19F(p,αγ)16O: Test Reaction for the Detection System PTOLEMEOS

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Abstract

The reaction ^{19}F(p,$\alpha\gamma$)^{16}O has been studied over the energy range E_p = 850 - 916 keV. The excitation function has been measured and the total cross section for the resonance at E_p = 872.11 keV has been deduced. By comparison of the deduced value of σ_R with previous ones, a test and/or a calibration of the results of simulation programs for the efficiency of our detection system can be extracted.

1 Introduction

The reaction ^{19}F(p, $\alpha\gamma$)^{16}O is the first of a series of reactions to be used for the efficiency calibration of the detection system PTOLEMEOS. This detection system is a 4π NaI spectrometer dedicated to (p,γ) reactions of interest in nuclear astrophysics [1]. The resonance selected to be measured is the one at E_p = 872.11 keV. The adopted values for the parameters E_R, Γ_R, of this resonance are ([2], [7]):

$$E_R = 872.11 \pm 0.20 \text{ keV} \qquad \Gamma_R = 4.53 \pm 0.16 \text{ keV}$$

The selection of this specific resonance was made taking into account the following criteria :

a. The large cross-section ($\sim$600mb) which turns the existence of the cosmic background to be negligible.

b. The existence of reliable previous measurements of the (p,α) part of the reaction ([2], [3], [4]. [5])

c. The fact that this resonance is often used for energy calibration [6] due to the accuracy and the reliability of the knowledge of E_R.

d. The absence of previous measurements of the total cross-section with 4π geometry.

It must be noticed here that another reaction $^{19}F(p,\gamma)^{20}Ne$ is also present, but the very low cross-section ($\sim 500\mu$b) and the high excitation energy ($E_x = 13678$ keV) of ^{20}Ne doesn't affect the measurements of the yield of the $^{19}F(p, \alpha\gamma)^{16}O$ reaction at all.

2   Theoretical analysis of the reaction

The Q-value of the $^{19}F + p$ reaction is $E_b = 12848$ keV [7]. For the resonance at $E_p = 872.11$ keV, $E_{cm} = 828.18$ keV, the excitation energy of the compound nucleus ^{20}Ne is 13678 keV, as mentioned above. ^{20}Ne transmits to ^{16}O via the emission of five groups of α-particles, as shown in figure 1. The α_0-group branch is not observable in our γ-ray measurements as it leads to the ground state of ^{16}O, while the α_π-group branch deexcitates via the production of an electron-positron pair. In fact, the ratio of γ-ray emission over e^+-e^- production is less than $2 \cdot 10^{-4}$ ([7] and references therein). The α_2-, α_3-, and α_4-group emission lead to the 2nd, 3rd and 4th excited state of ^{16}O respectively, which then deexcitate to the ground state emitting photons of corresponding energy 6.130, 6.917, and 7.117 MeV. The branching ratios for these three groups are [7] :

Branch	Branching ratio
α_2	73.3$\pm$ 3.7%
α_3	20.7$\pm$ 1.3%
α_4	6.0$\pm$ 0.3%

3   Experimental setup

The excitation function of the 872 keV resonance was measured for $E_p = 850$ - 916 keV in steps of 1 keV (figure 2) with the 4π NaI spectrometer PTOLEMEOS [1,8]. Considering the energies of the 3 γ-rays 6.130, 6.917, and 7.117 MeV, the window of integration was set to be 2.8 - 9.0 MeV. A typical
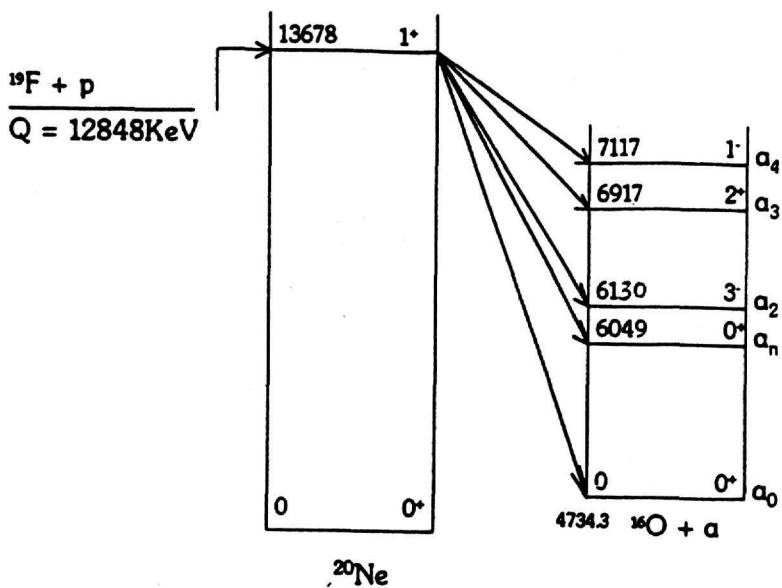
13678   **1⁺**

^{19}F + p

$\overline{Q = 12848KeV}$

7117   1⁻ a_4

6917   2⁺ a_3

6130   3⁻ a_2

6049   0⁺ a_n

0   0⁺ a_0

4734.3 ^{16}O + a

0   0⁺

^{20}Ne

Fig 1 : Decay scheme of ^{19}F(p,$\alpha\gamma$)^{16}O reaction

Yeff (mb*microgr/cm**2)

