INDC - 247

AEEW - R 597

INDC(UK)-005/G

AEEW-R 597

AEEW - R 597

UNCLASSIFIED

United Kingdom Atomic Energy Authority

REACTOR GROUP

# ON THE THERMAL NEUTRON CAPTURE CROSS-SECTIONS OF COBALT


J. S. STORY





General Reactor Physics Division,
Atomic Energy Establishment,
Winfrith, Dorchester,
Dorset.



1968

Available from H.M. Stationery Office,

PRICE 2s. 6d. NET

U.D.C.
539.172.4.162.2
546.73:539.172.4.162.2

# ON THE THERMAL NEUTRON CAPTURE CROSS-SECTIONS OF COBALT

J. S. STORY

## ABSTRACT

Experimental data on the thermal neutron capture cross-section of cobalt and the cross-sections for activation of the 10.5 minute and 5.26 year isomeric states of $Co^{60}$ are summarised, and the following weighted mean values are derived:

$$\sigma_{nA} = 37.55 \pm 0.13 \text{ barns}$$

$$\sigma_{act} = 37.50 \pm 0.13 \text{ barns}$$

for activation of the 5.26 year ground state of $Co^{60}$ both directly and by decay of the isomeric state.

$$\sigma_{act} = 19.9 \pm 0.91 \text{ barns}$$

for activation of the 10.5 minute isomeric state of $Co^{60}$.

A summary is made also of the experimental data on the half lives of the $Co^{60}$ isomers.

A.E.E.
Winfrith

May, 1968

C.20

W.9571

CONTENTS



TABLES

1. Introduction

Natural cobalt consists of the single stable isotope $Co^{59}$ with a mass of $58.9331893 \pm 0.0000038$ A.M.U. The neutron absorption cross-section follows the 1/v law below about 1eV, but deviates above that energy because of the resonance at 132 eV. Resonance absorption contributes appreciably to the effective absorption cross-section in a thermal neutron reactor.

By neutron capture the compound nucleus $Co^{60}$ is formed. This nucleus has a ground state of 5.26 years half-life, and an isomeric state at 59 keV excitation energy with a half-life of 10.5 minutes. The isomeric state decays mainly to the ground state by conversion electron and gamma ray emission, but in $(0.255 \pm 0.03)$ percent of transitions it decays by beta emission, mainly to the first excited state of $Ni^{60}$ at 1.33 MeV, and with a very weak branch to the 2.16 MeV level; DEUTSCH & SCHARFF-GOLDHABER (1951), SCHMIDT-OTT (1963). Activation measurements have shown that after thermal neutron capture by $Co^{59}$ $(53 \pm 4)$ percent of the compound nuclei go to the isomeric state. From these details it follows that the total thermal neutron cross-section for activation of the 5.2 year half-period, both directly and by decay of the isomeric state, is only $(0.135 \pm 0.016)$ percent less than the absorption cross-section of $Co^{59}$; this amounts to a difference of $51 \pm 6$ millibarns.

2. Half-lives of the $Co^{60}$ isomers

In Table 1A are listed measurements of the half-life of the ground state of $Co^{60}$, which is needed in the interpretation of cobalt activation experiments. The most accurate measurements appear to be those of GORBICS et al. (1963) and of ANSPACH et al. (1965) giving a weighted mean value of

$$5.260 \pm 0.003 \text{ years.}$$

This agrees very well with the weighted mean of the other measurements (which give $5.252 \pm 0.019$ years), and is adopted as the preferred value.

Table 1B lists the measured data on the half-life of the isomeric state of $Co^{60}$. There is good agreement between the data, and the best value is that of BARTHOLOMEW et al. (1953), giving

$$10.48 \pm 0.02 \text{ minutes.}$$

3. Thermal neutron absorption and activation cross-sections

In Tables 2A and 2B are listed absorption cross-section measurements, and activation cross-section measurements for production of the $Co^{60}$ ground state activity. Table 3 gives activation cross-section data for production of the 10.5 minute isomeric state of $Co^{60}$. These cross-section data have been revised, as necessary, using for the reference cross-section standards the values which are given in Table 4; the activation cross-section data in Tables 2B and 3 have also been revised using the preferred value given above for the half-life of the $Co^{60}$ ground state. Increased uncertainties have been assigned to the two data in Table 2A which were derived from transmission measurements, in order to allow for possible chemical binding effects on the scattering cross-sections of the samples.

