УДК 539.17

REACTIONS OF ISOTOPE ^{60}Co FORMATION AT INTERACTION OF NEUTRONS WITH ^{59}Co, ^{60}Ni AND ^{63}Cu (STATE-OF-THE-ART OF NEUTRON CROSS SECTIONS)

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The state-of-the-art of neuron cross sections of three reactions resulting in formation of an isotope ^{60}Co and commonly used as activation detectors at neutron flux and fluence measurements in wide neutron energy range has been analyzed. The analysis was conducted on the basis of information from the newest versions of the evaluated nuclear data libraries ENDF/B-VI, JEF-2. 2, JENDL-3.2, BROND-2, CENDL-2, international reactor dosimetry file IRDF-90 (version 2) and international library of experimental nuclear data CSISRS. A graphical cross section presentation of the reactions ^{59}Co(n,γ)^{60}Co, ^{60}Ni (n,p)^{60}Co and ^{63}Cu (n,α)^{60}Co in the energy range up to 20 MeV, brief analysis of the available evaluated and experimental data, including results of integral experiments in standard neutron fields, provide condensed, but rather complete information on present day state of the reactions concerned. The up-to-date information on characteristics of ^{60}Co decay and the reactions under consideration is also included.

This work is a part of review of the present-day state of activation reaction neuron cross sections, important for reactor dosimetry which is in preparation now at the sector "Centre of nuclear data ", KINR , National Academy of Sciences of Ukraine. The reactions ^{59}Co (n,γ) ^{60}Co, ^{60}Ni (n,p)^{60}Co and ^{63}Cu (n,α)^{60}Co are included in the specialized 640-group library of nuclear data - international file for reactor dosimetry IRDF-90 (International Reactor Dosimetry File) and are widely used for the definition of neutron fluxes and fluences not only in the field of reactor dosimetry, but in many activation studies as well. The wide utilization of these reactions is stipulated by sufficiently large values of cross sections of isotope ^{60}Co formation in neutron fluxes, and by convenience of gamma-quanta detection, which, as it is possible to see from the Fig.1 [1], are emitted by highly excited states of the ^{60}Ni nucleus, originated during beta decay of ^{60}Co. The gamma - transitions are well separated (even for Na (I) detectors) by energies and have almost absolute yields for both strongest lines:

$$E\gamma = 1173.237 \pm 0.004 \text{ keV}, \; I\gamma = 99.90 \pm 0.02 \%;$$
$$E\gamma = 1332.501 \pm 0.005 \text{ keV}, \; I\gamma = 99.9820 \pm 0.0010 \%.$$

The thermal neutron capture cross section (σ_γ at E_n =0.0253 eV) is equal 37.18 ±*0.06* barn and resonance integral RI is 74± 2 barn [2].

The half-life of ^{60}Co ($T_{1/2}$ = 5.2714 ± 0.0005 years) stipulates also wide utilization of this isotope as a source of gamma-rays in technique and metrology (^{60}Co is always a part of standard reference gamma-ray source set). However, due to long half-life and hard radiation, the ^{60}Co accumulation is a problem number one in the case of NPP decommissioning after one year and more from the moment of the reactor shut-down. Therefore it is necessary to take into account all three channels of ^{60}Co formation: (n, γ) reaction on ^{59}Co, (n, p) reaction on ^{60}Ni , (n, α) reaction on ^{63}Cu. The last reaction is considered as an important source of ^{60}Co accumulation in thermonuclear reactors.

Availability of the last versions of the evaluated nuclear data libraries: ENDF/B-VI, JEF-2, JENDL-3.2, BROND-2, CENDL-2, the international reactor dosimetry file IRDF-90 (version 2), the international library of experimental data CSISRS (Cross Section Information Storage and Retrieval System), computer programs for cross section calculations on the basis of the evaluated nuclear data libraries PRE-PRO and program ZVVIEW for graphical representation of

the whole data (V.V.Zerkin) enables to submit brief, but complete information on state-of-the-art of this or that reaction.

