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New measurement of thick target yield for narrow resonance at $E_x = 9.17$ MeV in the $^{13}C(p,\gamma)^{14}N$ reaction*

Yong-Le Dang(党永乐)[1,2], Fu-Long Liu(刘伏龙)[1,2], Guang-Yong Fu(付光永)[1,2], Di Wu(吴笛)[2], Chuang-Ye He(贺创业)[2], Bing Guo(郭冰)[2], and Nai-Yan Wang(王乃彦)[1,2,†]

[1] *College of Nuclear Science and Technology, Beijing Normal University, Beijing* 100875, *China*
[2] *China Institute of Atomic Energy, Beijing* 102413, *China*

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High energy γ-rays can be used in many fields, such as nuclear waste transmutation, flash photographics, and astrophysics. The $^{13}C(p,\gamma)^{14}N$ resonance reaction was used to generate high energy and mono-energetic γ-rays in this work. The thick-target yield of the 9.17-MeV γ-ray from the resonance in this reaction was determined to be $(4.7\pm0.4)\times10^{-9}\gamma$/proton, which was measured by a HPGe detector. Meanwhile, the angular distribution of 9.17-MeV γ-ray was also determined. The absolute efficiency of HPGe detector was calibrated using ^{56}Co and ^{152}Eu sources with known radioactive activities and calculated by GEANT4 simulation.

Keywords: high energy γ-ray, resonance reaction, absolute efficiency, thick-target yield

PACS: 07.85.Fv, 24.30.–v, 29.30.Kv, 29.40.–n **DOI:** 10.1088/1674-1056/28/6/060706

1. Introduction

High energy γ-rays are mainly generated by bremsstrahlung, positron annihilation in flight, laser Compton scatter, and nuclear reaction.[1] However, only the γ-ray from nuclear excitation is mono-energetic. As a method to obtain mono-energetic γ-ray, $^{13}C(p,\gamma)^{14}N$ has been of interest to various fields in nuclear physics.[2,3] In astrophysics, the $^{13}C(p,\gamma)^{14}N$ reaction plays an important role in the CNO cycle, which is responsible for the energy generation in stars.[4] There are several γ-rays emitted from the $^{13}C(p,\gamma)^{14}N$ reaction, and their energies are related accurately with the emission angles. In the inverse reaction $^{14}N(\gamma, p)^{13}C$, the 9.17-MeV γ-ray will be absorbed intensively at specific angle[5] of $^{13}C(p,\gamma)^{14}N$. Moreover, there is little attenuation when 9.17-MeV γ-rays cross through ordinary matter. Thus, they can be used for explosive detection because most explosives are nitrogen-rich.[6]

The measurement of the resonance parameters for the $^{13}C(p,\gamma)^{14}N$ reaction at $E_x = 9.17$ MeV have been observed by several investigators, in which they have obtained the resonant energy and the total width.[3,7] The thick target yield of the 9.17-MeV gamma ray has been measured by Seagrave and Hanna,[5,8] using a Geiger–Muller counter and NaI detector, respectively. However, in the former, no correction has been made for the branch to other levels, while doubts were raised about the efficiency of the NaI detector for the 9.17-MeV γ-rays in the latter research. Therefore, it is highly desirable to measure the thick target yield with state of the art detectors and accurate calibration.

In the present work, we aim at the precision measurement of the thick-target yield of 9.17-MeV γ-ray. First, the absolute efficiencies of HPGe detector in the energy range of 0 MeV–9.5 MeV is calibrated. Then, the angular distribution of 9.17-MeV γ-ray is measured. And finally, the thick-target yield of 9.17-MeV γ-ray is calculated.

2. Experiment

The experiment was performed at the 2×1.7 MV tandem accelerator in China Institute of Atomic Energy (CIAE). In the experiment, proton beams with 8-μA intensity around 1.75 MeV were directed onto the isotropically pure ^{13}C target with 100-μg/cm^2 thickness (the energy loss is about 14 keV), evaporated on an air-cooled Ta disk that is 300-μm thick.

The coaxial HPGe detector (GXM35P4-70, Ortec) and $LaBr_3$ crystal detector of $\phi3 \times 3$ inch (1 inch = 2.54 cm) were used for detecting γ-rays. In the experiment of this work, the HPGe detector was placed at 69-cm distance from the target position at 28° in the direction of proton beams. To calculate the yield of 4π, the $LaBr_3$ detector was used to measure the angular distribution of the yield from 0° to 140°. The HPGe detector was used to monitor the yield. The experimental setup is shown in Fig. 1. The measurement of background was done with a lead cone of 12 cm, which just matches the solid angle of the collimator used in the measurement.

