Evaluation of Neutron Nuclear Data on Cobalt-59 for JENDL-5

Nobuyuki Iwamoto
Nuclear Data Center, Nuclear Science and Engineering Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
e-mail: iwamoto.nobuyuki@jaea.go.jp

The neutron nuclear data of ^{59}Co were evaluated in the energy region of 10^{-5} eV to 20 MeV for the development of JENDL-5. The resonance parameters and total cross sections were taken from the measurement by de Saussure et al. in the resolved and unresolved resonance regions, respectively. The thermal capture cross section was evaluated using available measured data. The present data were consistent with the values in major evaluated libraries. In the fast neutron energy region the evaluation was made with various types of measured data by the nuclear reaction calculation code CCONE. It is found that the present results well reproduce the measured data.

1 Introduction

Cobalt is a monoisotope element, and the stable isotope is ^{59}Co. Cobalt is one of the important structural materials and is contained in carbon steel and concrete as well as SUS304. Therefore, the accurate nuclear data of ^{59}Co are requisite for analyses in nuclear and accelerator facilities; specifically radioactivity estimation of ^{59}Fe (half-life 44.5 d), ^{58}Co (70.9 d) and ^{60}Co (5.27 y) related to decommissioning of the facilities.

The nuclear data of ^{59}Co [1] in the general purpose library JENDL-4.0 are based on the evaluation in 1988. Since the early evaluation, a partial revision was made at the JENDL-3.3 evaluation in 2001 [2]. After the release of JENDL-3.3, many measurements have been done for, e.g., capture, $(n, 2n)$, (n, p), and (n, α) reactions. Therefore, the reconsideration of nuclear data is required for the development of JENDL-5.

2 Evaluation methods and results

The evaluation of ^{59}Co was divided into three energy regions: resolved resonance region, unresolved resonance region and fast neutron energy region. Evaluation details and obtained results will be explained below.

2.1 Resolved resonance region

The resonance parameters and scattering radius were taken from the data of de Saussure et al. [3], who made the detailed analysis of resonance parameters, using neutron transmission data with different sample thicknesses measured at ORNL. Figures 1 and 2 illustrate the present total cross sections and the data of JENDL-4.0, together with the measured data with sample thicknesses of 0.021, 0.075 and 0.301 atoms/barn in the energy range of 10^{-5} eV to 100 keV.

The capture cross sections calculated by the resonance parameters were compared with the data of Spencer & Macklin [4] in Figures 3 and 4. JENDL-4.0 has more resonances than the present result. They come from the resonance data [4, 5, 6], in which Spencer & Macklin [4] provided only capture kernel data for many resonances. The capture kernel data might be useful, if average values of radiation widths, for example, were assumed. Nevertheless, the use of their data was finally rejected because reasonable values of neutron width were not obtained for many resonances, assuming the average radiation width of 0.36 eV for p-wave resonances [3].

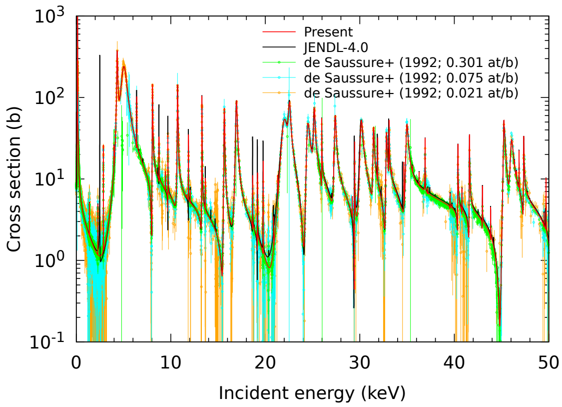


Figure 1: Comparison of the present total cross section with measured data, together with JENDL-4.0, in the energy region of 10^{-5} eV to 50 keV.