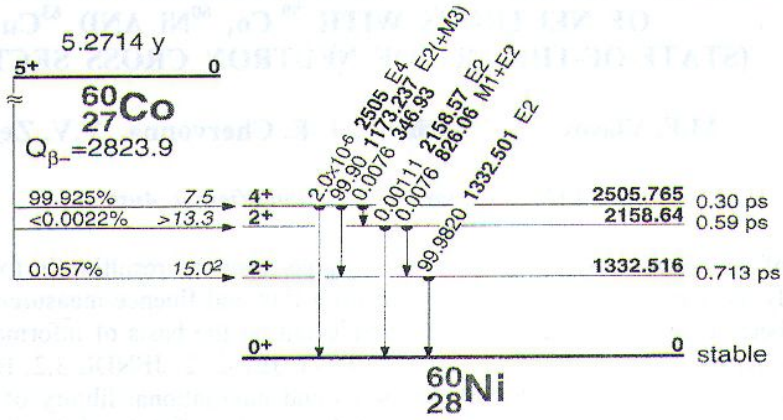

Fig. 1.

Let's consider in more details each of these reactions.

^{59}Co (n, γ) ^{60}Co. The ^{59}Co(n ,γ)^{60}Co reaction has energy dependence of ordinary $\sqrt{E}$ type with a strong s-resonance in the range of 101-167 eV (E_0 = 132.5±0.5eV) and sufficiently large cross section in the thermal point (En = 0.0253 eV) σ_{th} = 37.18 ± 0.06 b. As it can be seen from Figs. 2a and 2b, all four libraries of evaluated nuclear data: ENDF/B-VI, JEF-2, JENDL-3.2, CENDL-2 and international reactor dosimetry file IRDF-90 reasonably well describe experimental values of cross sections in the energy range from 10^{-5} eV up to 1 MeV with the exception perhaps of experimental data in the range 0.17 - 2.5 MeV, obtained by Johnsrud 59 (1959, further only two last digits are given). In the range from 1 MeV up to 20 MeV the best description of experimental data gives, in our opinion, JENDL-3.2. The sudden change in cross section near 8 MeV proposed in IRDF-90, is not observed experimentally. It is necessary however to note, that experimental data in this energy range are scarce. The reaction is often used as a detector for thermal neutron fluence measurements. It can be also used as a resonance detector since the cross section in the range from 10 eV up to 1 MeV is still sufficiently large, decreasing from 1 barn up to 10 mb, being increased in the resonances on 2 - 3 orders. In this case, however, it is necessary to define precisely a measured range of neutron energies.

^{60}Ni (n, p) ^{60}Co. The reaction is exoergic (Q = -2. 042000 MeV [4]) with threshold energy E_{thr} = 2.076 MeV.

Nickel is a component of structural materials (stainless steel) of thermal, fast and thermonuclear reactors. The reaction is used for fast neutron fluence definition and is a part of the international reactor dosimetry file.

The up-to-date state of the excitation function is presented in Fig. 3a. The evaluated data are from four libraries (ENDF/B-VI, JEF-2, JENDL-3. 2, BROND-2) and international reactor dosimetry file IRDF-90, experimental data are from CSISRS system. Three libraries (ENDF/B-VI, JEF-2, IRDF-90) contain the identical information, based on Larson 89 evaluation, in which Vonach 89 (up to 12 MeV), Greenwood 87 (14.5 - 15 MeV) and Paulsen 67 (15 - 20 MeV) experimental data were taken into account. The evaluations of BROND-2 and JENDL-3.2 libraries give considerably higher values of cross section from threshold of the reaction up to 12 MeV, following in this range to the Paulsen 67 experimental data and without other more recent results consideration.

The result of cross section measurements in the neutron field of californium – 252, conducted by Mannhart 82 [3], $\langle\sigma\rangle_{Cf252}$ = 2.39 ± 0.39 mb, is well agreed with calculation of this quantity on the ENDF/B-VI base [4]. Calculations of $\langle\sigma\rangle_{Cf252}$ on the ENDF/B-V base [5], where

