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GAMMA-RAY PRODUCTION CROSS SECTIONS OF SOME STRUCTURAL AND SHIELDING MATERIALS

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Abstract: Gamma-ray production cross sections have been measured for structural and shielding materials such as Al, Si, Fe, Pb and Bi at a neutron incident energy of 7.8 MeV. Neutrons were produced by the $^2H(d,n)^3He$ reaction at the JAERI Tandem Accelerator. Emitted gamma-rays were measured with a 7.6 cm diameter x 15 cm long NaI(Tl) detector surrounded by an 25.4 cm diameter x 25.4 cm long annular NaI(Tl) detector. The time-of-flight technique was used to eliminate the background caused by the scattered neutrons. In addition to corrections for neutron multiple scattering and gamma-ray self-shielding, special attention was paid to make an accurate correction for gamma-rays emitted due to Compton scattering in the samples. This effect appears to increase the observed low energy parts of the gamma-ray spectra by as much as 40 % in our samples. The measured results were compared with existing data and with the new evaluated data JENDL-3T based on the multi-step Hauser Feshbach calculation.

(Gamma-Rays production cross sections, Al, Si, Fe, Pb, Bi, En = 7.8 MeV, Tandem, NaI, Anti-Compton detector, Unfolding)

Introduction

Gamma-ray production cross sections are necessary to calculate the radiation shielding and the gamma-ray heating both for fission and fusion reactors. Experimental data measured using monoenergetic neutron sources are scarce especially in the energy range between 5 to 14 MeV, where adequate neutron sources have not been available. In most of the previous experiments with monoenergetic sources, only discrete gamma-rays have been measured for basic nuclear physics research below about 5 MeV. One of several exceptional works for applied purposes with continuum gamma-rays was made by Drake et al. from 4.00 to 7.67 MeV/1/.

Measurements to obtain whole gamma-ray spectra including the continuum part have been carried out mainly with the white neutron source using the electron linear accelerator ORELA by Dickens et al./2/. Their values are quite comprehensive with respect to the range of nuclear elements and the energy region which covered Z= 3 to 82 and En = 0.1 to 20 MeV, respectively. Their neutron energy spread, however, was usually very wide due to the low counting statistics especially in the high energy region.

The accuracy of the low energy part of the existing gamma-ray spectrum data has been somewhat questionable due to the various sample size corrections needed for neutron multiple-scattering, gamma-ray self-shielding and secondary gamma-rays emitted due to Compton scattering in the sample. It has been pointed out that total gamma-ray production cross sections disagreed with the evaluation based on theoretical calculations for some elements, where low energy parts have significant contributions.

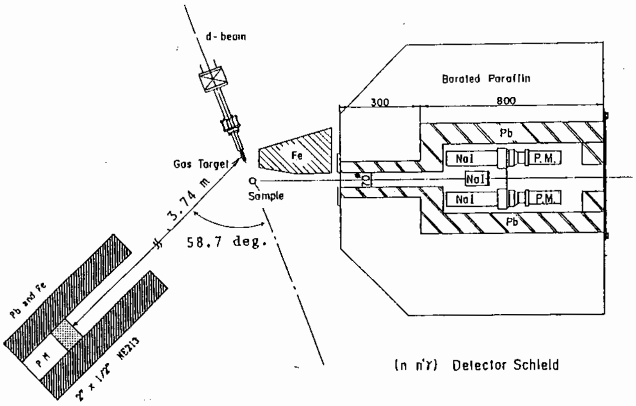

Fig. 1 Experimental arrangement

For the evaluation of JENDL-3 (Japanese Evaluated Nuclear Data Library - version 3), the gamma-ray production cross sections for several important nuclei of structural and shielding materials have been newly evaluated. The multi-step Hauser Feshbach code such as GNASH/3/ has been used to calculate cross sections. The evaluated results have now being tested with gamma-ray data as well as neutron data.

Our aims in this experiment are to provide accurate gamma-ray production data for applied purposes in the MeV region with higher neutron energy resolution and better low energy gamma-ray spectra.

