

Study on γ-ray source from the resonant reaction $^{19}F(p,\alpha\gamma)^{16}O$ at E_p=340 keV

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Study on γ-ray source from the resonant reaction $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ at $E_\mathrm{p} = 340$ keV*

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High energy γ-ray can be used in many fields, such as nuclear resonant fluorescence, nuclear medicine imaging. One of the methods to generate high-energy γ-ray is nuclear resonant reaction. The $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction was used to generate 6.13-MeV γ-ray in this work. The angular distribution of 6.13-MeV γ-ray was measured by six $LaBr_3$ detectors. The thick-target yield curve of 6.13-MeV γ-ray had been measured. The maximum yield was determined to be $(1.85\pm 0.01)\times 10^{-8}$ γ/proton, which was measured by HPGe detector and $LaBr_3$ detector. The absolute efficiency of all the detectors was calibrated using ^{60}Co and $^{27}\mathrm{Al}(\mathrm{p},\gamma)^{28}$Si reaction at $E_\mathrm{p} = 992$ keV. The cross section and total resonant width of the reaction were determined to be 95.1 ± 1.0 mb (1 b $= 10^{-24}$ cm^2) and $\Gamma_\mathrm{CM} = 2.21\pm 0.22$ keV, respectively.

Keywords: high-energy γ-ray source, thick-target yield, resonant reaction, cross section

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1. Introduction

High energy γ-ray can be used in many important applications from γ radiography to nuclear materials detection.[1–3] Lots of applications are strongly related to photonuclear reactions. The cross section of photonuclear reactions reaches its maximum in giant dipole resonance (GDR) energy range.[4] Therefore, γ-rays in a high energy range of 5 MeV–30 MeV have important significance in many aspects. Here we will mainly introduce the applications on nuclear reactor design[5] and nuclear astrophysics.[6–8] In nuclear reactor design, accurate cross sections of photonuclear reactions are needed in many areas as photonuclear reaction plays a non-negligible role in nuclear reactors, such as reactor in-core dosimetry, radiation damage estimates in reactor structural materials, safeguards, and fast reactor calculations, *etc*. In nuclear astrophysics, one of the unanswered questions is to determine how the heavy elements were synthesized during the evolution of universe.[9] It is widely accepted that the bulk of the nuclei heavier than iron has been synthesized by neutron capture in the astrophysical r- and s-processes. Those neutron-capture processes cannot account for the synthesis of some of the heavy ($A \geq 100$) neutron-deficient nuclei. These nuclei are shielded from the chain of β decays by other stable isobars. The production mechanism for these so-called p-nuclei[10] is photodisintegration in the astrophysical γ process by successive(γ, n), (γ, p), and (γ, α) reactions.

The difficulty among these studies discussed above is that photonuclear cross-section data are scarce in GDR energy range,[11,12] and especially there is a lack of data in some important cases. So a bright γ-ray source should be established for studying photonuclear cross-section data. The (p, γ) resonance is a good way to produce high energy monoenergetic γ-ray. There are several different reactions to be chosen to produce high energy γ-ray ranging from 6 MeV to 20 MeV. The energy range just fits in the GDR region. In this work, the 6.13-MeV γ-ray can be generated from the $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction. Also, the $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction plays a crucial role for the net CNO mass fraction in nuclear astrophysics.[13] In addition, particle-induced γ-ray emission (PIGE) is a common technique used to detect and analyze elements lighter than calcium.[14] $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction can help to study the concentration of fluorine in dentistry.[15,16] There are a variety of fundamental and applied reasons for studying this reaction.[17] Precise measurements of γ yield must be carried out before these applications are studied using the high-energy γ ray produced by the $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction. According to the Breit–Wingner formula, the cross section and

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the width of the resonance are the key parameters of the resonance reaction.[18,19]