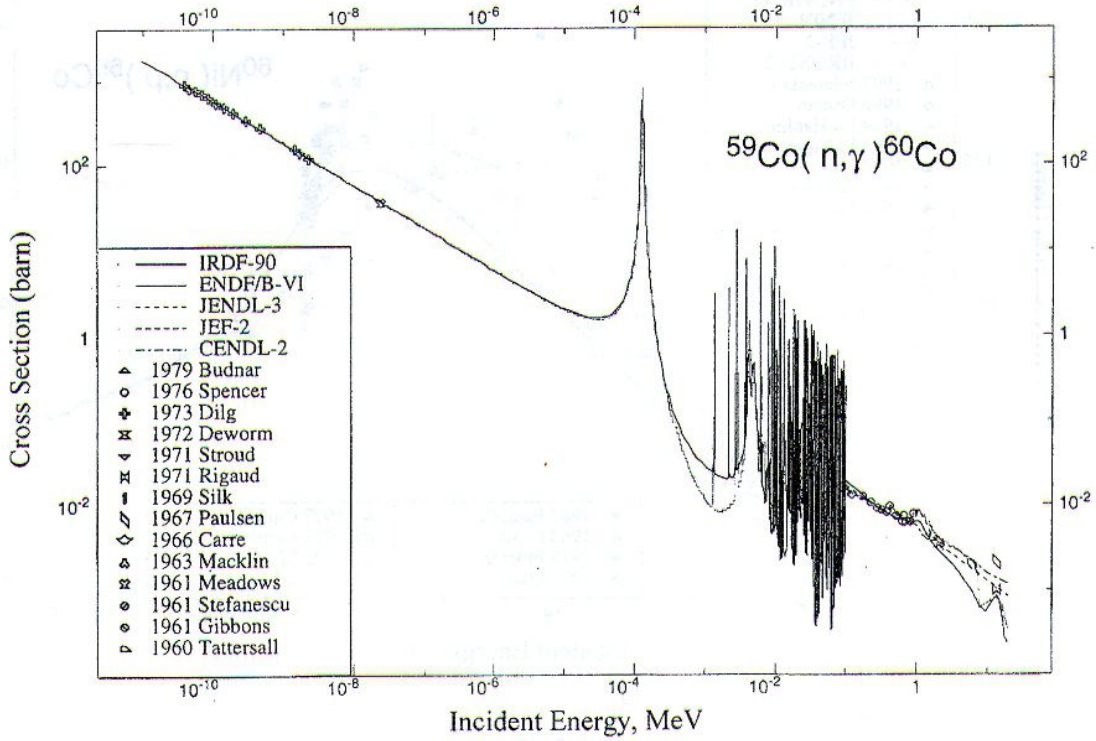
^{59}Co(n,γ)^{60}Co
IRDF-90
ENDF/B-VI
JENDL-3
JEF-2
CENDL-2
1979 Budnar
1976 Spencer
1973 Dilg
1972 Deworm
1971 Stroud
1971 Rigaud
1969 Silk
1967 Paulsen
1966 Carre
1963 Macklin
1961 Meadows
1961 Stefanescu
1961 Gibbons
1960 Tattersall
Cross Section (barn)
Incident Energy, MeV

Fig. 2a.

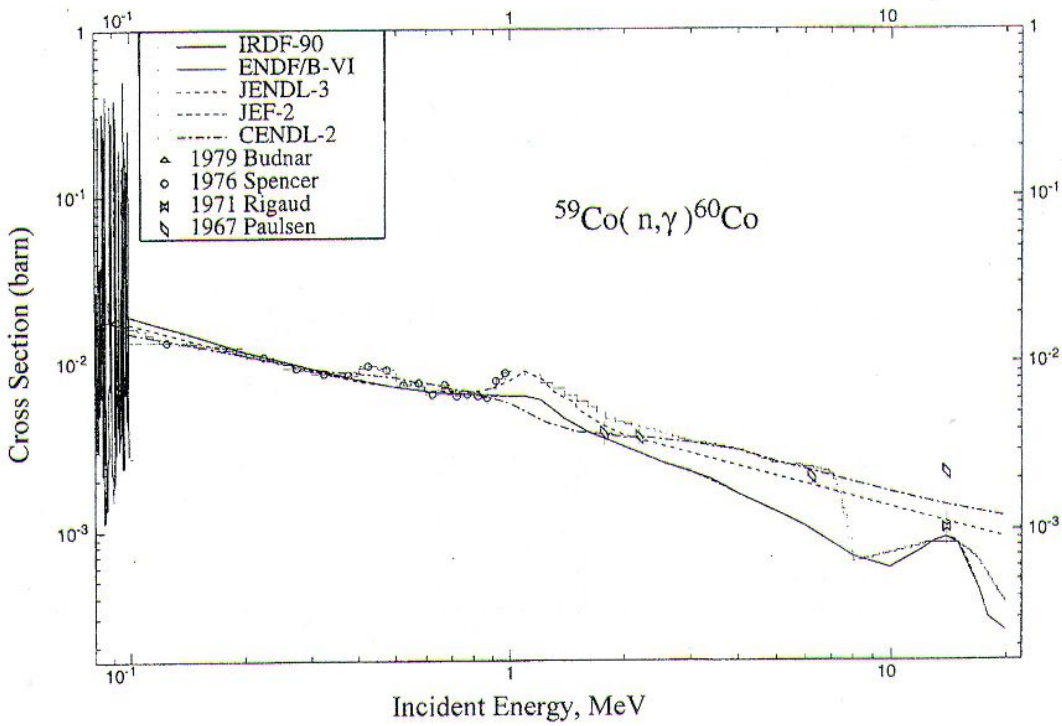
^{59}Co(n,γ)^{60}Co
IRDF-90
ENDF/B-VI
JENDL-3
JEF-2
CENDL-2
1979 Budnar
1976 Spencer
1971 Rigaud
1967 Paulsen
Cross Section (barn)
Incident Energy, MeV