Experiment

The experimental arrangement is shown in Fig. 1. Neutrons were produced by the $^2H(d,n)^3He$ reaction. The in-terminal ion source of the JAERI Tandem accelerator was used to extract a

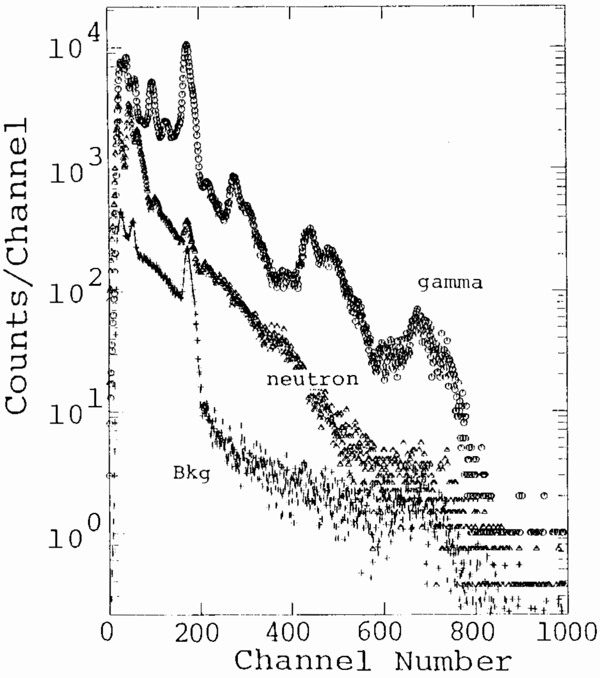

Fig. 2 Eaxmple of raw data of gamma-ray pulse height spectra for Si(n,n')

deuteron beam bombarding a 3 cm long pressurized (0.2 MPa) deuterium target. A 5 MeV deuteron beam was accelerated for our experiment where the effects of break-up neutrons could be ignored. The average beam current and pulse width were 0.5 uA and 4 ns, respectively, at a 2 MHz repetition rate. The size of all samples used was 3cm diameter x 3 cm long.

Gamma-ray spectra were measured with a 7.6 cm diameter x 15.2 cm long NaI(Tl) detector, which was surrounded by a 25.4 cm diameter x 25.4 cm long NaI(Tl) annular detector. These two detectors were operated in an anti-coincidence mode to suppress the Compton backgrounds in the NaI detector and neutron capture gamma-rays in the vicinity of the detector. The detector shield was made out of lead and borated paraffin and the iron shadow bar was also placed between the gas target and the gamma-ray detectors. The whole detector system could be rotated around the sample to measure the gamma-ray angular dependence. The sample was placed at a distance of 9.8 cm from the neutron target and the gamma-ray detector was located at about 80 cm from the sample. In the present experiment, only data taken at a 90 degree have been analyzed.

Four data sets for each sample were measured to determine the backgrounds with the following conditions; the sample inserted and removed from the sample position and ^{2}H gas filled and removed from the gas cell. The time-of-flight technique of the gamma-ray detection was used to separate the net count of prompt gamma-rays (gamma-gate) from the time dependent background (neutron-gate) due to capture gamma-rays by slowing down neutrons and the time independent constant backgrounds (bkg-gate).

The neutron spectra were also measured at the same time employing a 5 cm diameter x 1.27 cm thick NE213 detector located at a distance of 3.74 m from the neutron source and at an angle of 58.7 degree with respect to the deuteron beam line. The angular distribution of d-d neutrons is known to be relatively flat at this angle/4/.

Analysis

The response function of this anti-Compton NaI detector was determined to obtain the absolute gamma-ray yields. The several standard gamma-ray sources such as, ^{137}Cs, ^{60}Co, ^{88}Y, ^{22}Na and ^{24}Na were used to examine the response function. The spectra were also obtained for the 4.43 MeV gamma-rays from the ^{12}C(n,n') and the 6.1 MeV gamma-rays from ^{16}O(n,n') reactions. The raw data of the gamma-ray pulse height spectra (gamma-gate) for Si are shown in Fig. 2 together with the spectra of a neutron (neutron-gate) and constant background (bkg-gate). The discrete gamma-ray peak observed in the background is the 1.78 MeV gamma-ray from the beta-decay of ^{28}Al with the half life of 2.2 min. produced by ^{28}Si(n,p)^{28}Al reaction. Several discrete gamma-ray peaks are observed in the gamma-gate data above the continuum part of the spectrum as shown in the figure. After subtracting the backgrounds, the gamma-ray spectra were unfolded using the computer program FERDOR/5/.

The absolute neutron intensity was calculated from the evaluated values of the d-d cross section compiled by Liskien and Paulsen/4/ taking into account the angular distributions of emitted neutrons since the sample position is close to the target. The angular distribution of neutron source could not be ignored.

