Measurement of Gamma-Ray Production Double-Differential Cross Sections for the Spallation Reaction Induced by 0.8, 1.5 and 3.0 GeV Protons

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Gamma-ray production double-differential cross sections have been measured for 0.8, 1.5 and 3.0 GeV protons incident on C, Al, Fe, In and Pb targets. Gamma-rays were detected by NE213 liquid scintillators and gamma-ray signals were separated from neutron ones by a two-gate integration method. The photomultiplier-charge data of gamma-rays were unfolded with the FERDo-U code. Because of rather thick targets, effects of secondary particles on gamma-ray generation had to be removed and they were evaluated by particle transport calculations with the NMT/JAERI, MCNP4A and HETC-KFA2 codes. Attenuation of gamma-rays in the target was calculated by the EGS4 code. Gamma-ray production cross sections were obtained in a gamma-ray energy range up to 60 MeV. The experimental results were compared with calculated values by the HETC-KFA2 code. At gamma-ray energies up to 10 MeV, the calculated cross sections agree with experimental data for the Fe, In, and Pb targets typically within a factor of two.

KEYWORDS: gamma-ray production double-differential cross sections, incident protons, GeV range, proton reactions, 0.8-3.0 GeV, NE213, HETC-KFA2, targets, carbon, aluminum, iron, indium, lead, experimental data, evaluations

I. Introduction

Spallation reactions have recently been investigated for such applications as spallation neutron sources and accelerator-driven transmutation systems. Nuclear data at energies around GeV are required to design such systems, and are also necessary for researches on cosmic-ray irradiation and shield of high energy accelerators. Neutron production cross sections have been studied up to date, because above applications are mainly concerned with neutrons. Besides the neutron data, however, gamma-ray production cross sections are required to estimate radiation heating and shielding in detail.

High Energy Transport Code (HETC)(1) is often used for engineering purposes at a high energy. This code is based on the intranuclear-cascade evaporation model in the nuclear calculation part. The HETC-KFA2(2) code is one of improved versions of HETC. HETC-KFA2 includes the high-energy fission process, adopts the more realistic level-density parameters in the evaporation process and treats the gamma-ray emission. This code takes shell effects(3) into account in the level-density parameters. The gamma-ray emission is assumed to take place in the evaporation process as well as in the decay of π0 mesons.

Systematical measurement of gamma-ray production cross sections gives information useful for check of the calculation model. Prompt gamma-ray spectra have been measured at incident proton energies up to a few hundred MeV(4)-(6). However, spectra above these proton energies have not been systematically taken so far.

We measured double-differential cross sections on production of spallation neutrons before(7)(8). Prompt gamma-rays were measured together with neutrons. In this study, we present gamma-ray production double-differential cross sections for C, Al, Fe, In and Pb targets at incident proton energies of 0.8, 1.5 and 3.0 GeV. The
II. Experiment and Data Analysis

The experiment was carried out at the \( \pi 2 \) beam line of the 12 GeV proton synchrotron at National Laboratory for High Energy Physics (KEK, currently High Energy Accelerator Research Organization). The experimental method was written in Refs. (7) and (8), and is described briefly here. Incident proton beam intensity was as weak as about \( 10^5 \) protons/2.5 s. The weak intensity forced us to use 1.2- to 10-cm thick targets (7)(8) to accumulate sufficient events. NE213 liquid scintillators with a size of 12.5 cm in diameter and 12.5 cm long were placed in directions of 15°, 30°, 60°, 90°, 120° and 150° with respect to the proton beam direction and at a typical distance of 1 m from the target. The scintillators were used for simultaneous measurement of neutrons and prompt gamma-rays. The time-of-flight (TOF) and photomultiplier-charge data were taken by NIM and CAMAC modules. All data were analyzed with an offline method.