Fig. 2b.

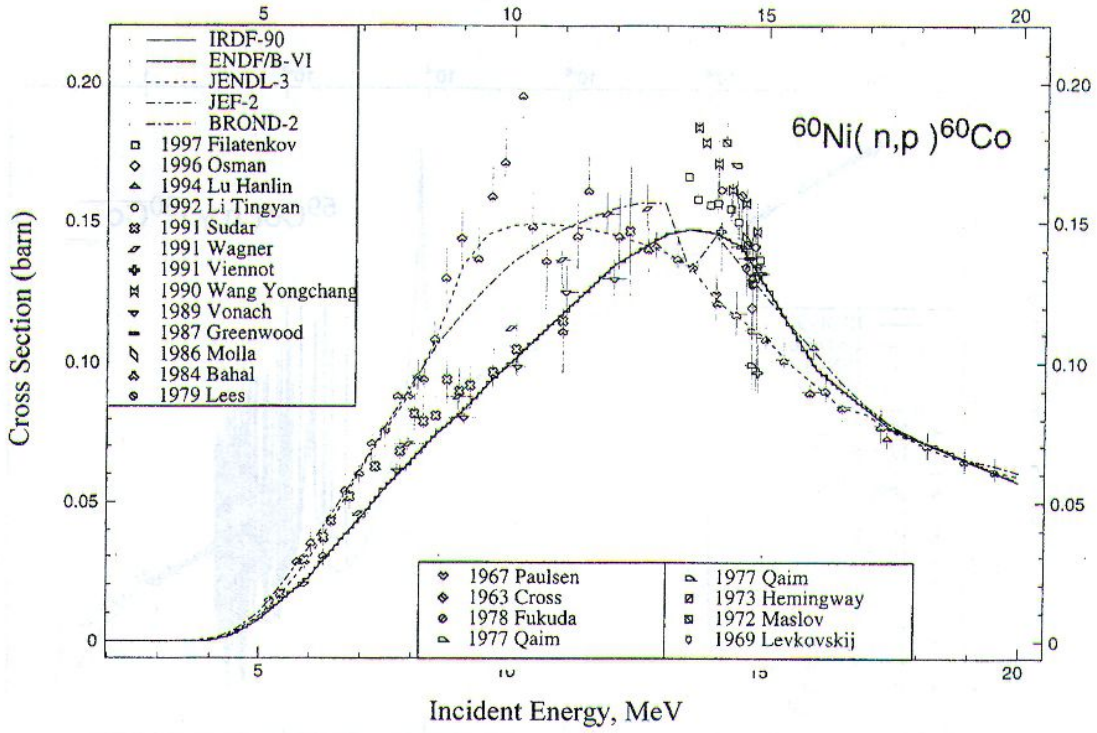
IRDF-90
ENDF/B-VI
JENDL-3
JEF-2
BROND-2
1997 Filatenkov
1996 Osman
1994 Lu Hanlin
1992 Li Tingyan
1991 Sudar
1991 Wagner
1991 Viennot
1990 Wang Yongchang
1989 Vonach
1987 Greenwood
1986 Molla
1984 Bahal
1979 Lees
1967 Paulsen
1963 Cross
1978 Fukuda
1977 Qaim
1977 Qaim
1973 Hemingway
1972 Maslov
1969 Levkovskij
60Ni(n,p)60Co
Cross Section (barn)
Incident Energy, MeV