Sample size correction

In general, a large sample size is needed for measurements of gamma-ray production cross sections, in order to decrease counting statistic uncertainty of raw data. However, the corrections for absorption and multiple scattering both for neutrons and gamma-rays in the sample become large as the sample size increases. Accurate determination of these corrections requires precise knowledge of behaviors for neutrons and gamma-rays which are dependent on the neutron and gamma-ray cross sections and angular distributions. The calculations for these correction are usually carried out by a Monte carlo method because the analytical solution is very complicated.

The computer programs MNSCAT and COMPCALC were newly prepared for these calculations. The

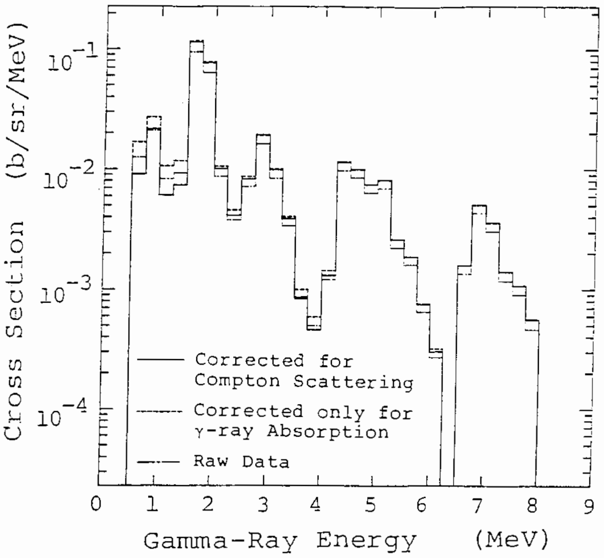

Fig. 3 Sample size corrections for gamma-ray spectra of Si

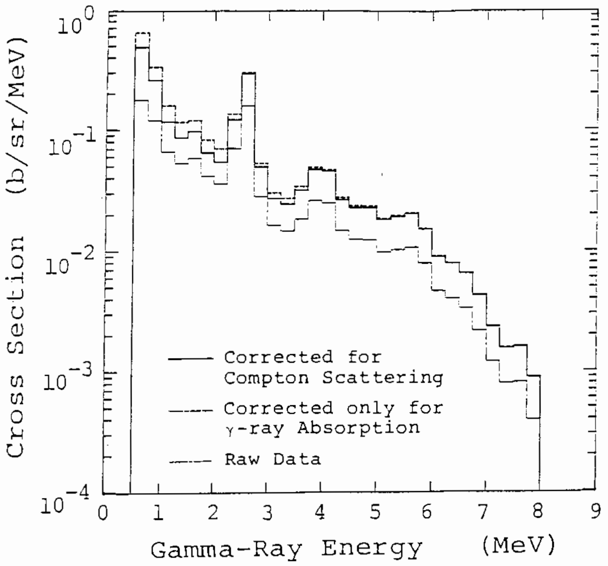

Fig. 4 Sample size corrections for gamma-ray spectra of Pb

neutron transport calculation code (MNSCAT) follows the procedure originally developed by Smith/6/ by expanding it for 3-dimensional treatment. The scattering sample is assumed to be a right circular cylinder centered on the beam line. The sample is divided into several cells vertically and horizontally. Evaluated macroscopic scattering and capture cross sections are used in the calculation for the neutron energy degradation and absorption at the sample position. The effects of other non-elastic reactions are also considered when they are significant. Neutrons scattered at a position and in the new direction were chosen by a random number method for each cell, assuming isotropic scattering. The neutron yield from the entire sample is computed by summing the contribution from various portions of the sample cells.

For the gamma-ray transport calculations, the program COMPCALC was newly developed. Gamma-ray spectra are simulated with a Monte Carlo calculation by taking into account gamma-ray absorption and Compton scattering in the samples. The angular distributions for gamma-ray emission are assumed to be isotropic. The correction factor was calculated iteratively until simulated spectra represent well the observed results. The initial guess of the spectra is assumed to have an evaporation shape originally proposed by Howerton and Plechaty/7/ and weighted by the neutron intensities for each sample cell calculated by the MNSCAT.