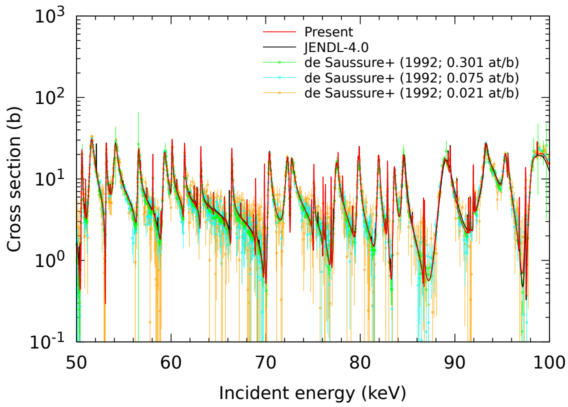


Figure 2: Same as Figure 1, but in the energy region of 50 to 100 keV.

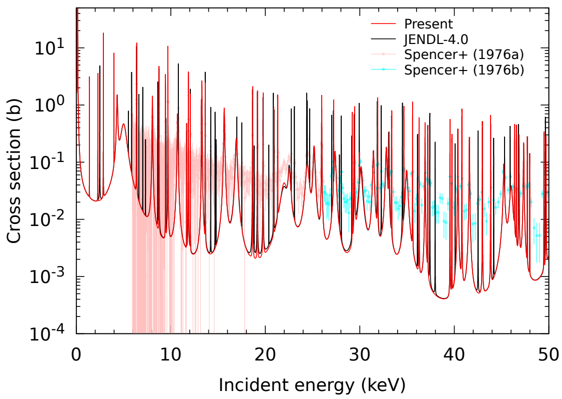


Figure 3: Comparison of the present capture cross section with measured data, together with JENDL-4.0, in the energy region of 10^{-5} eV to 50 keV.

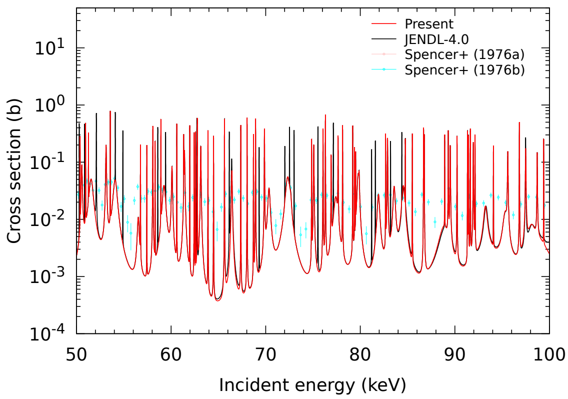


Figure 4: Same as Figure 3, but in the energy region of 50 to 100 keV.

Thermal capture cross section was evaluated with measured data. Most of the measurements was made, based on the absorption cross section of natural boron, and capture cross section of gold as a monitor cross section. In the present evaluation, the two monitor cross section values adapted in the published data were corrected with the IAEA Neutron Data Standards [7]. In addition, uncertainty estimation was made by the method in the report [8]. The obtained result of capture cross section was 37.31(21) b. This value is almost consistent with the data of JENDL-4.0 (37.20(524) b), ENDF/B-VIII.0 (37.17 b) [9] and JEFF-3.3 (37.17 b) [10] as shown in Figure 5. The neutron and radiation widths of negative resonance at −226 eV were revised to reproduce the present value.

2.2 Unresolved resonance region

Resonances are hard to be resolved one by one due to physical nature of resonances and/or experimental conditions as an incident energy increases. This region is called as unresolved resonance region, where cross sections fluctuate and are not smooth, in general. To keep these shapes is important for shielding calculations in nuclear and accelerator facilities. In the present evaluation, the data of thick sample (0.301 atoms/barn) of de Saussure et al. [3] were adopted

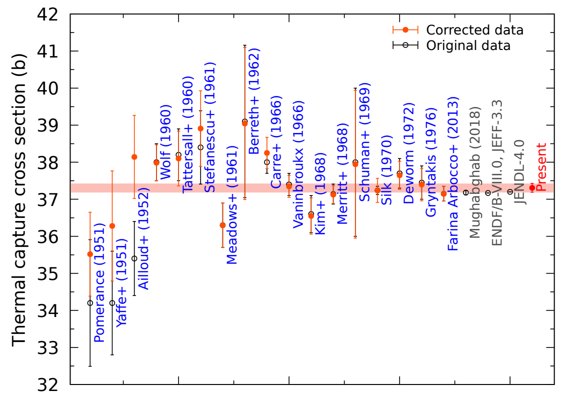


Figure 5: Comparison of capture cross section at thermal energy with measured data, together with evaluated data. The black open circles indicate the original values by the authors; the orange filled circles stand for the values corrected with the latest standard cross sections.

