# Activation Cross Sections for 14-Mev Neutrons*

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Cross sections for several nuclear reactions induced by 14-Mev neutrons were measured by the activation method. The number of activated atoms was determined by absolute beta-counting. Corrections for finite sample thicknesses were determined experimentally in every case. Cross sections for the following reactions were measured: $(n,2n)$ for $Cu^{63}$, $Cu^{65}$, $Ag^{107}$, and $Ag^{109}$; $(n,p)$ for $Al^{27}$, $P^{31}$, $Fe^{56}$, and $Cu^{65}$; $(n,\alpha)$ for $Al^{27}$.

## I. INTRODUCTION

IF a nuclear reaction leads to the formation of an unstable isotope, the resulting radioactivity provides a means for determining the reaction cross section. In particular, if there are beta-particles emitted from the product nucleus, they may be counted in order to determine the total number of active atoms present. The cross section for the formation of these active atoms can then be found from the neutron flux, sample weight, and the number of activated atoms. In cases involving $K$-capture, beta-counting may still be employed if a known fraction of the disintegrations involve beta-particle emission. Similarly the cross section for the production of isomers may be determined to obtain the cross section for the production of a particular isotope provided each isomer decays at least in part by beta-emission.

Activation methods have been applied to the measurement of reaction cross sections by Wäffler,[1] using neutrons from the D+Li and D+B reactions, and by Cohen,[2] using neutrons from the D+Be reaction. Fowler and Slye[3] investigated the $Cu^{63}(n,2n)$ reaction cross section near the threshold, using neutrons from the D+D reaction; and more recently Paul and Clarke[4] measured activation cross sections for forty elements using neutrons from the T+D reaction. The present activation experiments[5] utilized 14.1-Mev neutrons produced by bombarding a thick tritium-zirconium target with 125-kev deuterons.

## II. METHOD

For a measurement of the cross section $\sigma$ for the production of a particular radioactive isotope, one needs to know the neutron flux $nv$, the number of atoms $N$ in the sample, and the equilibrium activity $A$ of the sample. Then for a thin sample,

$$\sigma = A/(nvN).$$

By absolute beta-counting and from a knowledge of the bombarding and counting schedule, the half-life, and the decay scheme of the isotope under consideration, the equilibrium activity was found.

The neutron flux from the D+T source was determined by counting the alpha-particles produced by the reaction. Samples were located so as to receive neutrons emitted from the target at an angle of 90° with respect to the deuteron beam. By collision mechanics the number of neutrons per $cm^2$ incident on the sample was calculated from the number of alpha-particles entering a proportional counter at 135° to the deuteron beam. The angular distribution of the neutrons is known to be isotropic in the center-of-mass system at low bombarding energies.[6]

The number of atoms in each sample was calculated from the sample weight.

## III. BETA-COUNTING

Two counters were used. One was a Tracerlab type TGC-2 end-window Geiger counter and the other was a side-window proportional counter using a flow filling of methane at atmospheric pressure. The samples for the end-window counter were supported below the window on an adjustable shelf which was used in three positions to provide different counting efficiencies. The samples for the side-window counter were placed directly on the counter window (0.5 $mg/cm^2$ rubber hydrochloride) to obtain a high counting efficiency. Tests were performed on the proportional counter in order to show that it possessed a well-defined sensitive volume inside of which beta-particles were detected with essentially 100 percent efficiency. This was shown both by analysis of the pulse-height distribution curve produced by beta-particles from RaE and by intercalibration with the Geiger counter at two beta-energies. The pulse-height distribution indicated that less than 1 percent of all the pulses fell below the bias setting of the scaling unit. The relative sensitivity of the counter was the same for the 1.17-Mev beta-particles from RaE as for the 0.51-Mev beta-particles from $Cs^{137}$.

Calibrations of the counters were obtained by counting RaDEF standards certified by the National Bureau of Standards. In order to use these standards a correction must be applied because of scattering by the thick backing on which they are supplied and for the

* Work done under the auspices of the AEC.
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[1] H. Wäffler, Helv. Phys. Acta **23**, 239 (1950).
[2] B. L. Cohen, Phys. Rev. **81**, 184 (1951).
[3] J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 787 (1950).
[4] E. B. Paul and R. L. Clarke, Phys. Rev. **86**, 605 (1952).
[5] S. G. Forbes, Ph.D. thesis, Oregon State College, June, 1951 (unpublished).
[6] D. L. Allen and M. J. Poole, Proc. Roy. Soc. (London) **A204**, 500 (1951).

scattering in the active deposit itself which is about 1 mg/cm² thick. The corrections to be applied cannot be readily determined experimentally, but Burtt[7] found that (for source-to-window distances greater than about 1 cm) a correction factor of 1.79 for the combined effects gave good agreement with standards prepared in the laboratory. Therefore, for the three Geiger-counter geometries in the present work, the disintegration rate quoted by the Bureau of Standards was used to obtain geometry factors $G$ from the following relation:

$$1.79G \times \text{disintegrations/min} = \text{counts/min}.$$

Intercalibration of the one close (47 percent) proportional counter geometry with the Geiger-counter geometries was then accomplished by counting rate comparisons using a thin deposit of $Cs^{137}$ on Zapon. The geometry factors thus obtained were in good agreement with the values calculated from geometry considerations. Since the counter sensitivities varied slightly with time, frequent checks on the geometry factors were made using the standards.