The calculated results are shown in Figs. 3-4 for Si and Pb which represent the examples for light and heavy elements. The dashed line shows the uncorrected observed cross section, the

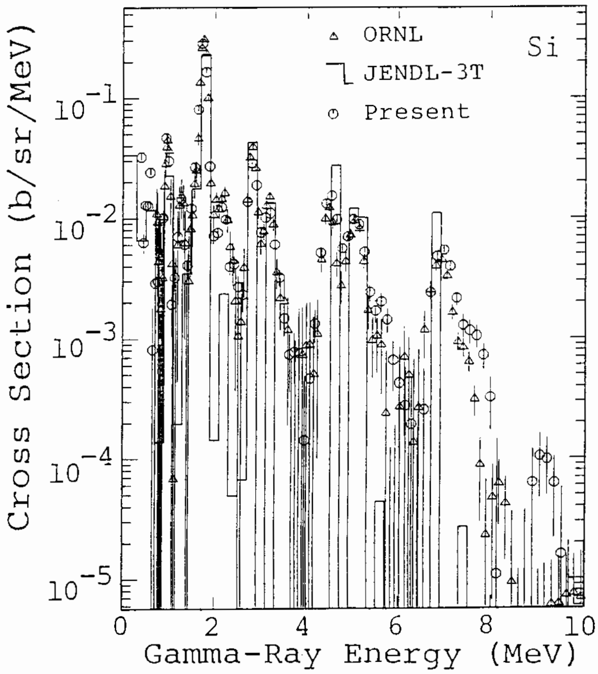

Fig. 6 Comparison of the present results with the data of ORELA and JENDL-3T for Si

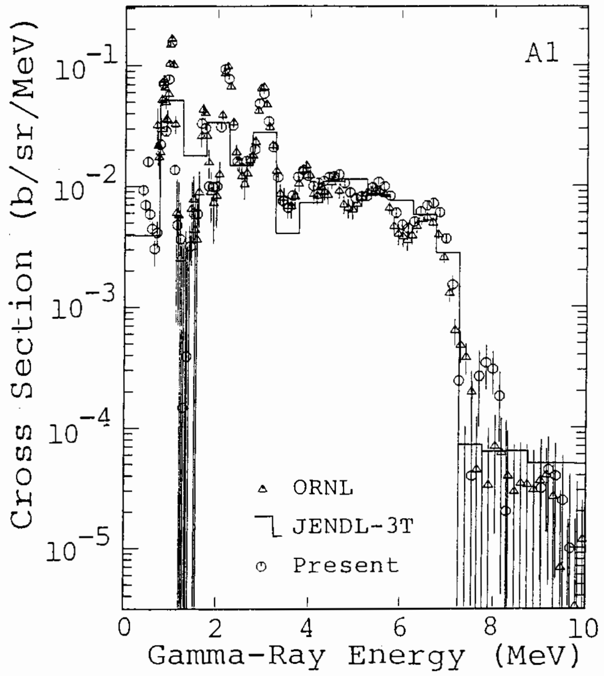

Fig. 5 Comparison of the present results with the data of ORELA and JENDL-3T for Al

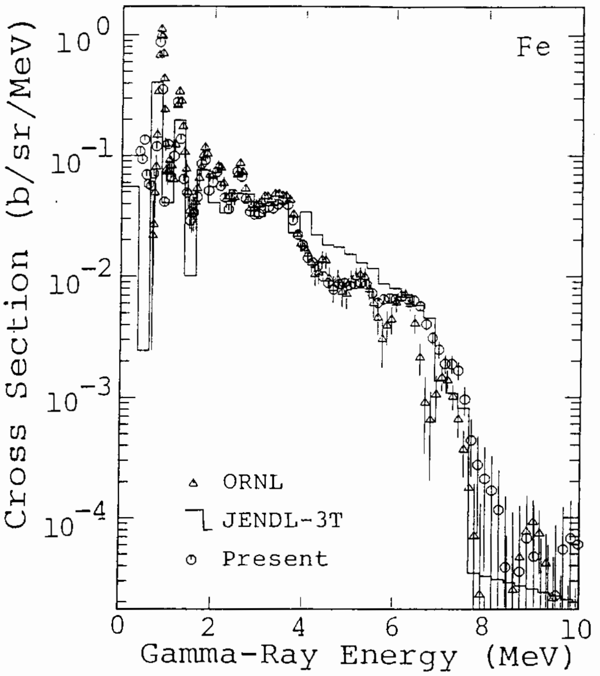

Fig. 7 Comparison of the present results with the data of ORELA and JENDL-3T for Fe

dotted line the one for which only the usual gamma-ray absorption corrections are carried out, and the solid line is the final results after correcting the Compton scattering effects. While the correction factors for Compton scattering both for light and heavy elements are negligible in the high energy region, they become as much as 40 % in the low energy region as shown in the figures.

