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Absolute Efficiency of A ϕ76mm × 100mm BGO Scintillation Detector

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Using monoenergetic gamma-ray generated from low energy (p,γ) resonant reactions, the full-energy-peak gamma-ray detecting efficiency of a ϕ76mm × 100mm BGO scintillating detector was measured. The efficiencies of 7%, 9% and 22% are obtained at gamma energies of 17.65, 17.23 and 6.13 MeV, respectively.

Key words: full-energy-peak detecting efficiency, non-linear fit, proton backscattering.

In order to meet the needs of heavy ion nuclear reaction experiments at intermediate energies, we have made up some ϕ76mm × 100mm BGO detectors [1], and have studied the energy response function [2]. We report here the measurement of absolute detecting efficiencies at various energies.

1. EXPERIMENT METHOD

(1) Definition

When considering the absolute gamma-ray efficiency of a big scintillating detector, only the results related to the full-energy-peak are meaningful. We define in this report the absolute efficiency as:

$$\varepsilon = A/N_\gamma$$

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Table 1

Low energy (p,γ) resonant reactions used in our experiment.

Reaction	E_γ (keV)	σ_γ (mb)	Γ (keV)	E_γ (MeV)	δ	E_0 (keV)
$^{11}B(p,\gamma)^{12}C$	1390	0.053	1270	17.23 12.80 4.43	66 34 34	1361
$^{19}F(p,\gamma\alpha)^{16}O$	340	102	2.4	6.13	96.5	367
$^{7}Li(p,\gamma)^{8}(Be)$	441	6	12	14.75 17.65	37 63	457

Table 2

Integral charge determined by proton backscattering method.

E_0(keV)	367		1361		457	1381
Target	LiF+Si	Si	BN+Si	Si	LiF+Si	Si
$Q(\mu c)$	135 ±2	44 ±2	3710 ±20	990 ±2	580 ±10	5.30 ±0.02

where A is the counts under the full-energy-peak of a energy spectrum and N_γ the number of monoenergetic gamma particles incident into the detector.

Three low energy (p,γ) nuclear resonant reactions were used which provided the gamma-ray with fixed energies (Table 1). The cross sections for gamma-ray productions do not depend on the emitting angle [3-5]. The targets of LiF and BN film on Si substrate were installed at the scattering chamber.

(2) Determination of the full-energy-peak

Electron-positron pair production is the main effect of interaction of multi-MeV gamma-ray with BGO crystal, which results in single and double escape peaks in the energy spectrum. Other escapes, such as bremsstrahlung X-ray emission and electron escape, also contribute to the tail of the spectrum.

We use a multi-parameter function to fit the experimental spectra by non-linear least-square method. The treatment of the escape portion is empirical but does not affect the full-energy-peak [2]. The function is defined as follows:

$$Y(x) = f_d(x) + f_s(x) + f_p(x) + f_c(x),$$

where x and $Y(x)$ are the channel number and its number of counts; $f_d(x)$ and $f_s(x)$ describe the double and single escape peaks whose centers are fixed at 1.022 and 0.511 MeV below the full-energy-peak $f_p(x)$, respectively; $f_c(x)$ describes the Compton plateau which is composed of a constant and a half Gaussian functions. Reference [2] has described this method and has commented on its validity.

(3) Measurement of N_γ

(a) $^{11}B(p,\gamma)$ reaction has a large resonant width. When using thin target film and appropriate beam energy, the reaction cross section can be treated as a constant. Therefore:

$$N_\gamma = \sigma_r \cdot \rho \cdot t \cdot N_p \cdot [\Omega/4\pi] \cdot \delta, \qquad (1)$$

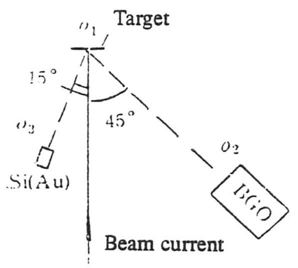

Fig. 1
Experimental setup.

where σ_γ is the resonant cross section, δ the branching ratio of the selected gamma-ray, ρ and t the density and the thickness of the target, N_p number of incident protons and Ω the solid angle opened to the detector.

(b) For other reactions the resonance width is smaller or comparable to the target energy-thickness. In this case a integral on energy of the cross section is necessary:

$$N_\gamma = [\Omega/4\pi] \cdot \rho \cdot N_p \cdot \delta \cdot \int_{E_0-E_b}^{E_0} \sigma(E) \cdot \frac{1}{S(E)} \cdot dE,$$

where E_0 is incident proton energy, $S(E)$ the stopping power of proton in the target film, which is approximately a constant in our case. Using Breit-Wigner formula to describe the resonant cross section, we obtain:

$$N_\gamma = [\Omega/4\pi] \cdot \rho \cdot N_p \cdot \delta \cdot \frac{1}{S} \cdot \left[\frac{\Gamma \cdot \sigma_r}{2}\right] \times \left\{ tg^{-1}\left[\frac{E_0 - E_r}{\Gamma/2}\right] - tg^{-1}\left[\frac{E_0 - E_r - E_b}{\Gamma/2}\right]\right\}. \quad (2)$$

(4) Since the absolution beam current can not be measured under our present conditions, we use the proton backscattering to obtain the integral charge impacting on the target which corresponds to the incident proton number. Since the film is very thin only the scattering from the Si substrate need to be fit in the analysis. In our energy range proton scattering from Si is purely Coulomb type [6]. Therefore the experimental spectra can be used to determine the integral charge Q which is the only parameter in the fitting program.