Fig. 3a

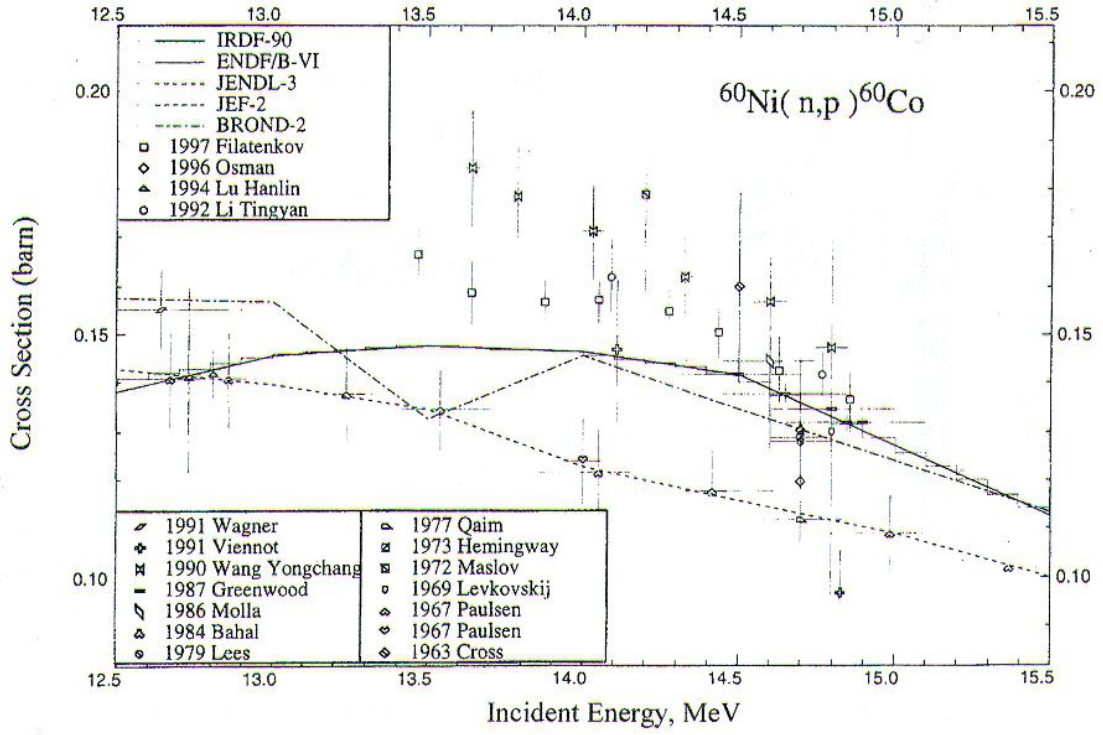
IRDF-90
ENDF/B-VI
JENDL-3
JEF-2
BROND-2
1997 Filatenkov
1996 Osman
1994 Lu Hanlin
1992 Li Tingyan
1991 Wagner
1991 Viennot
1990 Wang Yongchang
1987 Greenwood
1986 Molla
1984 Bahal
1979 Lees
1977 Qaim
1973 Hemingway
1972 Maslov
1969 Levkovskij
1967 Paulsen
1967 Paulsen
1963 Cross
60Ni(n,p)60Co
Cross Section (barn)
Incident Energy, MeV

