Designation: E523 – 21ε1

Standard Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Copper[1]

This standard is issued under the fixed designation E523; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—Fig. 2 was updated editorially in May 2021.

1. Scope

1.1 This test method covers procedures for measuring reaction rates by the activation reaction $^{63}Cu(n,\alpha)^{60}Co$. The cross section for ^{60}Co produced in this reaction increases rapidly with neutrons having energies greater than about 4.5 MeV. ^{60}Co decays with a half-life of 5.2711(8)[2] years (**1**)[3,4] and emits two gamma rays having energies of 1.173228(3) and 1.332492(4) MeV (**1**). The isotopic content of natural copper is 69.174(20) % ^{63}Cu and 30.826(20) % ^{65}Cu (**2**). The neutron reaction, $^{63}Cu(n,\gamma)^{64}Cu$, produces a radioactive product that emits gamma rays [1.34577(6) MeV (E1005)] which might interfere with the counting of the ^{60}Co gamma rays.

1.2 With suitable techniques, fission-neutron fluence rates above 10^9 $cm^{-2}{\cdot}s^{-1}$ can be determined. The $^{63}Cu(n,\alpha)^{60}Co$ reaction can be used to determine fast-neutron fluences for irradiation times up to about 15 years, provided that the analysis methods described in Practice E261 are followed. If dosimeters are analyzed after irradiation periods longer than 15 years, the information inferred about the fluence during irradiation periods more than 15 years before the end of the irradiation should not be relied upon without supporting data from dosimeters withdrawn earlier.

1.3 Detailed procedures for other fast-neutron detectors are referenced in Practice E261.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[5]

E170 Terminology Relating to Radiation Measurements and Dosimetry

E181 Test Methods for Detector Calibration and Analysis of Radionuclides

E261 Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques

E844 Guide for Sensor Set Design and Irradiation for Reactor Surveillance

E944 Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance

E1005 Test Method for Application and Analysis of Radiometric Monitors for Reactor Vessel Surveillance

E1018 Guide for Application of ASTM Evaluated Cross Section Data File

3. Terminology

3.1 *Definitions:*

3.1.1 Refer to Terminology E170.

4. Summary of Test Method

4.1 High-purity copper (<1 ppm cobalt) is irradiated in a neutron field, thereby producing radioactive ^{60}Co from the $^{63}Cu(n,\alpha)^{60}Co$ reaction.

4.2 The gamma rays emitted by the radioactive decay of ^{60}Co are counted in accordance with Test Methods E181 and the reaction rate, as defined by Practice E261, is calculated from the decay rate and irradiation conditions.

[1] This test method is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applicationsand is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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[2] The lightface numbers in parentheses are the magnitude of plus or minus uncertainties in the last digit(s) listed.

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

[4] For dosimetry purposes, a year is defined in accordance with BIPM (**1**) as 365 242 198 days = 31 556 926 s; see Terminology E170.

[5] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

4.3 The neutron fluence rate above about 4.5 MeV can then be calculated from the spectral-weighted neutron activation cross section as defined by Practice E261.

5. Significance and Use

5.1 Refer to Guide E844 for the selection, irradiation, and quality control of neutron dosimeters.

5.2 Refer to Practice E261 for a general discussion of the measurement of fast neutron fluence rate with threshold detectors. The general shape of the $^{63}Cu(n,\alpha)^{60}Co$ cross section is also shown in Fig. 1 **(3, 4, 5)** along with a comparison to the current experimental database **(6)**. This figure is for illustrative purposes only to indicate the range of the response of the $^{63}Cu(n,\alpha)^{60}Co$ reaction. Refer to Guide E1018 for descriptions of recommended tabulated dosimetry cross sections.

NOTE 1—The cross section appropriate for use under this standard is from the IRDFF-II library (**5**) which, up to an incident neutron energy of 20 MeV, is drawn from the RRDF-2002 library (**3**) and is identical to the adopted cross section in the IRDF-2002 library (**4**). See Guide E1018.

5.3 The major advantages of copper for measuring fast-neutron fluence rate are that it has good strength, is easily fabricated, has excellent corrosion resistance, has a melting temperature of 1083°C, and can be obtained in high purity. The half-life of ^{60} Co is long and its decay scheme is simple and well known.