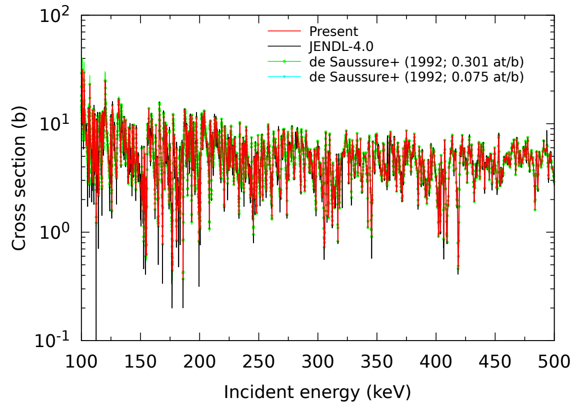


Figure 6: Comparison of total cross section with measured data, together with JENDL-4.0, in the energy region of 100 to 500 keV.

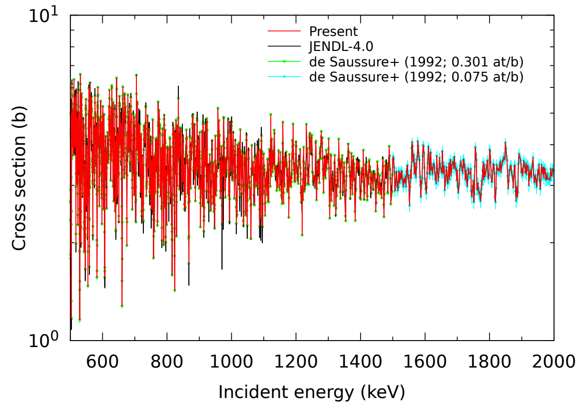


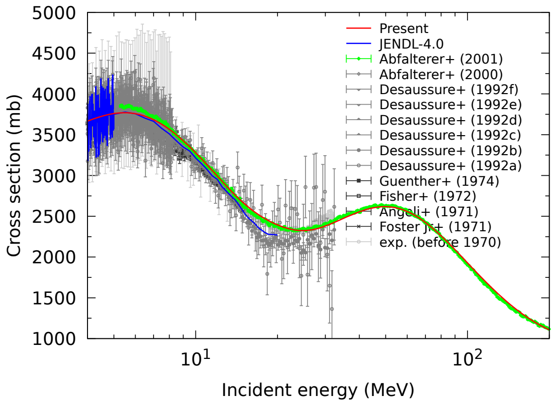
Figure 7: Same as Figure 6, but in the energy region of 500 to 2000 keV.

from 100 keV to 1.5 MeV, above which the data of thin sample (0.075 atoms/barn) were taken up to 5 MeV. The direct use of measured data have disadvantages because experimental effects of multiple-scattering and resolution function are not corrected. Nevertheless, the measured data were adopted without any changes, since we do not have proper ways to derive perfect cross sections in this region. The same choices were made in the past JENDL evaluation. The present result is thus similar to JENDL-4.0 as shown in Figures 6 and 7. The difference can be seen as deep valley of the resonances in JENDL-4.0. This might be due to improper interpolation of measured data.

2.3 Fast neutron energy region

In the fast neutron energy region, neutron cross sections were calculated by using the nuclear reaction calculation code CCONE [11], which composes of the coupled channels optical model code CCOM and the Hauser-Feshbach statistical model code CCSM.

The CCOM code was used to calculate neutron transmission coefficients of ^{59}Co. The optical model potential was taken from a functional form of Kunieda et al. [12]. The coupled levels were ground state (J^{π}=7/2$^-$) and two excited levels (E_x, J^{π})=(1.19, 9/2$^-$) and (1.46, 11/2$^-$), where J^{π} is the spin-parity and E_x is the excitation energy in MeV. The potential parameters were modified to reproduce the total cross section and elastic scattering angular distributions. In the use of total cross sections, the data of Abfalterer et al. [13] were taken into account up to 200 MeV, up to which the nuclear data will also be included in JENDL-5 with the form of the production cross sections of residual nuclides.