To ensure the absolute efficiency of HPGe detector used in the experiment, it was calibrated using the standard γ-ray sources, ^{56}Co and ^{152}Eu, and GEANT4 simulation. The distance between radioactive source and detector, and the solid

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†Corresponding author. E-mail: wangny@bnu.edu.cn
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angle of detection kept correspondence with that while bombarding the target.

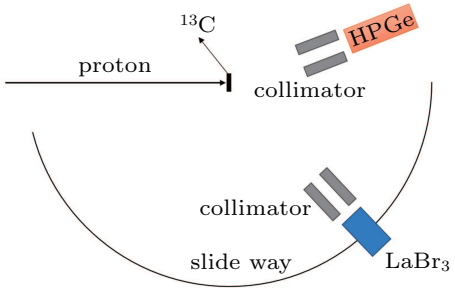


Fig. 1. Experimental setup.

3. Result and discussion

The energy calibration of detector has been performed with 1460.8-keV and 2614.5-keV γ-rays of natural radioactive nuclide, ^{40}K and ^{208}Bi. The spectrum of γ-rays measured by HPGe detector is shown in Fig. 2. There are several γ-ray lines in the spectrum and 9170 keV in the largest proportion.

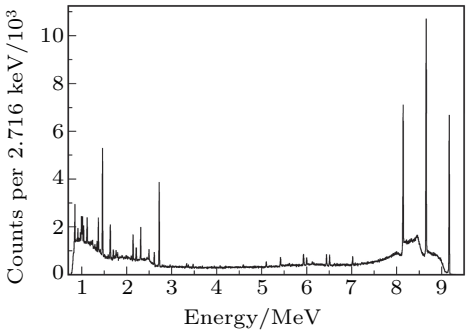


Fig. 2. Spectrum of γ-rays from the ^{13}C(p, γ)^{14}N resonance reaction. There are at least 10 lines, including 1635, 2143, 2313, 2726, 3338, 3480, 5105, 6445, 7027, and 9170 keV.

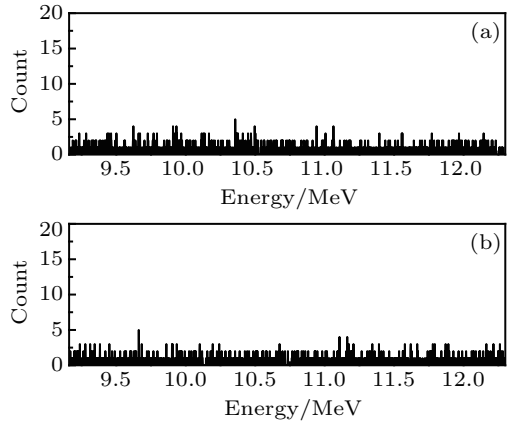


Fig. 3. Spectra of background with shielding of the lead cone: (a) with the accelerator on and (b) with the accelerator off.

As we can see in Fig. 2, 9170 keV is the maximum energy in the spectrum, so there should be no background disturbance except high energy cosmic rays. In the background spectrum, we did not find other peaks around 9170 keV. Figure 3(a) shows the background spectrum with shielding of the lead cone, and figure 3(b) shows the spectrum when the accelerator is turned off. The count rates are much the same in these two spectra. For 9170 keV, the background count rates are both about $3\times10^{-5}/(\mathrm{s}\cdot\mathrm{keV})$.

3.1. Detector efficiency

In ^{13}C(p, γ)^{14}N resonance reaction, the energy range of γ-rays is 1635 keV to 9170 keV, thus we should calibrate the efficiency of HPGe detector in this range. However, the maximum energy of γ-rays from γ-ray sources is only about 3.5 MeV. The common method for calibrating the efficiency in high energy range is using the γ-rays from (p, γ) and (n, γ) reaction.