The weighted mean value for the absorption cross-section data given in Table 2A is $37.62 \pm 0.21$ barns, and the internal consistency ratio of the set of data, $[\chi^2/(n-1)]$, is 1.97. This seems to indicate that the dispersion of the data is somewhat greater than the quoted uncertainties as may be seen from Table 5; the discrepancy stems mainly from the high value of $\sigma_A$ obtained from the transmission measurements of WU et al. (1947), and the low value reported by MEADOWS & WHALEN (1961). The weighted mean of the activation cross-section data in Table 2B is 37.38 ± 0.17 barns, with an internal consistency ratio of 1.68; the largest contribution to $\chi^2$ comes from the low value of $\sigma_{act}$ reported by CANCE et al. (1963).

The agreement between these two sets of measurements is remarkably good. Taking all the data together, and allowing for the expected small difference between the absorption and activation cross-sections one obtains a weighted mean value of 37.50 ± 0.13 barns for the absorption cross-section, for neutrons of 0.0253 eV. However the internal consistency ratio for this complete set of data is 1.76, and Table 5 shows that there is less than 2 percent probability that the data are all consistent within the quoted uncertainties. The major contributions to $\chi^2$ come from the 3 measurements already mentioned in the preceding paragraph; those of WU et al. (1947), MEADOWS & WHALEN (1961), and CANCE et al. (1963), and some down weighting of each of these three results seems justifiable. This has been done (in somewhat arbitrary fashion) by replacing the tabulated uncertainty of each of the 3 measurements by the average of the tabulated uncertainty and the deviation of the tabulated value from the weighted mean of all the results. The weighted mean of all the data then becomes

$$\sigma_A\ [Co^{59}] = 37.55 \pm 0.13 \text{ barns}$$

for thermal neutrons, and

$$\sigma_{act}\ [Co^{59}] = 37.50 \pm 0.13 \text{ barns}$$

for activation of the 5.26 year ground state of $Co^{60}$ both directly and by decay of the isomeric state. The internal consistency ratio is 1.32, and Table 5 shows that the set of data are now reasonably consistent.

The weighted mean of the data in Table 3 gives

$$\sigma_{act}\ [Co^{59}] = 19.9 \pm 0.91 \text{ barns}$$

for activation of the 10.5 minute isomeric state of $Co^{60}$. The internal consistency ratio of 0.785 shows that the three measurements are consistent within their quoted uncertainties.

TABLE 1A

Half-life of the $Co^{60}$ ground state

| Reference | Half-life years | Comments |
|---|---|---|
| LIVINGOOD & SEABORG (1941) | 5.3 ± (0.3) | |
| SEGRE' & WIEGAND (1949) | 5.08 ± 0.51 | Decay followed for 8 days, relative to Ra. |
| BROSI & KETELLE (1950) | 5.1 ± 0.1 * | |
| BROWNELL & MALETSKOS (1950) | 5.26 ± 0.18 | Decay followed for 18 months. |
| TOBAILEM (1950, 1955) | 5.27 ± 0.07 | |
| SINCLAIR & HOLLOWAY (1951) | 5.25 ± 0.21 | Preliminary value. |
| KASTNER & WHYTE (1953) | 5.21 ± 0.04 * | Apparently a preliminary result from the work reported by GEIGER (1957). |
| BROSI & KETELLE (1954) | 5.45 ± 0.1 | Decay followed for 6 months. |
| PERRY & DALE (1956) | 5.25 ± 0.04 * | Preliminary value. Decay followed for about 6 years. |
| LOCKETT & THOMAS (1956) | 5.20 ± 0.03 | Decay followed for 4.5 years relative to Ra. An earlier value of 4.95 years is rescinded. |
| EVANS (1956) | 5.28 ± 0.03 * | Unpublished result. |
| GEIGER (1957) | 5.24 ± 0.03 | Decay followed for 6.8 years relative to Ra. |
| KEENE et al. (1958) | 5.33 ± 0.04 | Decay followed for 15 months relative to Ra. |
| LOFTUS & LEE (1958) | 5.29 ± 0.02 * | Unpublished result. |
| BROSI & KETELLE (1958) | 5.29 ± 0.03 * | Unpublished result. |
| SELIGER & CAVALLO (1958) | 5.26 ± 0.03 * | Unpublished result. |
| GORBICS et al. (1963) | 5.263 ± 0.003 | Decay followed for 3 years relative to Ra. |
| ANSPACH et al. (1965) | 5.242 ± 0.008 | Decay followed for 5.2 years relative to Ra. |
| MERRITT & TAYLOR (1967) | 5.28 ± 0.03 | Decay followed for 5 to 6 years relative to Ra. |

* Preliminary or unpublished results, which were ignored in forming the weighted mean quoted in the text.