The measurement for the resonance parameters of the ^{19}F(p, $\alpha\gamma$)^{16}O reaction at $E_p = 340$ keV have been studied by several investigators. They have measured the resonant energy, maximum cross section, and the width of the total reaction, *etc*. In 1941, Strein measured the thick-target by using the electroscope.[20] In 1948, Bonner performed a new measurement, and obtained the new cross section and total resonance width of the reaction with GM counter.[21] With the development of detectors, Keszthelyi,[22] Dieumegrad,[23] Becker,[24] Uhrmacher,[25] Crof,[26] Spyrou,[27] and Couture[28] performed new experiments for the resonance parameters. But the parameters of resonance they had gotten were different from each other, and few people had measured the angular distribution of 6.13-MeV gamma ray's yield. The angular distribution of 6.13-MeV gamma ray's yield has been reported by Von Th Retz-Schmidt and Croft, respectively.[26,29] However, the results are vary widely from each other. There were no sufficient data to support the accuracy of yield of 6.13-MeV γ-ray in previous measurements. It is highly desirable to have a new measurement of the thick target yield with new detectors.

In the present study, we aim at getting the precise thick-target yield of 6.13-MeV γ-ray using the most advanced detectors up to now. First, the absolute efficiencies of HPGe and $LaBr_3$ detectors in energy range of 1.17 MeV–10.70 MeV was calibrated. Then the angular distribution of 6.13-MeV γ ray's yield had been measured, and the thick-target yield of 6.13-MeV γ-ray has been calculated. The flux of γ source from the resonant reaction ^{19}F(p, $\alpha\gamma$)^{16}O at $E_p = 340$ keV was determined finally. The new reference values of the total width of resonance and the maximum cross section were gained.

2. Experiment

The experiment was performed at the 2×1.7-MeV tandem accelerator in China Institute of Atomic Energy (CIAE). In this experiment, the current of proton beam was about 6 μA. In order to ensure the yield of 6.13-MeV γ-ray only from the resonant reaction at $E_p = 340$ keV, the proton beam was accelerated to the energies from 322 keV to 434 keV with a beam-spot of 4 mm, and the beam bombarded onto the natural LiF target. The thickness of target is 180 μg/cm^2. The target was evaporated on an air-cooled Ta disk which is 300-μm thickness with a diameter of 19.5 mm. As a vacuum barrier, the Ta disk placed at the end of the beam pipe. The beam pipe is 400-mm long and with an inner diameter of 18 mm. The beam pipe was electrically isolated from the the pipe in the upstream. So we used the beam pipe for recording the quantity of protons. The escape probability for secondary electrons is approximately 0.013% by assuming an isotropic emission. Wilson[30] and Criswell, *et al*.[31] had proven that the secondary electron emission has smaller cross sections at most backward angles. Therefore, the charge collection was reliable. A pure Ta disk of 300 μm in thickness was used to evaluate the in-beam background.

One coaxial HPGe detector and six $LaBr_3$ detectors of $\phi 3 \times 4$ inch (1 inch = 2.54 cm) were used for detecting the γ-ray. In the experiment, the HPGe detector was placed at 14.5-cm distance from the target position at 72° in the direction of proton beam. In order to get the yield of full space, the $LaBr_3$ detectors were used to detect the γ-ray angular distribution from 0° to 165°. We used six $LaBr_3$ detectors placed at 50-cm distance from the target position at 0°, 30°, 60°, 90°, 120°, and 150° to the beam axis, respectively. The experiment data of 15°, 45°, 75°, 105°, 135°, and 165° had been obtained by increasing 15° of each $LaBr_3$ detector's direction. The HPGe detector was used as a monitor of the yield at the same time. The experimental setup is shown in Fig. 1.

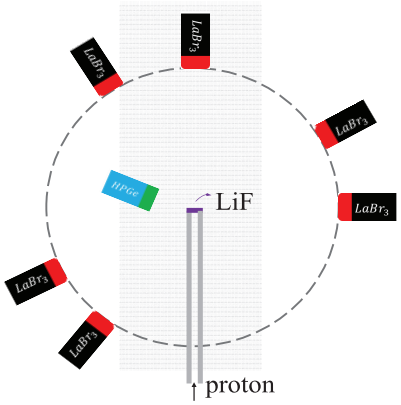


Fig. 1. Layout of experimental setup. The target is at the end of the beam pipe. $LaBr_3$ detectors were used for measuring the angular distribution of γ-ray's yield.