Many researchers simulated the relative efficiency using GEANT4 code, and found that the result is in good agreement with that using the γ-rays from nuclear reactions. We calibrated the absolute full-peak efficiencies in the energy range 0 MeV–3 MeV using standard sources and the relative full-peak efficiencies in energy range 0 MeV–9.5 MeV using GEANT4 Code. The simulation can only present relative efficiencies, so they should be normalized to the experimental data of standard sources using a transmission factor, s. For a better fit, the transmission factor was determined with the least-squares fit, $\chi^2 = \Sigma[(1/\sigma_i^2)(x_i - s*y_i)^2]$, in which the x_i and y_i are experimental data and simulation data, respectively. We found χ^2 will be the minimum when $s = 0.712$. We then used many functions to fit the efficiency curve, and found a power-law function giving an excellent fit to experimental and simulated efficiency data,

$$\varepsilon(E_\gamma) = aE_\gamma^{b+cE_\gamma}. \quad (1)$$

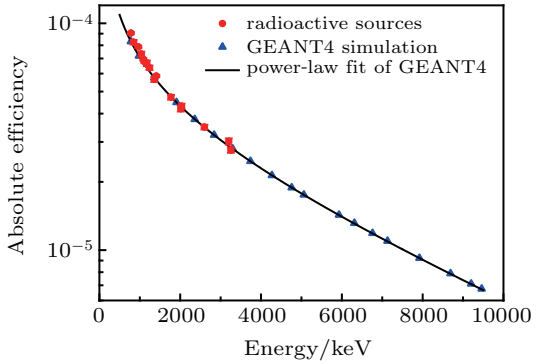


Fig. 4. Absolute full-energy-peak detecting efficiency of HPGe at 28°, 69-cm distance from the target, determined with ^{56}Co and ^{152}Eu sources and GEANT4 Code simulation. The circles are experimental data from sources; The triangles are GEANT4 Code simulation data; The line is the power-law fit to the simulated data.

The efficiencies determined by standard sources and GEANT4 simulation are shown in Fig. 4. We also determined the relative efficiencies with relative intensities of 2143, 2313, 2726, 6445, 7027, and 9170 keV, which have been measured by Kiener[9] and γ-ray counts of each energy in our experiment. This also gave a good fit to what we got from the

method mentioned earlier, as shown in Fig. 5. Finally, we determined the absolute efficiency of HPGe at 9.17 MeV to be $\varepsilon = 7.21 \times 10^{-6}$, which have been normalized to the experimental data.

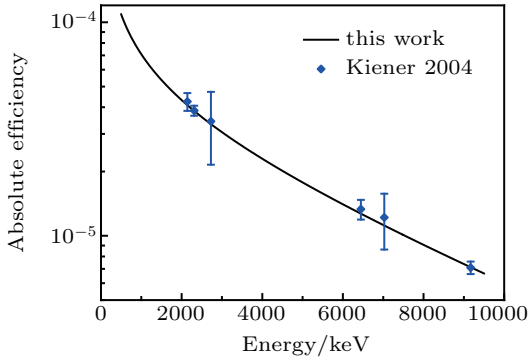


Fig. 5. Comparison of efficiencies obtained from this work and that from calculated with relative intensities of several lines measured by Kiener[9] which have been normalized to the fit line.

3.2. Angular distribution

There exists a yield angular distribution for the 9.17-MeV line in ^{13}C(p, γ)^{14}N resonance reaction. The measurement of angular distribution is necessary to calculate the yield in 4π. The angular distribution of emission probability of γ-rays is related to the primary and final spin angular momentum of the de-excitation. The following expression gives the angular distribution

$$W(\theta) = A_0 + A_2 \mathrm{P}_2 \cos(\theta) + A_4 \mathrm{P}_4 \cos(\theta) + \cdots, \tag{2}$$

where A_{2n} is the function of particle energy and angular momentum, $\mathrm{P}_{2n}(\cos\theta)$ is Legendre polynomial expansion:

$$\begin{aligned} &\mathrm{P}_0(\cos\theta) = 1, \\ &\mathrm{P}_2(\cos\theta) = \frac{1}{2}(3\cos^2\theta - 1), \\ &\mathrm{P}_4(\cos\theta) = \frac{1}{8}(35\cos^4\theta - 30\cos^2\theta + 3), \\ &\vdots, \end{aligned}$$

where n is the smaller value of the entrance and exit particle spin and compound nucleus spin. For 9.17-MeV line in ^{13}C(p, γ)^{14}N, n is 2, so the maximum power of $\cos\theta$ is 4.

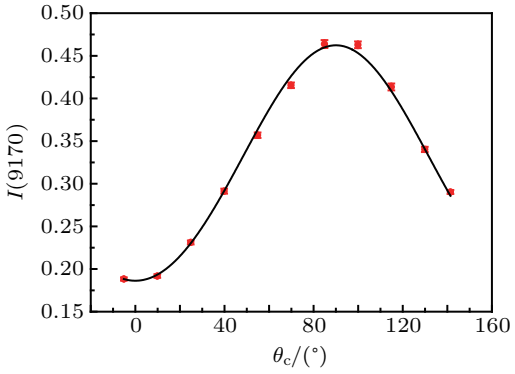


Fig. 6. Angular distribution for 9.17-MeV γ-ray from ^{13}C(p, γ)^{14}N. The circle is the experimental data using $LaBr_3$ detector. The line is the fitting curve following $W(\theta) = A_0 + A_2\mathrm{P}_2\cos(\theta) + A_4\mathrm{P}_4\cos(\theta)$.