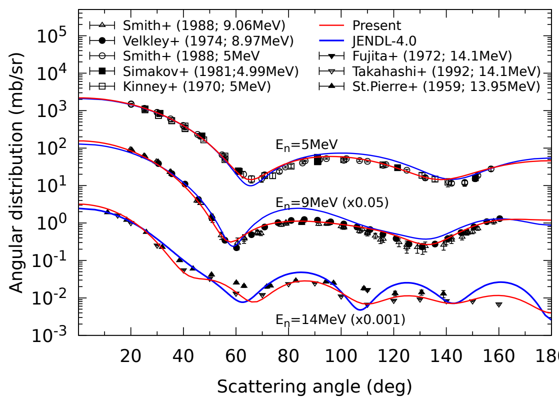
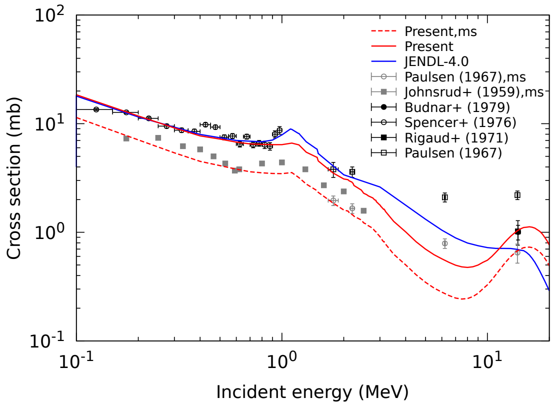


Figure 8: Comparison of the present total cross section with measured data, together with JENDL-4.0.

Figure 9: Comparison of the present elastic scattering angular distribution with measured data, together with JENDL-4.0.



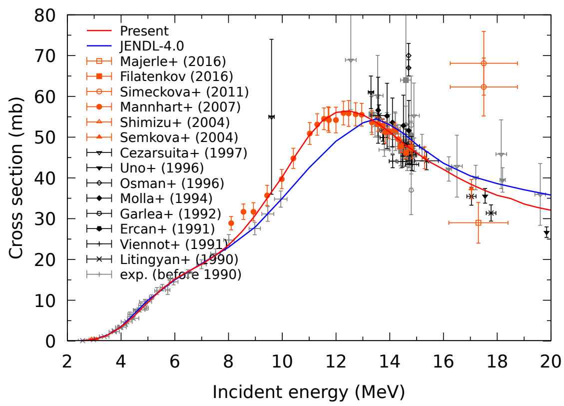
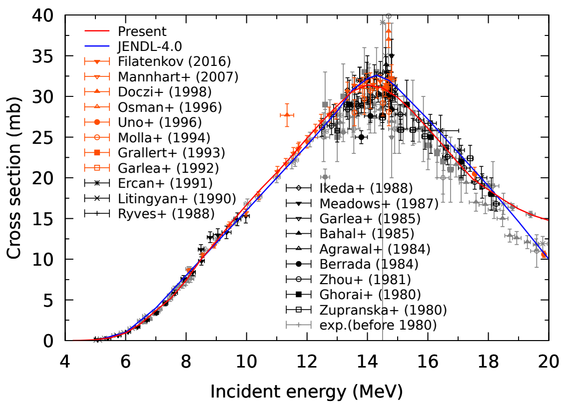


Figure 10: Comparison of the present capture cross section with measured data, together with JENDL-4.0. The evaluated production cross section of meta state of ^{60}Co is added.

Figure 11: Comparison of the present (n,p) reaction cross section with measured data, together with JENDL-4.0.



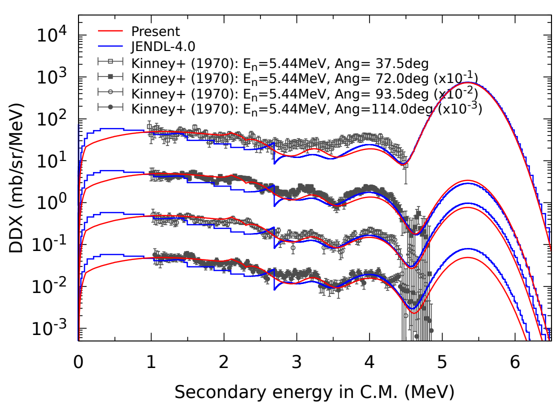


Figure 12: Comparison of the present (n,α) reaction cross section with measured data, together with JENDL-4.0.