Results and Discussion

The results are shown in Figs. 5-9, together with the data taken at ORELA/8-11/. Data for Bi were not available previously. The overall agreement of our spectral shapes for the all samples with the ORELA data seems quite good. Though detailed comparisons between the existing data have not been made, the peak areas in the low energy parts of the present result are generally lower than the previous results especially for the data taken at 7.67 MeV by Drake et al./1/. This may be partly affected by the difference of the sample size correction methods. A series of measurements with a Ge(Li) detector was also carried out by Dickens et al./12/ who used the d-d neutron source at ORNL. The comparisons with their data for discrete gamma-rays were made at 90 degree. Reasonable agreement was obtained, although there exist some difficulties for comparisons because of the difference of the energy resolution.

The data which were stored in JENDL-3T (temporary version)/13/, were also compared and checked with the present results. Because angular distributions for the gamma-ray spectrum are assumed isotropic for most nuclei in the JENDL-3T, evaluated spectra were simply divided by 4 pi for comparison. The evaluations represent the present experimental data reasonably well. However, the energy bin of 0.5 MeV for the evaluations in some cases appears to be too broad so that the several discrete peaks in the low energy regions are smeared out. Data on gamma-rays resulting from these reactions allow evaluators to check the validity of various reaction models to calculate these cross sections.

Summary

Gamma-ray production cross sections have been measured for structural and shielding materials of Al, Si, Fe, Pb and Bi. The overall agreement between the present data and previously available data is good. In our data, corrections for the effect due to the Compton scattering in the sample were made in the gamma-ray low energy region. Our data are compared to the newly evaluated JENDL-3T based on the multi-step Hauser Feshbach calculation. Our data were used to improve the quality of the evaluated file. The gamma-ray spectra at a neutron energy of 11 MeV have been measured but not analyzed yet.

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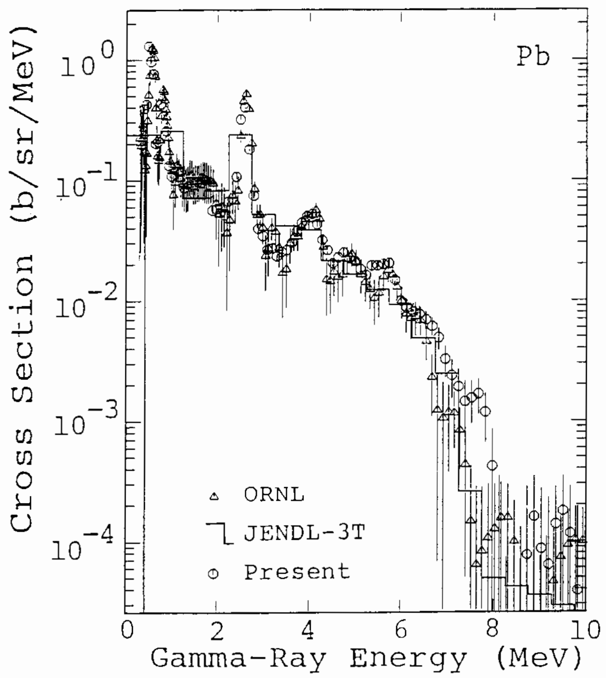

Fig. 8 Comparison of the present results with the data of ORELA and JENDL-3T for Pb

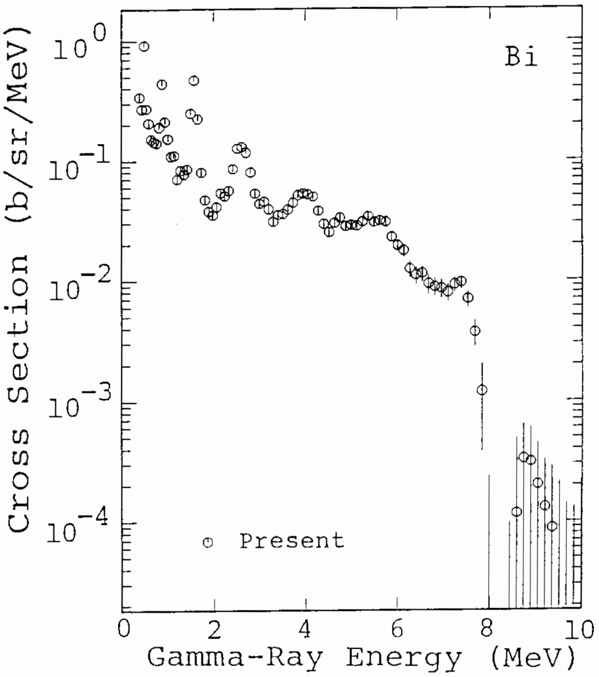

Fig. 9 Gamma-ray spectra for Bi