In ^{19}F(p, $\alpha\gamma$)^{16}O resonance reaction, the energy of γ-ray we concerned is 6.13 MeV, so we should calibrate the efficiency of HPGe and $LaBr_3$ detectors at this energy. However, the maximum energy of γ-ray 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-ray from (p, γ) and (n, γ) reactions. The γ-ray form 1.77 MeV to 10.76 MeV could be generated from the ^{27}Al(p, γ)^{28}Si reaction at $E_p =$ 992 keV which usually as a standard reaction for efficiency calibration.[32] So we used ^{60}Co and ^{27}Al(p, γ)^{28}Si reaction at $E_p = 992$ keV for calibrating the efficiency of all the detectors. The solid angle keeps the same during the calibration and bombarding the target. The energy calibration of detectors has been performed with 1.46-MeV γ-ray and 2.16-MeV γ-ray of natural radioactive nuclide, ^{40}K and ^{208}Bi.

We calibrated the absolute full-peak efficiencies at 1.17 MeV and 1.33 MeV using ^{60}Co and the absolute full-peak efficiencies in an energy range of 1.77 MeV–10.76 MeV using ^{27}Al(p, γ)^{28}Si reaction. Finally, we obtained the absolute full-peak efficiencies from an energy range of 1.17 MeV–10.76 MeV. For a better fit, the absolute full-peak efficiency

was determined by the full-peak efficiencies curve with the least-squares fit. Figure 2 shows the efficiency curve of HPGe and $LaBr_3$ detector at 0°.

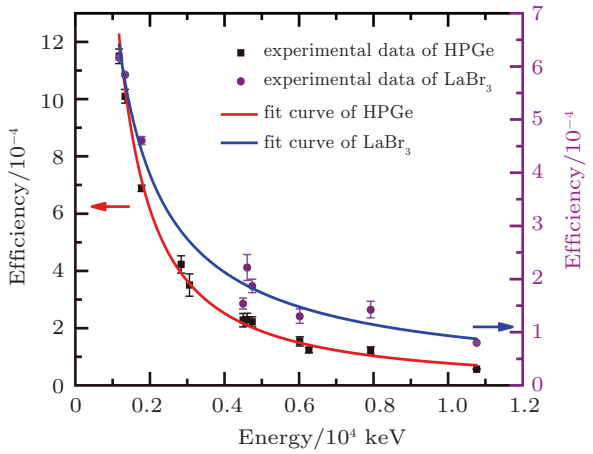


Fig. 2. Absolute full-energy-peak detecting efficiency of HPGe detector and $LaBr_3$ detector at 0°. The squares are experimental data of HPGe, the red line is the power-law fit to the experimental data, the circles are experimental data of $LaBr_3$ detector at 0°, the blue line is the power-law fit to the experimental data.

Finally, we determined the absolute efficiency of 6.13-MeV γ-ray for HPGe is $\varepsilon = 1.44 \times 10^{-4}$, and the absolute efficiency of 6.13-MeV γ-ray for $LaBr_3$ at 0° is $\varepsilon = 1.45 \times 10^{-4}$. These data were used for calculating the yield of 6.13-MeV γ-ray.

3. Data analysis

The spectrum of γ-ray measured by HPGe detector and $LaBr_3$ detector at 75° is shown in Fig. 3. There are several γ-ray lines in the spectrum and the intensity of 6.13-MeV γ-ray is the largest in the spectrum detected by HPGe and $LaBr_3$ detectors. In Fig. 3(a), the full width at half maximum (FWHM) of the 6.13-MeV full energy peak is 8.09 keV. In Fig. 3(c), the energy resolution of the 6.13-MeV full energy peak is 1.1%.

As we can see in Figs. 3(b) and 3(d), 6.13 MeV is not the maximum energy in the spectrum, the double escape peak of 7.12 MeV overlaps with the full energy peak of 6.13 MeV due to the energy resolution and the volume of the detector. The count of the double escape peak of 6.13 MeV is roughly the same as that of its total energy peak from the energy spectrum. Hence, we can approximately assume that the total energy peak count of 7.12 MeV is equal to its double escape peak count. The intensity of 6.13-MeV γ-ray would increase by 0.98% as a result of double escape of 7.12-MeV γ-ray. There should not be background from the disturbance except high energy cosmic rays and the double escape peak of 7.12 MeV. In the background spectrum, we did not find other high energy peak than 7.12 MeV. The cosmic background count rates had been discussed in the previous work.[19]