Fig. 3b

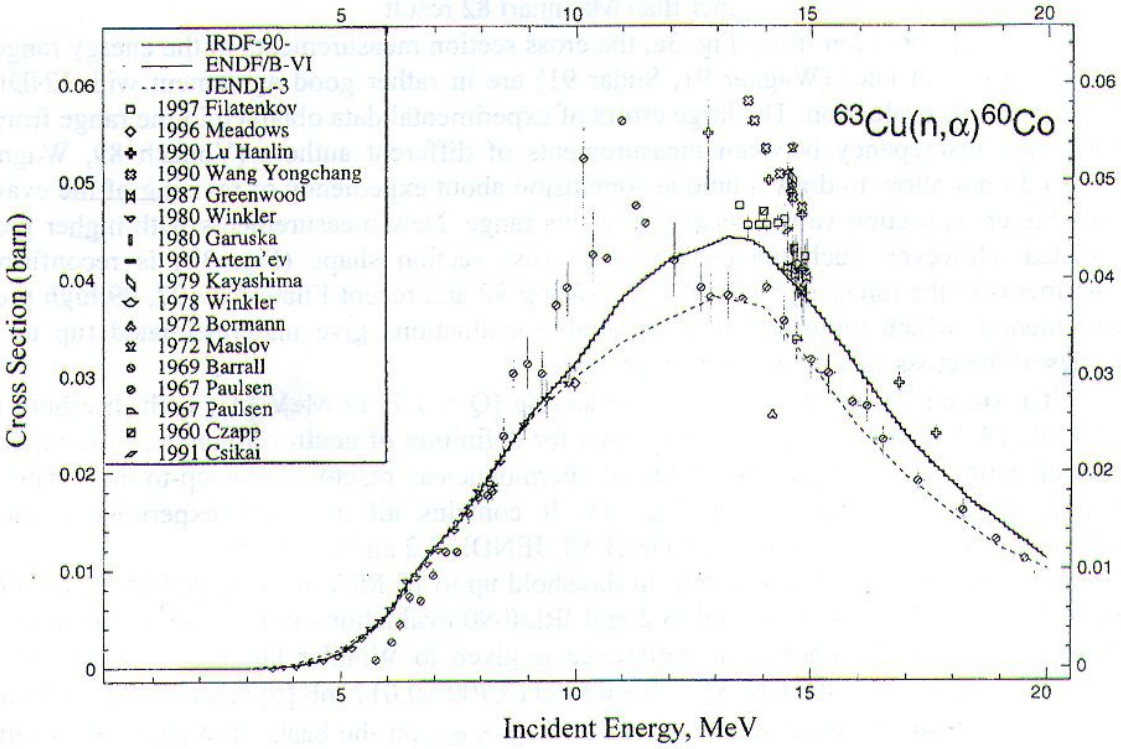
IRDF-90-
ENDF/B-VI
JENDL-3
1997 Filatenkov
1996 Meadows
1990 Lu Hanlin
1990 Wang Yongchang
1987 Greenwood
1980 Winkler
1980 Garuska
1980 Artem'ev
1979 Kayashima
1978 Winkler
1972 Bormann
1972 Maslov
1969 Barrall
1967 Paulsen
1967 Paulsen
1960 Czapp
1991 Csikai
^{63}Cu(n,α)^{60}Co
Cross Section (barn)
Incident Energy, MeV

Fig. 4a.

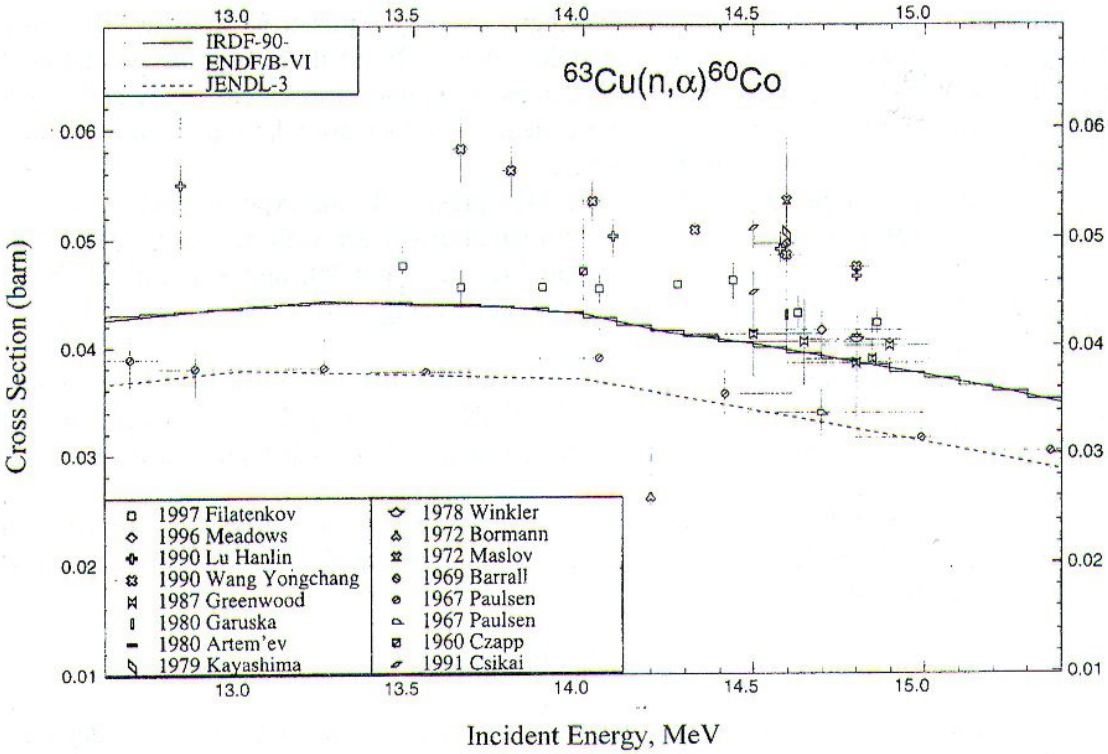
IRDF-90-
ENDF/B-VI
JENDL-3
^{63}Cu(n,α)^{60}Co
1997 Filatenkov
1996 Meadows
1990 Lu Hanlin
1990 Wang Yongchang
1987 Greenwood
1980 Garuska
1980 Artem'ev
1979 Kayashima
1978 Winkler
1972 Bormann
1972 Maslov
1969 Barrall
1967 Paulsen
1967 Paulsen
1960 Czapp
1991 Csikai
Cross Section (barn)
Incident Energy, MeV