The relative intensity data were measured with $LaBr_3$ detector and fitted by $W(\theta)$ described earlier, as shown in Fig. 6. The coefficients were determined to $A_2/A_0 = 0.512 \pm 0.010$, $A_4/A_0 = 0.021 \pm 0.011$.

3.3. Thick-target yield of 9.17-MeV γ-ray

We measured the yield curve for 9.17-MeV γ-ray from ^{13}C(p, γ)^{14}N in the energy range 1.74 MeV–1.78 MeV of protons, as shown in Fig. 7. There is a plateau from 1.750 MeV to 1.758 MeV. We also simulated the yield curve by use of GEANT4 Code. The simulation gives a well fit with the experimental data. So we confirm that this is a thick-target and we can measure the thick-target yield using the proton with energy from 1.750 MeV to 1.758 MeV.

The calculation of thick-target yield can be written as

$$Y = \int Y(\theta)\mathrm{d}\Omega, \tag{3}$$

where $Y(\theta)$ is the yield in unit solid angle at θ. $Y(\theta) = Y(\theta_0)W(\theta)/W(\theta_0)$, θ_0 is degree where the detector was established, and

$$Y(\theta_0) = \frac{N_\gamma}{N_\mathrm{p}\varepsilon}, \tag{4}$$

where N_γ is the counts of γ-ray of 9.17 MeV with detector, N_p is the number of protons which irradiated on ^{13}C target during the measurement, and ε is the absolute efficiency of the detector. Since $\mathrm{d}\Omega = \sin(\theta)\mathrm{d}\theta\mathrm{d}\varphi$, equation (4) can be written as

$$Y = \iint_0^\pi Y(\theta)\sin(\theta)\mathrm{d}\theta\mathrm{d}\varphi = 2\pi\int_0^\pi Y(\theta)\sin(\theta)\mathrm{d}\theta. \tag{5}$$

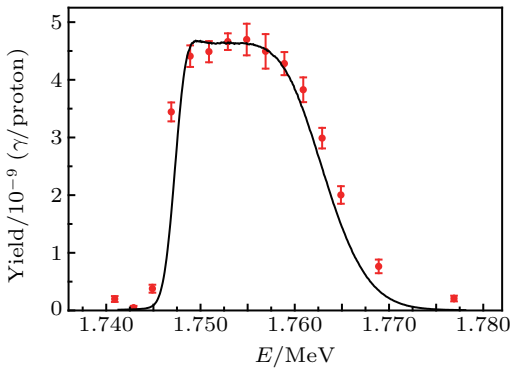


Fig. 7. Yield curve for 9.17-MeV γ-ray from ^{13}C(p, γ)^{14}N.

Finally, we determined the thick-target yield of 9.17-MeV γ-ray to $(4.7\pm0.4)\times10^{-9}\gamma$/proton. The values with obtained by Seagrave and Hanna[5,8] are 11.5×10^{-9} γ/proton and $(7.4\pm3)\times10^{-9}$ γ/proton, respectively. As mentioned earlier, the former used Geiger–Muller counter to detect γ-ray, thus there was no separation for 9.17-MeV γ-ray from other energy. The resolution of NaI detector is not enough high to distinguish full-energy peak and single escape peak, so the number of 9.17-MeV γ-ray may be not precise.

4. Summary

To explore the potential of γ-ray from resonance reaction in nuclear waste transmutation, flash photographics, and astrophysics, we determined the thick-target yield of 9.17-MeV γ-ray from $^{13}C(p,\gamma)^{14}N$ to be $(4.7\pm0.4)\times10^{-9}$ γ/proton. The detector that we used in our experiment was a high resolution coaxial HPGe detector, the absolute efficiencies of the detector have been calibrated with radioactive sources and GEANT4 simulation. To calculate the yield of 9.17-MeV γ-ray at 4π, angular distribution of 9.17-MeV γ-ray has been determined. According to this value, the γ-ray flux will be about 3.7×10^{9}/s in an accelerator with proton flux of 125 mA, which is already achieved.[10]

Acknowledgments

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