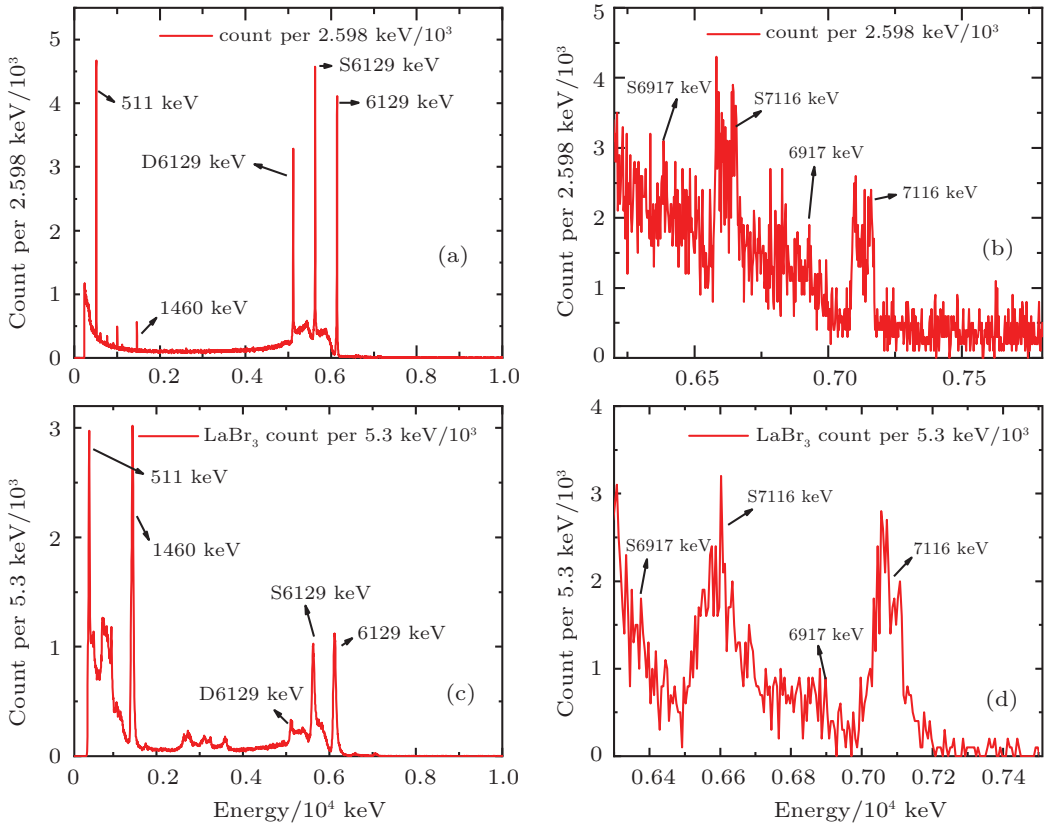


Fig. 3. Spectrum of γ-rays from the $^{19}F(p, \alpha\gamma)^{16}O$: panels (a) and (b) came from HPGe detector; panels (c) and (d) came from $LaBr_3$ detector. S6129 and D6129 represent the single escape peak and the double escape peak of 6129-keV γ-ray, respectively.

To determine the ^{19}F(p, $\alpha\gamma$)^{16}O reaction cross sections, it is necessary to obtain the absolute number of produced compound nuclei $N_{\rm comp}$. An excited compound nucleus always decays to the ground state. So the $N_{\rm comp}$ is equal to the total counts 6.13-MeV γ-ray of 4π. We use Y as the thick-target yield of 4π.

The measurement of the angular distribution is necessary for calculating the yield in full space.[26,29] The γ-ray angular distribution of emission probability is related to the initial and final spin angular momenta of the de-excitation. The relative intensity data were measured with $LaBr_3$ detectors and fitted by Legendre function which could be expressed to $W(\theta) = A_0 + A_2P_2\cos(\theta) + A_4P_4\cos(\theta)$. The angular distribution of 6.13-MeV gamma ray is shown in Fig. 4. The coefficients were determined to be $A_2/A_0 = -0.0821 \pm 0.0053$, $A_4/A_0 = -0.0203 \pm 0.0061$.

