. The range 100–250 kev was measured in the 60° geometry.

width to be 45–50 kev in agreement with the target thickness prediction.

## DATA

The gold scatterer consisted of a one-half inch thick cylinder of pure gold $1\frac{3}{4}$ inches in diameter. Figure 3 gives the results for gold, and it is to be noted that these data were taken before installing the beam spreaders and the water can absorbers. A comparison of the gold data with either the chlorine or phosphorus data shows the extent of the reduction in the fluctuations effected by the use of the beam spreaders and the water cans. (See Figs. 4 and 5.) Several check points were made on gold after the spreaders and the water cans were installed, and these repeat points fell right along the average line drawn through the points. From these results it is felt that the total cross section for gold does

[8] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).
[9] R. E. Fields and M. Walt, Phys. Rev. **83**, 479 (1951).

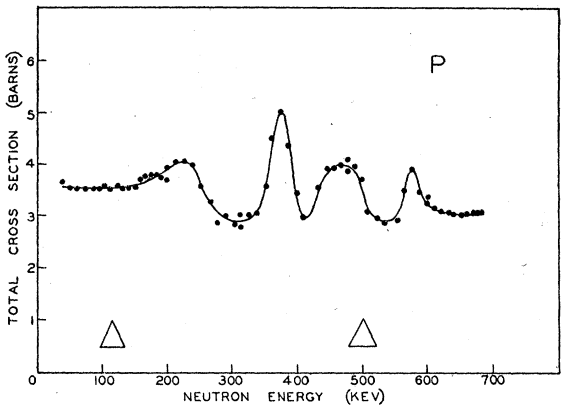


FIG. 5. Total cross section of phosphorus for neutrons in the energy range 100–700 kev. The range 100–250 kev was measured in the 60° geometry.

not have resonances in the energy range 100 to 700 kev. Furthermore, the magnitude of the cross section agrees well with those of neighboring atomic weight elements.

The total cross section for chlorine was measured using $CCl_4$ in a $1\frac{3}{4}$-inch diameter cylinder, 2 inches in length. The effect of the carbon was subsequently subtracted using the carbon cross section given by Adair.[1] Indications of resonances occur at several neutron energies and are separated by about 100 kev.

The total cross section for phorphorus was measured, using white phosphorus cast into a $1\frac{3}{4}$-inch diameter cylinder, $1\frac{1}{2}$ inches in length. There are several prominent resonances in this energy range, but higher resolution experiments, which we hope to be able to carry out, probably are needed to give any details concerning the nature of the resonances. The average value agrees well with that reported by Adair.[1]

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## APPENDIX

The forward direction yield of the $H^3(p,n)He^3$ reaction from a target of finite thickness as measured by our finite sized counter (assumed to be a flat circular disk) is given by

$$Y=(N_0 n/4\pi)\int\int \eta(\theta)\sigma(E) \times(d\Omega\phi_1/d\Omega_\theta+d\Omega\phi_2/d\Omega_\theta)d\Omega_\theta dx,$$

where $N_0$ is the number of protons striking the target per second, $n$ is the number of tritium nuclei per cubic centimeter, $\theta$ is the laboratory angle measured from the proton beam direction, $\phi_1$ and $\phi_2$ are the two center-of-mass angles from which emergent neutrons contribute to the laboratory solid angle $d\Omega_\theta$, and $\eta(\theta)$ is the zonal efficiency of the detector. The differential cross section in laboratory coordinates has been calculated with the

assumption that the differential cross section in the center-of-mass coordinates is a constant. The total cross section $\sigma(E)$ is then only a function of the energy of the proton $E$ in the layer $dx$ of the target.

For convenience in integration, a parameter

$$k=(M_TM_R/M_BM_O)^{\frac{1}{2}}(1-E_0/E)^{\frac{1}{2}}$$

is introduced, where $M_T$, $M_R$, $M_B$, and $M_O$ are the masses of the target, residual, bombarding, and outgoing particles, respectively. $E_0$ is the threshold energy of the reaction in laboratory coordinates. The total cross section of the reaction is assumed to vary as $(E-E_0)^{\frac{1}{2}}$ near threshold, and since the exact variation above threshold is not known, it is chosen for convenience in integrating to be such that $\sigma dx\sim k^2dk$. The zonal efficiency of the counter $\eta(\theta)$ is also assumed to be a constant.