Fig. 4b.

(as well as in BROND-2 and JENDL-3.2) Paulsen 67 experimental data were accepted, give averaged cross section on 44 % higher than Mannhart 82 result.

As it can be seen from Fig. 3a, the cross section measurements in the energy range up to 10 MeV carried out later (Wagner 91, Sudar 91) are in rather good agreement with ENDF/B-VI (IRDF-90, JEF-2) evaluation. The large errors of experimental data obtained in the range from 10 to 13 MeV and discrepancy between measurements of different authors (Vonach 89, Wagner 91, Sudar 91) do not allow to draw a unique conclusion about expediency of revising of the evaluation towards the cross section value increasing in this range. New measurements with higher precision are needed. However, such tendency in the cross section shape (Fig. 3b) is reconfirmed by measurements in the range 13,5 - 14.8 MeV (Wang 90 and recent Filatenkov 97, 99 high precision measurements), which indicate that all available evaluations give underestimated (up to 20 %) quantities of the cross section in this energy range.

^{63}Cu (n, α) ^{60}Co. The reaction is endoergic (Q = 1.7149 MeV [4]) with threshold energy E_{thr} = 1.742 MeV. The reaction is widely used for definition of neutron fluences. It is important in connection with the ecological problems of thermonuclear reactors. The up-to-date state of the excitation function is presented in Fig. 4a. It contains all available experimental data and evaluations, given in three libraries: ENDF/B-VI, JENDL-3.2 and IRDF-90.

The experimental information from threshold up to 10 MeV is presented by Paulsen 67 and Winkler 80. The ENDF/B-VI, JENDL-3.2 and IRDF-90 evaluations in this energy range are based on the results of these authors, but preference is given to Winkler 80 data as more recent and detailed. Measurements in the Cf-252 neutron field (0.709 ±0.017 mb [6] and 0.671 ±0. 018 mb [7]) are also in favour of the last data: calculations of $\langle\sigma\rangle_{Cf252}$ on the basis of Winkler 80 results give 0.6761 mb, whereas on the basis of Paulsen 67 it is 0. 7577mb [8]. However, the knowledge of the cross section near threshold is particularly important due to the fact that up to 95 % of the reaction response in reactor fission neutron spectrum is from the energy range 3.5-4 MeV above threshold. Therefore, in our opinion, there is a necessity of new measurements.

In the range between 10 and 13 MeV there are only Paulsen 67 and Lu 90 measurements with large errors. Due to scattering of data points it is difficult do define the excitation function shape. The ENDF/B-VI evaluated data may be considered underestimated, whereas the JENDL 3.2 evaluation higher 10 MeV can not be recommended, for it does not take into account a state of data in the field of 13 - 15 MeV and at higher energies.

In the energy range 13 - 15 MeV (Fig. 4b) practically all experimental results lay above evaluated curves. The Filatenkov 97 results with small errors are well agreed with results of other high-precision experiments, but lay below than Lu 90, Wang 90, and Kayashima 79 data. The evaluated ENDF/B-VI data in this interval are on average 10 - 15 % lower than available experimental data.

Above 15 MeV there are Paulsen 67 and Lu 90 data, and the last ones are considerably (approximately 25 %) higher. The ENDF/B-VI (IRDF-90) library takes into account both these experimental data sets, going equidistantly between them, whereas JENDL 3.2 is oriented only on Paulsen 67 data.

The present-day state of the reaction cross section data denote necessity of new measurements near threshold, in the range of 10 - 13 MeV, where data are practically missing, and higher 15 MeV, where they are discrepant.