5.4 The disadvantages of copper for measuring fast neutron fluence rate are the high reaction apparent threshold of 4.5 MeV, the possible interference from cobalt impurity (>1 μg/g), the reported possible thermal component of the (n,α) reaction, and the possibly significant cross sections for thermal neutrons for ^{63}Cu and ^{60}Co [that is, 4.50(2) and 2.0(2) barns, respectively], **(7)**, which will require burnout corrections at high fluences.

6. Apparatus

6.1 *NaI(Tl) or High Resolution Gamma-Ray Spectrometer*—Because of its high resolution, the germanium detector is useful when contaminant activities are present or when it is necessary to analyze before the 12.701-h half-life ^{64}Cu has decayed away.

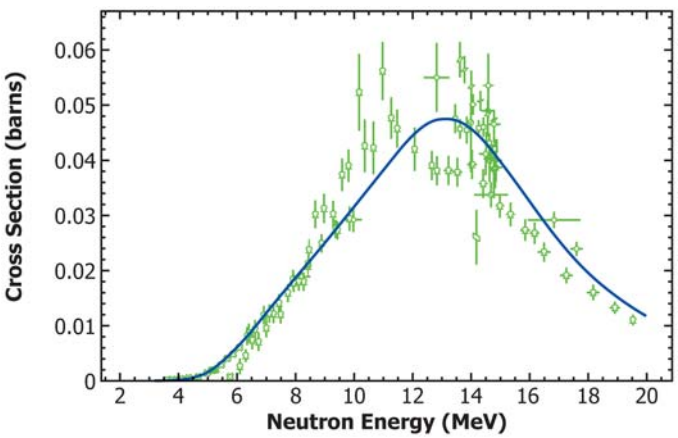

FIG. 1 $^{63}Cu(n,\alpha)^{60}Co$ Cross Section with EXFOR Experimental Data

6.2 *Precision Balance,* able to achieve the required accuracy.

7. Materials

7.1 *Copper Metal*—Pure copper metal in the form of wire or foil is available.

7.1.1 The metal should be tested for impurities by a neutron activation technique. If the measurement is to be made in a thermal-neutron environment, there must be no cobalt impurity (<1 μg/g) because the reaction $^{59}Co(n,\gamma)^{60}Co$ produces the same product as produced in the subject reaction. To reduce this interference, the use of a thermal-neutron shield during irradiation would be advisable if cobalt impurity is suspected.

7.2 *Encapsulating Materials*—Brass, stainless steel, copper, aluminum, quartz, or vanadium have been used as primary encapsulating materials. The container should be constructed in such a manner that it will not create significant flux perturbation and that it may be opened easily, especially if the capsule is to be opened remotely (see Guide E844).

8. Procedure

8.1 Decide on the size and shape of the copper sample to be irradiated, taking into consideration the size and shape of the irradiation space. The mass and exposure time are parameters that can be varied to obtain a desired disintegration rate for a given neutron fluence rate level (see Guide E844).

8.2 Weigh the sample.

8.3 Irradiate the sample for the predetermined time period. Record the power level and any changes in power during the irradiation, the time at the beginning and end of the irradiation, and the relative position of the monitors in the irradiation facility.

8.4 A waiting period of about 6 days is recommended between termination of the exposure and analyzing the sample for ^{60}Co content. This allows the 12.701-h ^{64}Cu **(1)** to decay so that there is no interference from the gamma rays emitted by ^{64}Cu, that is, the 0.511 and 1.34577 MeV gamma rays **(1)**. However, analysis may be performed sooner if a suitable gamma-ray or peak analysis technique is used.

8.5 Check the sample for activity from cross-contamination by other irradiated materials. Clean, if necessary and reweigh.

8.6 Analyze the sample for ^{60}Co content in disintegrations per second using the gamma-ray spectrometer (see Test Methods E181 and E1005).

8.7 Disintegration of ^{60}Co nuclei produces 1.173228 MeV and 1.332492 MeV gamma rays with probabilities per decay of 0.9985(3) and 0.999826(6) respectively. **(1)** When analyzing either peak in the gamma-ray spectrum, a correction for coincidence summing may be required if the sample is placed close to the detector (10 cm or less) (see Test Methods E181).