In the experiment, target-in and -out measurements were performed. Figure 1 shows the TOF spectra of the target-in and -out measurements for an Fe target at the incident proton energy of 0.8 GeV. The gamma-ray events were separated from neutron ones by the pulse-shape discrimination based on a two-gate integration method(9). Gamma-ray spectra were derived by subtracting the results of the target-out experiment from those of the target-in with normalization by the number of incident protons. The data analysis was restricted to the prompt gamma-ray production. A TOF time window of 2.8 ns on both sides of prompt gamma-peak was chosen to cover the peak. A charge sensitive Analog-to-Digital Converter (ADC) spectrum of gamma-rays is shown in Fig. 2, for 0.8 GeV proton incidence on the Fe target. The counts of gamma-ray event decrease rapidly with increasing the ADC channel. The gamma-ray energy calibration of the charge spectra was made by the use of checking sources of \(^{137}\)Cs and \(^{60}\)Co, and the 4.4 MeV gamma-rays from interaction of Am–Be source neutrons with C(10). Above 4.4 MeV, the calibration was performed by the neutron energy obtained by the TOF method: When an incident neutron deposits its whole energy in the scintillator, the photomultiplier-charge output corresponds to its incident energy. In this calibration process, the charge output for neutron events was obtained from the ADC data and the neutron energy was determined by the TOF method. Then, the relation between the charge output and the neutron energy was obtained in case of the whole energy deposition. The neutron energy was converted into electron-equivalent energy MeVee by an empirical relationship(11) for NE213. Measured charge spectra were unfolded to obtain gamma-ray emission spectra. Unfolding was carried out by the FERDo-U(12)(13) code. A width of Gaussian smoothing function(12)(13) in unfolding was optimized to give positive cross section values. Response functions of NE213 were calculated by the EGS4(14) code, where energy resolutions of detectors were taken into account. The energy resolution \( R \) was determined on the basis of the experimental shapes of Compton edges(10) obtained at the energy calibration, where the energy dependence was simply approximated(15)(16) as \( R(\%) = C/\sqrt{E_\gamma} \), where \( E_\gamma \) is the gamma-ray energy and \( C \) is a constant. Typical response functions are shown in Figs. 3 and 4. The discrimination level was set at 0.3 MeV in Fig. 3. The peak around 0.3 MeV appeared due to background gamma-rays in the \( \pi 2 \) area. The calculation result reproduces the measured spectrum above 0.6 MeV. In Fig. 4, the deposited energy is 60 MeV at maximum, even for gamma-rays with energies above 60 MeV. This situation limited the energy range in un-
folding below 60 MeV. The clear peak for gamma-rays below 20 MeV facilitates the unfolding of good accuracy.

The use of rather thick targets forced us to correct the unfolded data. Effects of the secondary reactions were evaluated by the following calculations. The yields of gamma-rays due to the secondary neutrons having energies below 20 MeV were calculated by combination of NMTC/JAERI(17) and MCNP4A(18) codes. The results are shown in Fig. 5. The figure points out that the results take up less than 10% of the measured values. The obtained data were corrected for the effect of gamma-ray attenuation in the target by using the EGS4 code: Gamma-ray spectra produced by the target nuclei were iteratively changed until the computed results by the EGS4 code at the detector positions agreed with the measured ones. This iteration was carried out at gamma-ray energies of 1 to 20 MeV, and at 67 MeV, i.e. the energy of gamma-rays from the \( \pi^0 \) decay. The cross sections above 20 MeV obtained by this unfolding became apparent values due to the influence of the \( \pi^0 \) decay gamma-rays as described in the next section. Hence, the apparent cross sections in this region were neglected in the iterative correction for the gamma-ray attenuation.

The experiment was carried out under the circumstances of many neutrons coming from the spallation reaction. When a high energy neutron is incident on the NE213 scintillator, it can produce the 4.4 MeV gamma-ray from the \( {^{12}\text{C}(n, n')}{^{12}\text{C}^*} \) reaction. If the scattered neutron goes through the scintillator without interaction and the energy of the recoil nucleus is negligibly small, the event may be mistreated as the gamma-ray incident one. The neutron TOF of 2.8 ns corresponds to the energy of 180 MeV, and the use of this time window disables us to remove such gamma-ray events generated by neutrons with energies above 180 MeV. For this reason, the measured spectra contained the neutron effect.

In forward directions, the 4.4 MeV peak was obvious and removed by eye measurement for the results of Al, Fe, In and Pb targets. The secondary gamma-rays constitute as plotted in the same figure. These additional yields were evaluated with ratios of calculated results of the HETC-KFA2 code for the thick target to those for an ideally thin one. The yields range from 10 to 50% of the measured values. The obtained data were corrected for the effect of gamma-ray attenuation in the target by using the EGS4 code: Gamma-ray spectra produced by the target nuclei were iteratively changed until the computed results by the EGS4 code at the detector positions agreed with the measured ones. This iteration was carried out at gamma-ray energies of 1 to 20 MeV, and at 67 MeV, i.e. the energy of gamma-rays from the \( \pi^0 \) decay. The cross sections above 20 MeV obtained by this unfolding became apparent values due to the influence of the \( \pi^0 \) decay gamma-rays as described in the next section. Hence, the apparent cross sections in this region were neglected in the iterative correction for the gamma-ray attenuation.

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In forward directions, the 4.4 MeV peak was obvious and removed by eye measurement for the results of Al, Fe, In and Pb targets. The secondary gamma-rays constitute
30 to 40% of the cross sections around 4.4 MeV before this correction. For the C target, however, the 4.4 MeV gamma-rays generated in the scintillators were not distinguished from those coming from the target, and they were unable to be removed.