REFERENCES

1. *Firestone R.B., Shirley V. S., Frank Chu S.Y. et al.* // Table of Isotopes, CD edition, JWiley Interscience, March 1996.
2. *Robert R. Kinse.* The NuDat Program for Nuclear Data on the Web, Version 2.5, NNDC BNL, 1996.
3. *Mannhart W.* // Proceed. 4th ASTM-EURATOM Symposium on Reactor Dosimetry, Gaithersburg, USA, 1982. - Vol. 2. - P. 637.
4. *Hetrick D.M., Fu C.Y., Larson N.M.* ORNL evaluation, ENDF/B-VI // ORNL/TM-7341, 1989.

5. *Cullen D.E., Kocherov N.P., McLaughlin P.M.* Comparison of Experimental and Calculated Spectrum Averaged Neutron Cross Sections for the IAEA International Reactor Dosimetry File (IRDF-82) // Nucl. Sc. Eng. - 1983 - Vol. 83. - P. 497.
6. *Winkler V., Spiegel V., Eisenhauer C.M., Smith D.L.* // Nucl. Sc. Eng. - 1980. - Vol. 76. - P. 630.
7. *Mannhart W.* Nuclear Data for Science and Technology // Proceed. Int. Conf., Antwerp. 1982, D. Reidel Publ.Comp. - Dordrecht, Holland. - 1983. - P. 429.
8. *Mannhart W.* Californium-252 Spectrum Averaged Neutron Cross Sections // Handbook on Nuclear Activation, IAEA. - 1987. - P. 413.

РЕАКЦІЇ УТВОРЕННЯ ІЗОТОПУ ^{60}Co ПРИ ВЗАЄМОДІЇ НЕЙТРОНІВ З ^{59}Co, ^{60}Ni І ^{63}Cu (СУЧАСНИЙ СТАН НЕЙТРОННИХ ПЕРЕРІЗІВ)

М.Ф. Власов, О.О. Грицай, Л.Є. Червонна, В.В. Зеркін

Проаналізовано сучасний стан нейтронних перерізів трьох реакцій, що призводять до утворення ізотопу ^{60}Co і широко використовуються як активаційні детектори для визначення нейтронних потоків і флюенсів. Аналіз проводився на основі інформації з новітніх версій бібліотек оцінених ядерних даних ENDF/B-VI, JEF-2, JENDL-3.2, BROND-2, CENDL-2, міжнародного файла для реакторної дозиметрії IRDF-90, версія 2, і міжнародної бібліотеки експериментальних ядерних даних CSISRS. Графічне представлення перерізів реакцій ^{59}Co(n,γ)^{60}Co, ^{60}Ni(n,p)^{60}Co, ^{63}Cu(n,α)^{60}Co в інтервалі енергій до 20 МеВ, короткий аналіз наявних оцінених і експериментальних даних, включаючи результати інтегральних експериментів у стандартних нейтронних полях, дають стислу, але досить повну картину сучасного їх стану. Подано сучасну інформацію з характеристик розпаду ^{60}Co та розглянутих реакцій.

РЕАКЦИИ ОБРАЗОВАНИЯ ИЗОТОПА ^{60}Co ПРИ ВЗАИМОДЕЙСТВИИ НЕЙТРОНОВ С ^{59}Co, ^{60}Ni И ^{63}Cu (СОВРЕМЕННОЕ СОСТОЯНИЕ НЕЙТРОННЫХ СЕЧЕНИЙ)

М.Ф. Власов, Е.А. Грицай, Л.Е. Червонная, В.В. Зеркин

Проанализировано современное состояние нейтронных сечений трех реакций, приводящих к образованию изотопа ^{60}Co и широко использующихся в качестве активационных детекторов при определении нейтронных потоков и флюенсов. Анализ проводился на основе информации из новейших версий библиотек оцененных ядерных данных ENDF/B-VI, JEF-2, JENDL-3.2, BROND-2, CENDL-2, международного файла для реакторной дозиметрии IRDF-90, версия 2, и международной библиотеки экспериментальных ядерных данных CSISRS. Графическое представление сечений реакций ^{59}Co(n,γ)^{60}Co, ^{60}Ni(n,p)^{60}Co, ^{63}Cu(n,α)^{60}Co в области энергий до 20 МэВ, краткий анализ имеющихся оцененных и экспериментальных данных, включая результаты интегральных экспериментов в стандартных нейтронных полях, дают сжатую, но достаточно полную картину современного их состояния. Дана современная информация по характеристикам распада ^{60}Co и рассматриваемым реакциям.