Background, coincidence loss, and window and air absorption corrections were applied to the observed counting rates. Scattering by the housing was assumed to be negligible. Backscattering was made negligible by using Zapon films of about 40 $\mu$g/cm² to support all samples. The samples were in the form of disks $\frac{1}{2}$ inch in diameter in order to simulate closely the size of the RaDEF beta-standards.

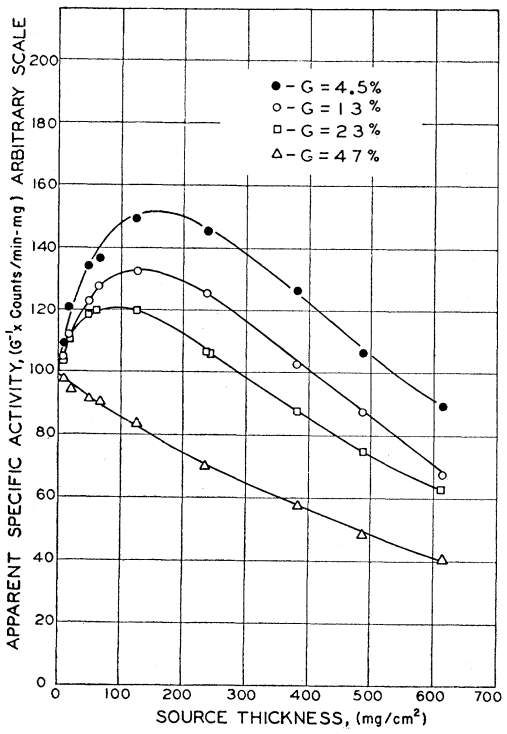


FIG. 1. Effect of sample thickness on apparent specific activities for $Cu^{64}$ beta-rays in copper foils for the three Geiger-counter geometries of 4.5, 13, and 23 percent, and for the 47 percent proportional counter geometry.

[7] B. P. Burtt, Nucleonics 5, No. 2 (1949).

Because of complications introduced by scattering effects, the self-absorption and scattering in the sample were determined experimentally in every case. This was done by measuring the apparent specific activity ($G^{-1} \times$ counts/min-mg) as a function of the source thickness (mg/cm²) and extrapolating to zero thickness to obtain the true specific activity which would be observed in the absence of scattering and absorption in the sample. Typical results of such an experimental determination are shown in Fig. 1 for four different counting geometries. These curves were obtained by giving a series of foils of different thicknesses equal bombardments with 14-Mev neutrons so that the true specific activities of all the foil were equal. Similar curves have been obtained by other observers.[8–10] The use of a thick sample support tends to flatten these curves somewhat but does not remove the necessity of extrapolation to zero sample thickness and the determination of the corresponding backscattering factor.

Curves similar to those shown in Fig. 1 were obtained experimentally in the 23 percent and 47 percent geometries for every beta-activity used in the cross-section determinations with one exception. The self-scattering of $Ni^{65}$ beta-particles by the copper sample was assumed to be the same as that of $Mn^{56}$ beta-rays scattered by iron. All the curves showed the same general shape, although the magnitude and location of the peaks for the 23 percent geometry varied considerably.

An attempt was made to simulate a thick foil by stacking several thin foils, but the experimental data consistently fell below that obtained from single layers and was considerably more erratic. Evidently poor contact between successive layers permitted sufficient "leakage" of the beta-particles emitted in the plane of the sample to reduce the fore-scattering appreciably.

In practice, the shape of the curves of activity *vs* sample thickness was determined by bombarding a series of foils simultaneously in the strongest neutron flux available in order to obtain reasonable counting statistics for the very thin foils. The absolute cross-section measurement could then be made by bombarding a relatively thick foil at a greater distance from the source in order to increase the precision of the flux determination.

## IV. RESULTS

The values of the cross sections found from the measurements are listed in Table I. The isotopic cross sections were calculated on the basis of isotopic abundances and branching ratios for beta-decay as given by the National Bureau of Standards summary of nuclear

[8] Collie, Shaw, and Gale, Proc. Phys. Soc. (London) **A63**, 282 (1950).

[9] Solomon, Gould, and Anfinsen, Phys. Rev. **72**, 1097 (1947).

[10] K. D. George, National Research Council of Canada, Document CR TEC-309 (1946) (unpublished).

data.[11] A correction was made to the decay of $Cu^{64}$ for 46 percent $K$-capture. No other $K$-capture corrections were made. The half-lives quoted in Table I are those used in the calculations. Deviations from published values are based on actual observations.