III. Results and Discussion

The gamma-ray production double-differential cross sections for the spallation reaction are plotted in Figs. 6 and 7 with the calculations by the HETC-KFA2 code. Other results are available at our web page(19). The error bars indicate total uncertainty including the experimental-statistical and data-analysis errors. The values of experimental-statistical errors through the unfolding process were obtained by the FERDo-U code. The sum of uncertainties both in the response functions given by EGS4 and in the effective area of the proton beam affecting data corrections was assumed to be less than 10% of unfolded data(20)(21). For the evaluation of the multiple-scattering effects, the statistical errors of NMTC/JAERI, MCNP4A and HETC-KFA2 calculations were below 5%. The systematic uncertainty in the correction for the multiple-scattering effects was decided as 20%(22). The uncertainty in the iterative correction for the gamma-ray attenuation in the target was estimated to be 10%. The dotted error bars in the figures stand for the error ranges reaching negative values.

The HETC-KFA2 code calculates the gamma-ray production from exited nuclei after intranuclear-cascades by using discrete nuclear energy levels and branching ratios specified in the data library of CDRL82(2). For excitation levels beyond the specified levels, the continuum is assumed(23). Since the angular distribution is not given, it is presumed to be isotropic. The calculation produced gamma-rays in the energy range up to about 10 MeV. The computed cross sections are mostly in good agreement with the experiments up to 10 MeV for the Fe, In and Pb targets typically within a factor of two. The calculated results for the C target have a peak at 2 MeV which is ascribed to the gamma-rays emitted from the transition from the first excited state to the ground state of $^{11}$B and $^6$Li. This peak is not seen in the experiment.

Fig. 6 Gamma-ray production cross sections for 1.5 GeV proton incidence
Dots show the experimental results. Solid lines indicate calculation results by the HETC-KFA2. Cross marks present calculated cross sections of the gamma-ray production from the $\alpha^0$ decay, and dotted lines show the contribution of the gamma-rays to the experimental results.
since the peak might become indistinct by the use of the Gaussian smoothing function\textsuperscript{[12],[13]} with a standard deviation of 30\% in the unfolding. There is no peak at 4.4 MeV in the experiment of the C target. The spectrum before the multiple-scattering effect correction owned the peak at 4.4 MeV, but it accidentally disappeared probably because of overestimation of the effect in the 4.4 MeV peak by MCNP4A. As for the Al target, the calculation results exceed the experimental data at energies around several MeV regardless of incident proton energy. We do not thoroughly understand the reason for this overestimation. For 3.0 GeV proton incidence in Fig. 7, the experimental cross sections are larger than the calculated values below 10 MeV in the forward directions. This exhibits a somewhat forward peaking of the gamma-ray emission.

When a gamma-ray above about 60 MeV is incident on the scintillator, the deposited energy distribution has no clear peak and is almost independent of the incident energy, as shown in Fig. 4. In addition, the NE213 scintillators have a low efficiency for the high energy gamma-rays. These gamma-rays are, therefore, mistreated in the unfolding as the events with lower energies. Two reactions produce such high energy gamma-rays: One is the decay of $\pi^0$ mesons and the other is the nuclear bremsstrahlung which occurs in the interaction between the incident protons and intranuclear nucleons. The total production cross sections from the $\pi^0$ decay are given by the HETC-KFA2 calculation. The emission of the gamma-rays was approximated to be isotropic in the center-of-mass system constituted of the incident proton and intranuclear nucleon. The cross sections were relativistically converted into those in the laboratory system and the converted cross sections are plotted with cross marks. The gamma-ray production cross sections by the nuclear bremsstrahlung have been represented by empirical expressions\textsuperscript{[23],[24]}. These cross sections are far below 1\% of those due to the $\pi^0$ decay and negligible in the present analysis. The influence of the high energy gamma-rays on the unfolding was checked as follows: The photomultiplier-charge output spectra were calculated by EGS4 for $\pi^0$ decay gamma-rays. The attenuation in the target and the detection efficiency in the scintillator were taken into consideration in the simulation calculation. The simulated charge output spectra were unfolded, similarly to analysis of the measured data. The results are given by dashed lines in the figures. One can see that the evaluated influence of the $\pi^0$ decay gamma-rays are comparable to the cross sections above 20 MeV. Hence, the experimental cross sections above 20 MeV should be mainly ascribed to the mistreated events.

IV. Conclusion

Gamma-ray production cross sections were obtained for 0.8, 1.5 and 3.0 GeV protons incident on C, Al, Fe, In and Pb at directions of 15\°, 30\°, 60\°, 90\°, 120\° and 150\°. The experimental results were compared with the calculations by the HETC-KFA2 code. The calculation results agree with the experimental data for the Fe, In, and Pb targets typically within a factor of two at gamma-ray energies up to 10 MeV.

Fig. 7 Gamma-ray production cross sections for Fe
Dots show the experimental results. Solid lines indicate calculation results by the HETC-KFA2. Cross marks present calculated cross sections of the gamma-ray production from the $\pi^0$ decay, and dotted lines show the contribution of the gamma-rays to the experimental results.

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