(5) The thickness of LiF film is measured using the $^{19}F(p,\alpha\gamma)$ resonant reaction at 340 keV, and that of BN using $^{11}B(p,\alpha)$ reaction at 2.62 MeV [7].

2. EXPERIMENT

Proton beams of 2.67 MeV, 1361 keV, 457 keV and 367 keV were provided by 2 × 1.7 MV tandem at Department of Technical Physics. The size of the beam spot is about 5mm × 5mm. Gamma-ray and backscattered protons were detected by the BGO scintillation detector and Si(Au) semiconducting detector, respectively. The geometry is shown in Fig. 1. The BGO detector was set at 28 cm from the target, corresponding to a solid angle of 56.5 msr. A collimator with a hole of 2.86

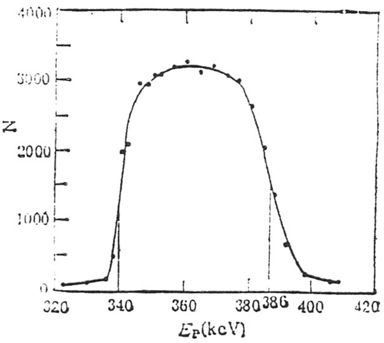

Fig. 2

Excitation function of $^{19}F(p,\alpha\gamma)$ resonant reaction at around 340 keV beam energy for production of 6.13 MeV gamma-ray. dot: experiment data; Solid line: smooth line of data.

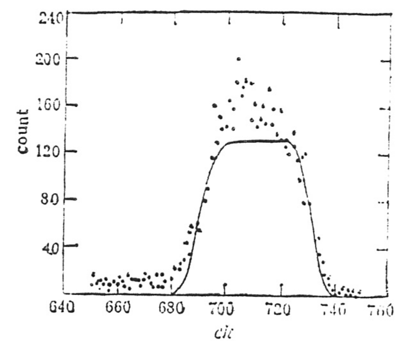

Fig. 3

Energy spectrum of α-particles from the $^{11}B(\alpha,\gamma)^{8}Be$ reaction at E_p = 2.67 MeV. Dot: experiment data; Solid line: Simulated spectrum from deconvolution calculation.

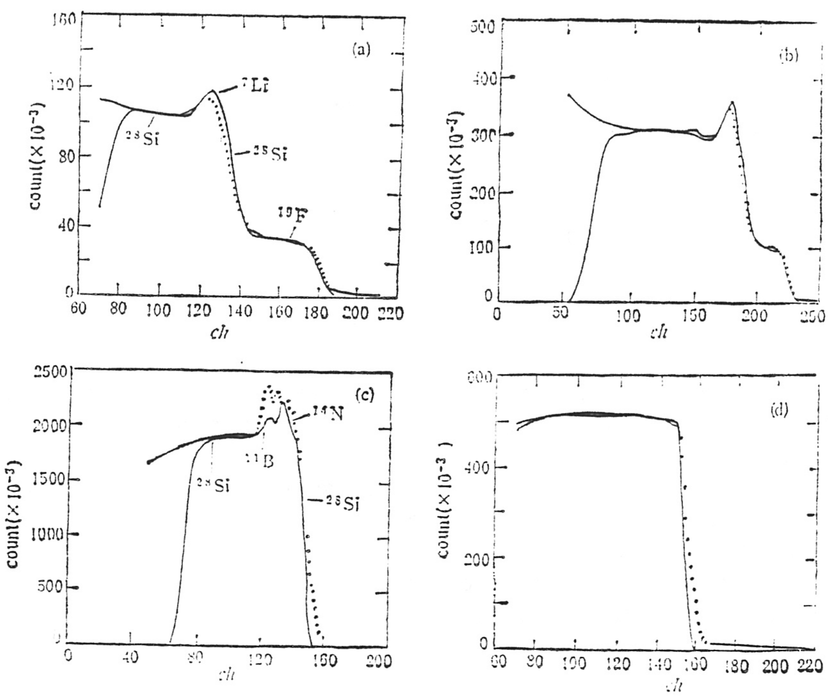

Fig. 4

Energy spectrum of backscattered protons. Dot: experimental data; Solid line: Calculations. (a) p → LiF + Si, E_p = 367 keV; (b) p → LiF + Si, E_p = 457 kev; (c) p → BN + Si, E_p = 1361 keV; (d) p → Si, E_p = 1381 keV.