The cross section for the $Cu^{65}(n,p)Ni^{65}$ reaction was found by comparing the activity of the 2.56-hour $Ni^{65}$ to the activity of the 12.8-hour $Cu^{64}$. The cross section for the $(n,p)$ reaction is relatively small, so that it was necessary to follow special procedures in order to resolve the two activities. A relatively thick foil of 120 mg/cm$^2$ was used in order to attenuate the lower energy $Cu^{64}$ beta-rays. The activation was made in the strongest flux available to improve the counting statistics, and the bombardment was limited to two hours in order to avoid saturation of the longer-lived $Cu^{64}$. The counting was done in the 47 percent geometry to avoid complications in estimating the self-scattering correction for the $Ni^{65}$ beta-rays.

The ratio of the $Al(n,\alpha)$ and $Al(n,p)$ cross sections was found also by comparing the activities produced by a single bombardment. The resulting ratio was $\sigma(n,\alpha)/\sigma(n,p)=1.70$, which is in excellent agreement with the ratio obtained from the individual determinations.

## V. DISCUSSION OF ERRORS

The largest error in many cases is introduced by the calibration of the counters with the RaDEF beta-standards. The standard error in the disintegration rates of the standards is given as 3 percent. An additional error of 2 to 3 percent is introduced by the necessity of making long extrapolations of the absorption curves in order to correct for absorption in the window and air. The error in the product of the backscattering and self-scattering factors is not known but is believed to be about 5 percent on the basis of the results obtained by Burtt. The estimated standard error in the counter calibration is therefore 6 percent. This could be reduced to 1 or 2 percent if accurately calibrated thin beta-ray standards free from alpha-radiation and mounted on thin backings were available.

Determination of the true specific activity from the extrapolation to zero sample thickness is another source of large error. For elements of low atomic number such as aluminum for which very thin foils are readily obtained, the extrapolation has about 2 percent uncertainty. In cases where the beta-energy is low or where the atomic number is high, the use of very thin foils is required in order to determine the shape of the initial portion of the curve. The effects of wrinkles in the foils or variations in the thickness become more prominent in this region, and the accuracy of the measurements is reduced.

[11] Way, Fano, Scott, and Thew, *Nuclear Data*, National Bureau of Standards Circular 499 (1950).

TABLE I. Reaction cross sections for 14.1-Mev neutrons.

| Reaction | Half-life | Isotopic cross section (millibarns) | Estimated error (percent) |
|---|---|---|---|
| $Al^{27}(n,p)Mg^{27}$ | 9.6 min. | 79 | 7 |
| $Al^{27}(n,\alpha)Na^{24}$ | 15.0 hr | 135 | 7 |
| $P^{31}(n,p)Si^{31}$ | 170 min | 91 | 10 |
| $Fe^{56}(n,p)Mn^{56}$ | 2.59 hr | 124 | 10 |
| $Cu^{63}(n,2n)Cu^{62}$ | 9.9 min | 510 | 7 |
| $Cu^{65}(n,2n)Cu^{64}$ | 12.8 hr | 970 | 8 |
| $Cu^{65}(n,p)Ni^{65}$ | 2.56 hr | 19 | 20 |
| $Ag^{107}(n,2n)Ag^{106}$ | 24.5 min | 560[a] | 10 |
| $Ag^{109}(n,2n)Ag^{108}$ | 2.3 min | 1000 | 10 |

[a] Cross section for the production of the 24.5-min isomer only.

The standard error for the neutron flux is estimated as 2 percent. This value is based on the sentivity of the calculations to variations in the different parameters involved. At the low bombarding energies (125-kev deuterons) used, the corrections for the asymmetry in the angular distribution of the particles in the laboratory system of reference is not very great, and hence the calculations are not very sensitive to changes in the bombarding energy, the rate of deuteron energy loss in the thick target, or uncertainties in the variation of the D+T reaction cross section with energy. Errors in the distance between source and sample introduced by motion of the deuteron beam over the target will cancel out if several runs are averaged.

The purity of all samples used was known to be at least 99 percent; hence the number of atoms is subject to errors of less than 1 percent from this source.

It is unlikely that any of the observed activities are assigned to the wrong radioisotope, since such a wrong assignment would involve either an improbable reaction or the presence of an impurity with an extremely large cross section. Small amounts of an activity having a half-life similar to that under investigation would be difficult to detect, however, since no chemical separations were made.

Errors in the sample weights and statistical errors in the beta-counting were less than 1 percent in most cases.

The estimated error in Table I is the rms value of the standard errors directly involved in the measurements and does not include estimates of the uncertainties in the decay schemes.

The relative values of the cross sections should be more accurate than the absolute values since the counter calibration error does not enter. There will be 1 or 2 percent error remaining caused by fluctuations in the counter sensitivities even though these were checked periodically.

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