TABLE 1B

Half-life of the isomeric state of $Co^{60}$

| Reference | Half-life minutes | Comments |
|---|---|---|
| LIVINGOOD & SEABORG (1941) | 10.7 | |
| HARDWICK (1952) | 10.44 | Followed for at least 94 minutes. |
| MOSS & YAFFE (1953) | 10.5 $\pm$ 0.2 | |
| BARTHOLOMEW et al. (1953) | 10.48 + 0.02 | Several samples followed for 40 to 80 minutes. |
| SCHMIDT-OTT (1963) | 10.35 $\pm$ 0.20 | |

TABLE 2A

Absorption cross-section measurements for Co for neutrons of 0.0253 eV

| Reference | Reported value barns | Revised value barns | Method and Comments |
|---|---|---|---|
| WU et al. (1947) | 40.2 ± 0.9 | 40.2 ± 1.4 | Transmission using time-of-flight with a pulsed cyclotron; analysis of $\sigma_T$ into constant + 1/v term. |
| COLMER & LITTLER (1950) | 38.2 ± 3.0 | 38.5 ± 3.1 | Reactivity oscillator in reactor spectrum, relative to boron. Revised value corrected for resonance absorption. |
| HARRIS et al. (1950) | 35.7 ± 1.8 | 36.7 ± 1.9 | Reactivity oscillator in reactor spectrum, relative to boron. Revised value corrected for resonance absorption. |
| GRIMELAND et al. (1951) | 33.9 ± 0.4 | 36.8 ± 0.5 | Reactivity oscillator in reactor spectrum, relative to boron, corrected for resonance absorption. |
| POMERANCE (1951) | 34.2 ± 1.7 | 35.5 ± 1.8 | Local oscillator, relative to gold. |
| AILLOUD et al. (1952) | 35.4 ± 1.0 | 38.4 ± 1.1 | Local oscillator, relative to boron. |
| BERNSTEIN et al. (1952) | 38.4 ± 0.6 | 38.4 ± 1.2 | Transmission using a crystal spectrometer in the range 0.03 to 1.2 eV; analysis of $\sigma_T$ into constant + 1/v term. |
| JOWITT et al. (1958) | 38.2 ± 0.7 | 38.4 ± 0.7 | Reactivity oscillator in a thermal well, relative to boron. |
| MEADOWS & WHALEN (1961) | 36.3 ± 0.6 | 36.3 ± 0.6 | Pulsed neutron source in small geometries. |
| HUTTEL & LIEWERS (1964) | 34.8 ± 0.2 | 35.0 ± 0.5 * | Local oscillator relative to boron. |
| CARRÉ & VIDAL (1966) | 38.0 + 0.3 | 38.0 ± 0.3 | Reactivity oscillator, relative to boron; it is not clear if any correction was made for the weak resonance absorption. |
| Weighted mean value | | 37.62 ± 0.21 | Internal consistency ratio 1.97 |

* Not included in the weighted mean value because inadequate details are available.

TABLE 2B

Activation cross-section measurements for Co for neutrons of 0.0253 eV; results are for activation of the 5.26 year ground state of $Co^{60}$, both directly and by decay of the isomeric state

| Reference | Reported value barns | Revised value barns | Comments ⌿ |
|---|---|---|---|
| YAFFE et al. (1951) | 34.2 ± 1.4 | 36.6 ± 1.5 | Activation in NRX reactor; $Co^{60}$ half-life taken as 5.26 year. |
| EASTWOOD & WERNER (1959) | 36.4 ± 1.5 | 36.3 ± 1.5 | Activation in Z2 and NRX reactors; $Co^{60}$ half-life 5.28 year. |
| WOLF (1960) | 38.0 ± 0.5 | 38.3 ± 0.5 | Activation in FRM reactor; $Co^{60}$ half-life 1905 days |
| BERRETH & SCHUMAN (1962) | 39.1 | 39.0 ± 1 | Preliminary result; activation in MTR; $Co^{60}$ half-life 5.27 year. |
| de SWINIARSKI et al. (1963) | 34.9 ± 1.0 * | | No details available. |
| CANCE et al. (1963) | 35.51 ± 0.87 | 35.47 ± 0.88 | Value used for $Co^{60}$ half-life is not stated. |
| TAYLOR & LINACRE (1964) | 37.0 ± 2.0 | 37.2 ± 2.0 | Activations in GLEEP and BEPO; $Co^{60}$ half-life 5.23 year. |
| VANINBROUKX (1966) | 37.4 ± 0.3 | 37.3 ± 0.3 | Activation in BR1 reactor; $Co^{60}$ half-life 5.265 year. |
| DEWORM (1967) | 37.7 ± 0.4 | 37.7 ± 0.4 | Activation in thermal column of BR1 reactor. |
| MERRITT & GREEN (1968) | 37.1 ± 0.3 | 37.1 ± 0.3 | Activation in thermal column of NRU; $Co^{60}$ half-life taken as 5.265 year. |
| Weighted mean value | | 37.38 ± 0.17 | Internal consistency ratio 1.68 |