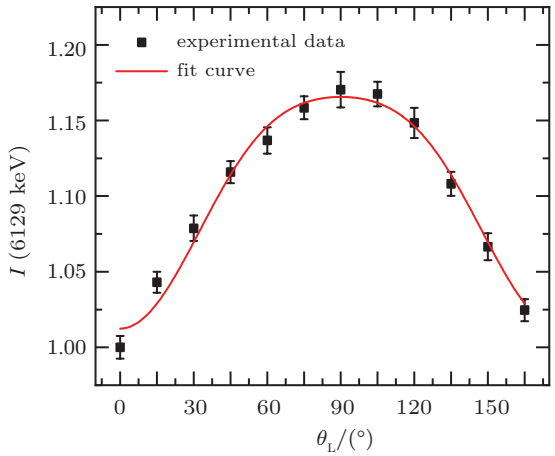


Fig. 4. Angular distribution for 6.13-MeV γ-ray from ^{19}F(p, $\alpha\gamma$)^{16}O. The squares are the experimental data using $LaBr_3$ detector. The line is the fitting curve following $W(\theta) = A_0 + A_2P_2\cos(\theta) + A_4P_4\cos(\theta)$.

The formula of thick-target yield can be written as

$$Y_{\rm max} = \int Y(\theta)\,{\rm d}\Omega, \tag{1}$$

where $Y(\theta)$ is the yield in unit solid angle at a certain angle θ. $Y(\theta) = Y(\theta_0)W(\theta)/4\pi W(\theta_0)$, θ_0 is degree where the detector was established,

$$Y(\theta_0) = \frac{N_\gamma}{N_{\rm p}\varepsilon}, \tag{2}$$

where N_γ is the count of γ-ray of 6.13 MeV measured with detector, $N_{\rm p}$ is the number of protons which irradiated on LiF target during the measurement, and ε is the absolute efficiency of the detector. Since ${\rm d}\Omega = \sin(\theta)\,{\rm d}\theta\,{\rm d}\varphi$, equation (1) can be written as follows:

$$\begin{aligned} Y_{\rm max} &= \int_0^{2\pi}\int_0^{\pi} Y(\theta)\sin(\theta)\,{\rm d}\theta\,{\rm d}\varphi \\ &= 2\pi\int_0^{\pi} Y(\theta)\sin(\theta)\,{\rm d}\theta. \end{aligned} \tag{3}$$

The calculation of cross section can be written as

$$\sigma_{\rm r} = \frac{4\varepsilon_1 Y_{\rm max}}{2\pi\Gamma}, \tag{4}$$

where $\sigma_{\rm r}$ is the maximum cross section of the reaction. ε_1 is the energy loss of a single molecule of LiF.[33] Γ is the total width of resonance after correction. $Y_{\rm max}$ is the maximum yield of the reaction which can be obtained from Eq. (3).

The width of the resonance can be correction as

$$\Gamma'^2 = \Gamma^2 + \Delta E_{\rm a}^2, \tag{5}$$

where Γ' is the width of the resonance which can be obtained from Fig. 5. $\Delta E_{\rm a}$ is the energy dispersion of the accelerator.

4. Results and discussion

We measured the thick target yield curve of 6.13-MeV γ-ray from ^{19}F(p, $\alpha\gamma$)^{16}O reaction with beam energy of 322 keV–434 keV, as shown in Fig. 5. There is a plateau from 350 keV to 362 keV, which corresponds to the max thick target yield of 6.13-MeV γ-ray measured from the detector.

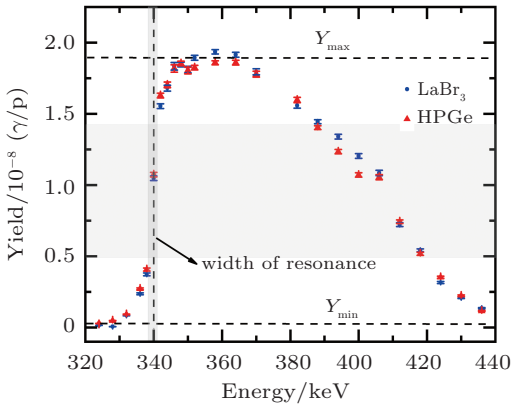


Fig. 5. Yield curve for 6.13-MeV γ-ray from ^{19}F(p, $\alpha\gamma$)^{16}O. The blue circles are experiment data of the $LaBr_3$ detector at 0°, and the red triangles are experiment data of the HPGe detector.