9. Calculations

9.1 Calculate the saturation activity A_s, as follows:

$$A_s = \frac{A}{(1-e^{-\lambda t_i})\cdot e^{-\lambda t_w}} \quad (1)$$

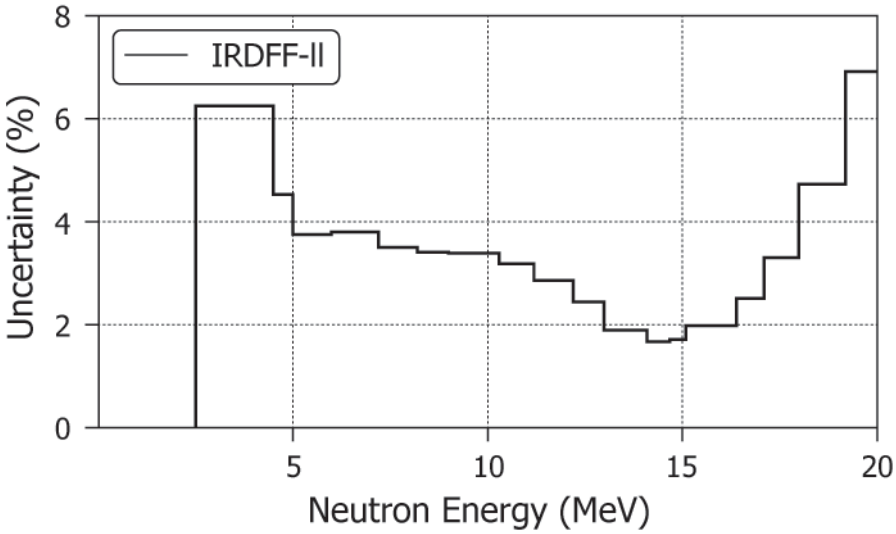

FIG. 2 Energy-dependent Uncertainty (%) for the $^{63}Cu(n,\alpha)^{60}Co$ Cross Section

where:

A = ^{60}Co disintegrations per second measured by counting,

λ = decay constant for $^{60}Co = 4.1670577 \times 10^{-9}$ s^{-1},

t_i = irradiation duration s,

t_w = elapsed time between the end of irradiation and counting, s.

NOTE 2—The equation for A_s is valid if the reactor operated at essentially constant power and if corrections for other reactions (for example, impurities, burnout, etc.) are negligible. Refer to Practice E261 for more generalized treatments.

9.2 Calculate the reaction rate, R_s, as follows:

$$R_s = A_s/N_0 \quad (2)$$

where:

A_s = saturation activity, and

N_0 = number of ^{63}Cu atoms.

9.3 Refer to Practice E261 and Guide E944 for a discussion of fast-neutron fluence rate and fluence.

10. Report

10.1 Practice E261 describes how data should be reported.

11. Precision and Bias

NOTE 3—Measurement uncertainty is described by a precision and bias statement in this standard. Another acceptable approach is to use Type A and B uncertainty components (**8, 9**). This Type A/B uncertainty specification is now used in International Organization for Standardization (ISO) standards and this approach can be expected to play a more prominent role in future uncertainty analyses.

11.1 General practice indicates that disintegration rates can be determined with a bias of ± 3 % (1σ %) and with a precision of ±1 % (1σ %).

11.2 When this measured activity is used in conjunction with a neutron spectrum to determine a neutron fluence, the energy-dependent uncertainty of the spectrum and the cross section are important considerations. The energy-dependent uncertainty, expressed as a percentage, for the $^{63}Cu(n,\alpha)^{60}Co$ cross section is shown in Fig. 2(**3**)

11.3 Test results have been reported in well characterized neutron benchmark fields.

11.3.1 In the ^{252}Cf spontaneous fission reference neutron field, the measured cross section is 0.6887 b ± 1.9 % (**10**) and the calculated cross section using the RRDF-2002 cross section is 0.69248 b with a spectrum integrated cross section uncertainty of 1.399 % (**3**) and a spectrum characterization uncertainty of 1.37 %. This results in a calculated-to-experimental (C/E) ratio of 1.0055 ± 2.73 %.

11.3.2 In the ^{235}U thermal neutron field, the measured cross section is 0.4935 b ± 4.9 % (**11**) and the calculated cross section using the RRDF-2002 cross section is 0.53294 b with a spectrum integrated cross section uncertainty of 1.461 % (**3**) and a spectrum characterization uncertainty of 6.042 %. This results in a calculated-to-experimental (C/E) ratio of 1.08 ± 7.92 %.

12. Keywords

12.1 activation; activation reaction; copper; cross section; dosimetry; fast-neutron monitor; neutron metrology; pressure vessel surveillance; reaction rate; $^{63}Cu(n,\alpha)^{60}Co$