⌿ All the data listed in this table were made in comparison with gold as reference standard, and cadmium difference measurements were made in every case except perhaps that of DEWORM (1967):

* Not included in the weighted mean because no details are available.

## TABLE 3

Activation cross-section measurements for Co for neutrons of 0.0253 eV; results are for activation of the 10.4 minute isomeric state of $Co^{60}$

| Reference | Reported value barns | Revised value barns | Comments |
|---|---|---|---|
| DEUTSCH & SCHARFF-GOLDHABER (1951) | | 15.4 ± 3.9 | Activation in BNL reactor; ratio of cross-sections $\sigma[\rightarrow 5.2\ \text{year}]/\sigma[\rightarrow 10.5\ \text{minute}] = 1.4 \pm 0.6$ |
| MOSS & YAFFE (1953) | 18.3 ± 1.7 | 19.6 ± 1.8 | Activation in NRX reactor with Cd differences relative to Au. |
| KEISCH (1963) | | 20.4 ± 1.1 | Activation in MTR, probably with Cd differences; $\sigma[\rightarrow 10.5\ \text{minute}]/\sigma[\rightarrow 5.27\ \text{year}] = 1.19 \pm 0.16$ |
| Weighted mean value | | 19.9 ± 0.91 | Internal consistency ratio 0.785 |

TABLE 4

Values used for the reference cross-section standards

| Reference standard | $\sigma_A$, barns at 0.0253 eV |
|---|---|
| Gold | 98.7 ± 0.3 |
| Boron: BCMN II (new international standard) | 760.4 ± 2.0 |
| ANL I (old standard) | 758.2 ± 2.6 |
| Fontenay (old standard) | 770.1 ± 2.6 |
| Harwell (old standard) | 770.5 ± 2.6 |

The values listed in this table are not necessarily the best available, but it is expected that the values obtained from a detailed study would not differ from these by more than 0.2%. The uncertainties listed in the table are nominal values, sufficiently realistic for the requirements of this paper.

TABLE 5

Distribution of the internal consistency ratio

| No. of degrees of freedom | Probability 50% | 30% | 20% | 10% | 5% | 2% | 1% |
|---|---|---|---|---|---|---|---|
| N | Value of internal consistency ratio, $\chi^2/N$ | | | | | | |
| 8 | 0.918 | 1.191 | 1.375 | 1.670 | 1.938 | 2.271 | 2.511 |
| 9 | 0.927 | 1.184 | 1.360 | 1.632 | 1.880 | 2.187 | 2.407 |
| 18 | 0.963 | 1.145 | 1.264 | 1.444 | 1.604 | 1.797 | 1.934 |

References


1. AILLOUD J., BRETON D., ERTAUD A. & RAIEVSKY V. (1952) J. Phys. Rad. 13, 171.

2. ANSPACH S. C., CAVALLO L. M., GARFINKEL S. B., HUTCHINSON J. M. R. & SMITH C. N. (1965) NP-15663.

3. BARTHOLOMEW R. M., BROWN F., HOWELL W. D., SHOREY W. R. J. & YAFFE L. (1953) Can. J. Phys. 31, 714.

4. BERNSTEIN S., BORST L. B., STEPHENSON T. E. & DIAL J. B. (1952) Phys. Rev. 87, 487.

5. BERRETH J. R. & SCHUMAN R. P. (1962) IDO-16827, 18.

6. BROSI A. & KETELLE B. (1950); cited in NBS Circular 499, Supplement 1.

7. BROSI A. & KETELLE B. (1954) ORNL-1674, 36.

8. BROSI A. & KETELLE B. (1958); private communication cited in Nuclear Data Sheets.

9. BROWNELL G. L. & MALETSKOS C. J. (1950) Phys. Rev. 80, 1102.

10. CANCE M., COMERA J. & HYVER C. (1963), CEN Saclay DPE-SPE 63/503/831, cited by VANINBROUKX (1966).

11. CARRÉ J. C. & VIDAL R. (1966) Proc. IAEA Conference on Nuclear Data for Reactors, at Paris in Oct. 1966, 1, 479 (paper CN-23/74).