Figure 13: Comparison of the present neutron emission double differential cross section with measured data, together with JENDL-4.0.

The CCSM code is employed to calculate the compound, pre-equilibrium and direct processes in nuclear reaction. The pre-equilibrium and direct processes were considered by two-component exciton and DWBA models, respectively. The contribution from the direct process to inelastic scattering cross sections was determined to reproduce corresponding measured data.

Figure 8 shows the present total cross sections compared with measured data, together with JENDL-4.0 given by averaged values of de Saussure et al. [3] and Cierjacks [14]. The data of JENDL-4.0 has cross sections smaller than the present results above 6 MeV. The calculated total cross sections were illustrated below 5 MeV, for checking the reproducibility of the measured cross sections by the optical model. Figure 9 shows the angular distributions of neutron elastic scattering at incident energies of 5, 9 and 14 MeV, where the contribution of compound elastic scattering has negligible. The present data were in good agreement with measured data. It is found that JENDL-4.0 has larger cross sections at the scattering angles between 60 and 180 degrees, compared to the measured data.

The present capture cross sections are compared with measured data and JENDL-4.0 in Figure 10. The result was obtained to reproduce the data of Spencer & Macklin [4] below 1 MeV. The adjustment of direct/semi-direct capture contribution was done to reproduce the data of Rigaud et al. [15] and Budnar et al. [16]. The evaluated production cross section for meta state ($E_x = 58.59$ keV) of ^{60}Co populated by capture reaction was also shown in Figure 10 and will be included in JENDL-5. The gamma-ray strength function (in unit of 10^{-4}) of s-wave resonances in the present evaluation is 2.53, which is small in comparison with 3.88(35) [17] and 3.83 [3]. This fact might indicate that the radiation width (or resonance spacing) is smaller (or larger) than that ever known in resonance analyses.

The present (n, p) reaction cross sections are illustrated in Figure 11. The result is different from the data of JENDL-4.0 above 8 MeV, especially, in the energy range between 8 and 14 MeV, due to incorporation of new data measured by activation method [18].

Figure 12 represents the comparison of the present (n, α) reaction cross sections with the several measurements and JENDL-4.0. The present evaluation followed the data of Mannhart et al. [18] and Filatenkov [19] between 8 and 15 MeV, supplemented with the data published after 1980 above and below the energy region. JENDL-4.0 has a little bit higher cross sections than the present result above 13 MeV.

The comparisons of the present data with the data of Kinney et al. [20] were made for double differential cross sections of secondary neutrons at incident energy of 5.44 MeV and emission angles of 37.5, 72, 93.5 and 114 deg. in Figure 13. These secondary neutrons come from inelastic and elastic scattering. A discrepancy is evident when the present data below 1 MeV are compared to JENDL-4.0 in Figure 13. The small contribution of low energy neutrons in the present evaluation may be attributed to low level density, characteristic of structural materials.

3 Summary

The evaluation of neutron induced reaction data of ^{59}Co was made in the energy range of 10^{-5} eV to 20 MeV. The evaluation was separately done in the three energy regions: resolved and unresolved resonance regions and fast neutron energy region. For the resolved and unresolved resonance regions the data derived by de Saussure et al. were adopted without including extra resonances appeared in JENDL-4.0. The thermal capture cross section was evaluated using available cross section data, which were corrected, based on the latest standard cross sections. The obtained value reasonably matches the data of ENDF/B-VIII.0 and JEFF-3.3. In the fast neutron energy region, the evaluations were performed for various types of nuclear data by using the nuclear reaction calculation code CCONE. The potential parameters of the optical model were fixed with the measured total cross sections up to 200 MeV and elastic scattering angular distribution. The evaluated results show good agreement with the measured data. These data will be compiled into the next general purpose library JENDL-5.

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