Table 3
Fitting results of three gamma energy spectra.

E_γ(MeV)	Full-energy-peak				Single escape peak	
	FWHM (channel)	Height (counts)	$\Delta E/E$ (%)	Area (counts)	FWHM (channel)	Relative height
6.13	6.0±0.1	1192±44	6.5 (1±2%)	18016 (1±5%)	7.2±0.8	47%
17.23	3.0±0.4	131±16	3.7 (1±14%)	985 (1±23%)	2.4±0.3	98%
17.65	5.4±0.6	333±85	4.3 (1±10%)	4506 (1±34%)	4.3±0.6	92%

mm in diameter was placed in front of the Si(Au) detector. When measuring the thickness of BN the target was turned 60° relative to the normal of the beam direction.

3. RESULTS

(1) Figure 2 shows the excitation function of 19F(p,γ) reaction around the 340 keV beam energy for production of 6.13 MeV gamma-ray. The FWHM of the spectrum was used to determine the thickness of LiF film, assuming that the stopping power of proton in LiF is known (TRIM90 calculation). The results is 470 nm with an uncertainty of 10%.

(2) Figure 3 shows the energy spectrum of the α-particle from the $^{11}B(p,\gamma)^{8}Be$ reaction at 2.67 MeV. A thickness of 540 nm for the BN film was obtained by fitting the spectrum with a deconvolution program. The uncertainty is about 7%, including the contributions from the detector geometry and the stopping power. The thickness after the (p,γ) experiment was changed to 500 nm, due to the long time bombardment of the film by the intense proton beam. An average thickness of 520 nm was then used with an additional uncertainty of 8%.

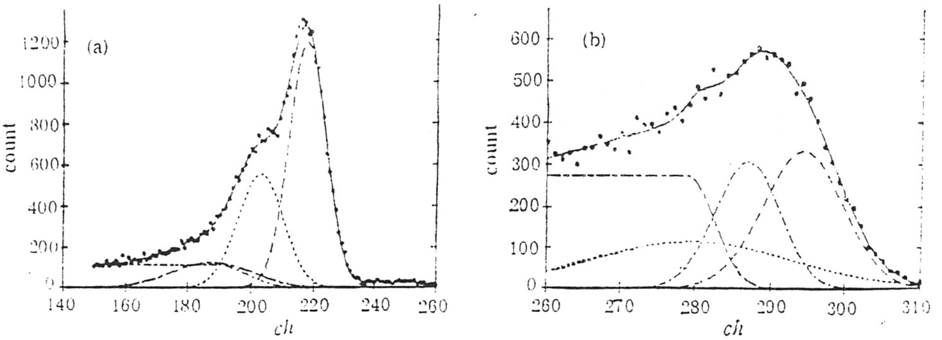

Fig. 5
Energy response of the BGO detector to monoenergetic gamma-ray. (a) E_γ = 6.13 MeV; (b) E_γ = 17.65 MeV. Dot: Experimental data; Solid line: Fitting spectra; Other lines: Various portions of the fitting function.

(3) Figure 4 shows the energy spectrum of backscattered protons from various targets, together with the calculations. The integral charges were obtained from the fitting and are shown in Table 2. The average uncertainty is about 2%.

(4) Determination of N_γ

(a) For $^{19}F(p,\gamma)$ $N_\gamma = 81695$ can be derived from Eq.(2). The uncertainty is about 10% mostly resulted from the error of stopping power.

(b) For $^{11}B(p,\gamma)$, Eq.(1) can be applied and $N_\gamma = 10485$ with an uncertainty of 8% is obtained.

(c) For $^{7}Li(p,\gamma)$, Eq.(2) is used and $N_\gamma = 64500$ with a 10% uncertainty.

(5) The counts under the full-energy-peak were determined through the multi-parameter fit. The results are listed in Table 3. The statistical uncertainty is quite large at higher gamma energies due to the smaller cross sections.

(6) Finally we obtain the efficiencies as follows:

$$E_\gamma = 6.13\text{MeV} \quad \varepsilon = 22\%(1 \pm 0.12);$$
$$E_\gamma = 17.23\text{MeV} \quad \varepsilon = 9\%(1 \pm 0.25);$$
$$E_\gamma = 17.65\text{MeV} \quad \varepsilon = 7\%(1 \pm 0.36).$$

Reference [8] has reported the efficiency of a ϕ76mm × 76mm BGO detector at 4.43 MeV gamma energy which is consistent with our results within the uncertainty. Other articles [9-11] only give the results for the whole energy peak including single and double escape peaks.

4. CONCLUSION

Based on this work we can conclude that the absolute full-energy-peak efficiency of the ϕ76mm × 100mm BGO detector for gamma-ray of 17 MeV is close to 10%. This is acceptable in measuring high energy gamma-rays.

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