12. COLMER F. C. W. & LITTLER D. J. (1950) Proc. Phys. Soc. A63, 1175.

13. DEUTSCH M. & SCHARFF-GOLDHABER G. (1951) Phys. Rev. 83, 1059.

14. DEWORM J. P. (1967) EANDC(E) 76U, 106.

15. EASTWOOD T. A. & WERNER R. D. (1959) CI-207. The author is indebted to Dr. Eastwood for permission to cite this work.

16. EVANS R. D. (1956); private communication to WAY cited in Nuclear Data Sheets.

17. FROSCH R., HUBER P. & WIDDER F. (1964) Helv. Phys. Acta 37, 409.

18. GEIGER K. W. (1957) Phys. Rev. 105, 1539.

19. GORBICS S. G., KUNZ W. E. & NASH A. E.
(1963) Nucleonics 21, No. 1, 63.

20. GRIMELAND B., HELLSTRAND E. & NETTER F.
(1951) Comptes rendus 232, 2089.

21. HARRIS S. P., MUEHLHAUSE C. O., RASMUSSEN S., SCHROEDER H. P. & THOMAS G. E.
(1950) Phys. Rev. 80, 342; see also HARRIS, MUEHLHAUSE & THOMAS (1950) Phys. Rev. 79, 11.

22. HARDWICK J.
(1952) PR-P-14-E.

23. HÜTTEL G. & LIEWERS P.
unpublished work cited by ALEXANDER K. F. (1964) ZFK-RN23.

24. JOWITT D., PATTENDEN S. K., ROSE H., SMALL V. G. & TATTERSALL R. B.
(1958) AERE R/R 2516.

25. KASTNER J. & WHYTE G. N.
(1953) Phys. Rev. 91, 332.

26. KEENE J. P., MACKENZIE L. A. & GILBERT C. W.
(1958) Phys. in Med. Biol. 2, 360.

27. KEISCH B.
(1963) Phys. Rev. 129, 769.

28. LIVINGOOD J. J. & SEABORG G. T.
(1941) Phys. Rev. 60, 913.

29. LOCKETT E. E. & THOMAS R. H.
(1956) Nucleonics 14, No. 11, 127.

30. LOFTUS T. P. & LEE R. M.
(1958); private communication cited in Nuclear Data Sheets.

31. MEADOWS J. M. & WHALEN J. F.
(1961) Nucl. Sci. Eng. 9, 132.

32. MERRITT J. S. & GREEN R. E.
(1968) EANDC (Can) 34, 6.

33. MERRITT J. S. & TAYLOR J. G. V.
(1967) AECL-2780, 34.

34. MOSS N. & YAFFE L.
(1953) Can. J. Chem. 31, 391.

35. PERRY W. E. & DALE J. W.
(1956); private communication cited by LOCKETT & THOMAS (1956).

36. POMERANCE H.
(1951) Phys. Rev. 83, 641.

37. SCHMIDT-OTT W. D.
(1963) Zeits. Phys. 174, 206.

38. SEGRÈ E. & WIEGAND C. E.
(1949) Phys. Rev. 75, 39.

39. SELIGER H. H. & CAVALLO L. M.
(1958); private communication cited in Nuclear Data Sheets.

40. SINCLAIR W. K. & HOLLOWAY A. F.
(1951) Nature 167, 365.

41. de SWINIARSKI R., CZERNY J. & DROULERS V.
(1963), CEN Grenoble Int/Pi-171/135, cited by VANINBROUKX (1966).

42. TAYLOR N. K. & LINACRE J. K.
(1964) AERE - R 4111.

43. TOBAILEM J.
(1950) Comptes rendus 233, 1360;
(1955) J. Phys. Rad. 16, 48.

44. VANINBROUKX R.
(1966) Nucl. Sci. Eng. 24, 87.

45. WOLF G.
(1960) Nukleonik 2, 255.

46. WU C. S., RAINWATER L. J. & HAVENS W. W.
(1947) Phys. Rev. 71, 174.

47. YAFFE L., HAWKINGS R. C., MERRITT W. F. & CRAVEN J. H.
(1951) Phys. Rev. 82, 553.

Available from

HER MAJESTY'S STATIONERY OFFICE

TO BE PURCHASED FROM

49, High Holborn, London W.C.1.
423 Oxford Street, London W.1.
13a Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
258-259 Broad Street, Birmingham 1
7-11 Linenhall Street, Belfast BT2 8AY
or through any bookseller.

Printed in Great Britain

S.O. Code No. 91 - 3 - 22 - 33