Finally, we determined the thick-target yield of 6.13-MeV γ-ray from the resonant reaction ^{19}F(p, $\alpha\gamma$) ^{16}O at $E_{\rm p}$ = 340 keV is $(1.85 \pm 0.01) \times 10^{-8}$ γ/proton. The total resonance width of the reaction was determined by the absolute value of the energy difference corresponds to 25%–75% of the maximum yield in the thick target yield curve. An apparent resonance width of 2.7 keV is deduced from Fig. 5. After correction for the beam energy dispersion and transformation to the centre-mass reaction frame a resonance width parameter, $\Gamma_{\rm CM} = 2.21 \pm 0.22$ keV was obtained. The maximum cross section was also determined by the thick-target yield and the resonance width. The value of maximum cross section is 95.1 ± 1.0 mb.

Precise measurements of 6.13-MeV γ-ray have been made by our laboratory. Some key parameters havee been provided. The experimental parameters measured in the present work are also compared with the previous experimental data. And the specific details were shown in Table 1. As we can see

from Table 1, the values of the thick-target yield and the resonance obtained by the former researchers were different from each other. As mentioned above, in 1940s, Bonner, *et al.* used the Geiger–Muller counter to detect the γ-ray, so it could not distinguish the 6.13-MeV γ-ray from other energies of the γ-ray. So the error of 6.13-MeV γ-ray's yield is relatively large. The value of Croft's results might also be not accurate enough because of the angular distribution. The angular distribution of the present work is different from that of Croft's result. Yet the trend is the same as it was shown by Retz-Schmidt[29] which is symmetric about 90°. In this work, we used the up-to-date detectors including $LaBr_3$ and HPGe to gain the precise thick target yield of the 6.13-MeV γ-ray by accurate efficiency calibration and measurement of the angular distribution. Some new reference values of the total width of the resonance and the maximum cross section have been achieved in our experimental studies.

Table 1. Measured resonance parameters compared with others.

Works	Cross section/cm^2	Total widthΓ_t/keV	Thick target yield/proton
Strein[20]	–	–	1.8×10^{-8}
Bonner[21]	5.9×10^{-26}	3.2	6.56×10^{-9}
Fowler[33]	6.5×10^{-26}	4	1.74×10^{-8}
Keszthelyi[22]	–	2.9	–
Dieumegrad[23]	–	2.5 ± 0.2	–
Beacker[24]	8.8×10^{-26}	2.2 ± 0.06	–
Uhrmacher[25]	–	2.4 ± 0.1	–
Croft[26]	–	2.08 ± 0.13	$(1.40\pm0.06)\times10^{-8}$
Spyrou[27]	9.3×10^{-26}	2.34 ± 0.04	–
Couture[28]	–	2.08 ± 0.34	–
Present work	$(9.51\pm0.95)\times10^{-26}$	2.21 ± 0.22	$(1.85\pm0.01)\times10^{-8}$

5. Conclusion

High energy γ-ray is useful in many fields. The yield of 6.13-MeV γ-ray from ^{19}F(p, $\alpha\gamma$)^{16}O reaction was reported diverse from each experiment. For exploring the high energy γ-ray from resonant reaction, we performed a new measurement for confirming 6.13-MeV γ-ray's thick target yield of ^{19}F(p, $\alpha\gamma$)^{16}O reaction. The detector we used in our experiment is a high resolution coaxial HPGe detector and high resolution $LaBr_3$ detectors. Besides, in order to calculate the yield of 6.13-MeV γ-ray at 4π, the angular distribution has been determined. We determined the 6.13-MeV γ-ray's flux from ^{19}F(p, $\alpha\gamma$)^{16}O to be $(1.85\pm0.01)\times10^{-8}\gamma$/proton. The width of the resonance and the maximum cross section were obtained from the present research.

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