Using the dynamics of the $H^3(p,n)He^3$ reaction, the value of $d\Omega\phi/d\Omega_\theta$ may be found as a function of $k$ and $\theta$. The integration then may be carried out with the result that

$$Y=(N_0nA/3a)k_1^2 \text{ for } 0<k_1<\sin\theta_0,$$

$$Y=(N_0nA/3a)[k_1^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } \sin\theta_0<k_1<(M_RM_T/M_BM_O)^{\frac{1}{2}} \times[1-E_0/(E_0+at)]^{\frac{1}{2}},$$

$$Y=(N_0nA/3a)[k_1^3-k_2^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } 0<k_2<\sin\theta_0,$$

$$Y=(N_0nA/3a)[k_1^3-k_2^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}} +\cos\theta_0(k_2^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } k_2>\sin\theta_0, \text{ but } k_1\leqslant 1.$$

In the formulas $A$ is an unknown constant depending on the efficiency of the counter and other constants of the reaction, $a$ is the energy loss per cm for the proton beam in the target, $\theta_0$ is the half-angle subtended by the counter (7.50°), and $t$ is the thickness of the target in cm. $k_1$ is the value of $k$ at the front edge of the target, and $k_2$ is the value of $k$ at the back edge of the target, each for an incident proton beam of energy $E_B$.

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# Total Cross Sections of Chlorine, Sodium, Titanium, and Bromine for Fast Neutrons*

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Relatively new liquid scintillation counter methods were adapted to detect fast neutrons with a heretofore unattainable efficiency of about 19 percent. The geometry obtained was the so-called "good" geometry, which was a half-angle at the counter of 2.7°. With the more efficient counter reasonable counting times could be obtained with the detector subtending a half-angle of only 2.7° from the target.

The neutrons were obtained by using a modified Cockcroft-Walton linear accelerator of 100-kev bombarding energy. The neutron energy range was 2.15 to 2.82 Mev.

All the scatterers used were contained in almost identical glass "cells," and the effects of the glass cells were subtracted out by using an empty glass cell of the same type as a reference. The probable error, calculated statistically from the counting rates of the experiment, was 1.3 percent on total cross-section values. Actual reproducibility of each result was about 3 percent or better.

A carbon cross-section curve was obtained as a check on this method, and agreement with previously reported values was excellent. The chlorine and sodium cross sections were found to be about $3\times10^{-24}$ cm², as determined indirectly by using carbon tetrachloride and sodium chloride. The titanium cross section was found to be about $4.1\times10^{-24}$ cm² by using powdered titanium metal. The bromine cross section was found to be about $3.7\times10^{-24}$ cm², by using a sample of liquid bromine. No large resonances were found in the energy region available.

Data were also taken on the angular distribution of the number of neutrons with respect to the forward direction of the incident deuteron beam, and they were found to agree well with theory except in the region where experimentally necessary geometric conditions dictated a deviation.

## I. INTRODUCTION

In the past few years there has been much work done with regard to obtaining total cross sections of the elements for fast neutrons. In reviewing many articles, it has been found that there is still work to be done before all the total cross sections have been measured as accurately and with as good an energy resolution as the theoretical physicists would like. Hence, we have taken up a program of augmenting the available data with the apparatus being used here. Several elements were found that have not been reported as yet, and we are planning a systematic study of these elements as well as those elements that have only sparse data for our energy region. Wisconsin,[1,2] Aoki,[3] Argonne,[4] Stafford,[5] Los Alamos,[6,7] Oak Ridge,[8] MacPhail,[9] Ricamo,[10]

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† Part of a dissertation presented to the Faculty of the Graduate School of The University of Texas as partial fulfillment for the degree of Doctor of Philosophy.

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