4000

3000

2000

1000

0

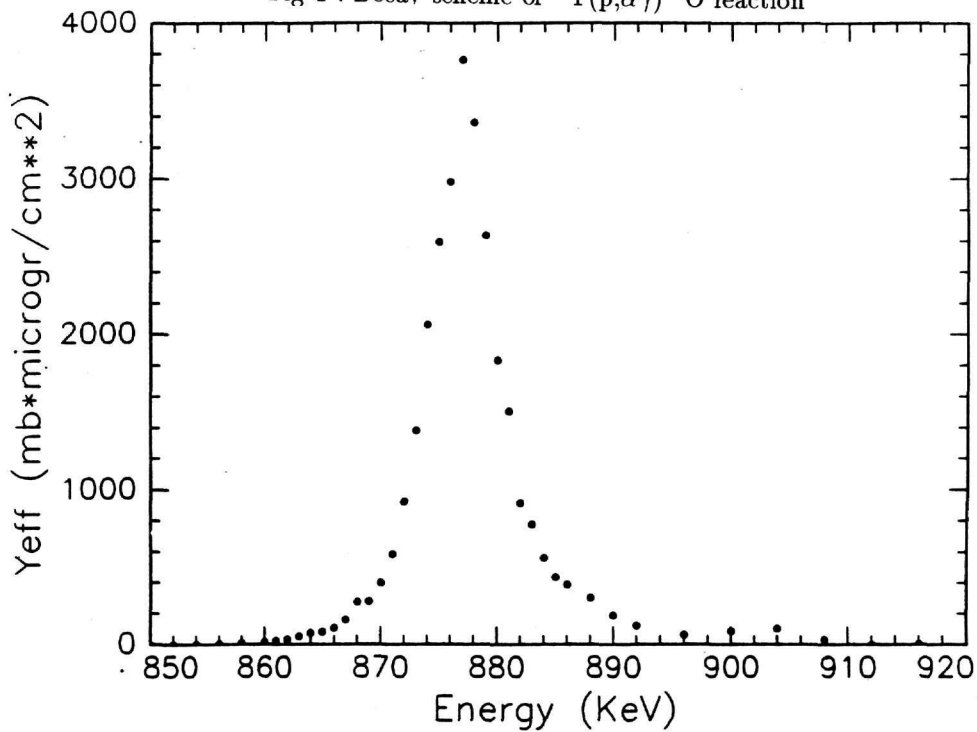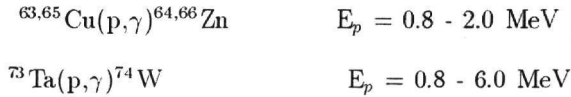850   860   870   880   890   900   910   920

Energy (KeV)

Fig. 2 : Excitation function for E_p = 850 - 916 keV.

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spectrum at E_p = 876 keV is shown in figures 3a and 3b. These figures refer to the single spectrum taken from one of the ten detectors and the sum spectrum respectively.

The target used in that experiment was made by evaporation of CaF_2 on a thick (0.7mm) copper backing. Cu and Ta, two candidates for backing of the target were tested with (p,γ) reactions :

$$^{63,65}Cu(p,\gamma)^{64,66}Zn \qquad\qquad E_p = 0.8 - 2.0 \text{ MeV}$$

$$^{73}Ta(p,\gamma)^{74}W \qquad\qquad E_p = 0.8 - 6.0 \text{ MeV}$$

As a result of these series of reactions, Ta was found to be unsuitable because of the existence of fluorine as a contamination. On the other hand, the yield from Cu(p,γ) reaction was negligible compared to the cosmic background, as shown in figures 4 and 5 respectively.

The thickness of the CaF_2 target was determined using two independent methods:

a. X-Ray Fluorescence (XRF)

b. From the experimental width of the excitation function which is related to the target thickness via the following equation :

$$\Gamma^2 = \Gamma_R^2 + \Delta_R^2 + \Delta_{beam}^2$$

where (in our case) :

$\Gamma = 6.2 \pm 0.5$ the experimental width

$\Gamma_R = 4.53 \pm 0.16$ the natural width of the resonance

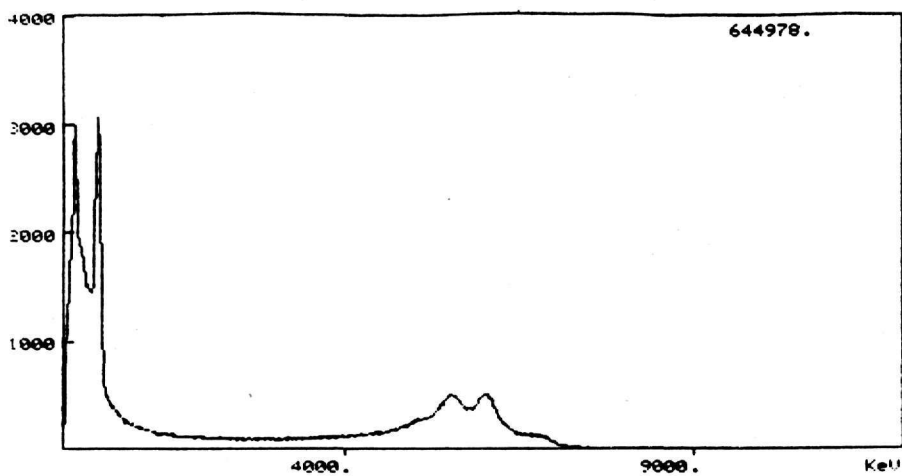$\Delta_{beam} = 1.0 \pm 0.2$ the beam energy spread

Fig 3a : Single spectrum from one of the ten detectors at E_p = 876 keV. Both the existence of 6.130 MeV γ - ray and the single-escape peak at 5.620 MeV are clearly shown.
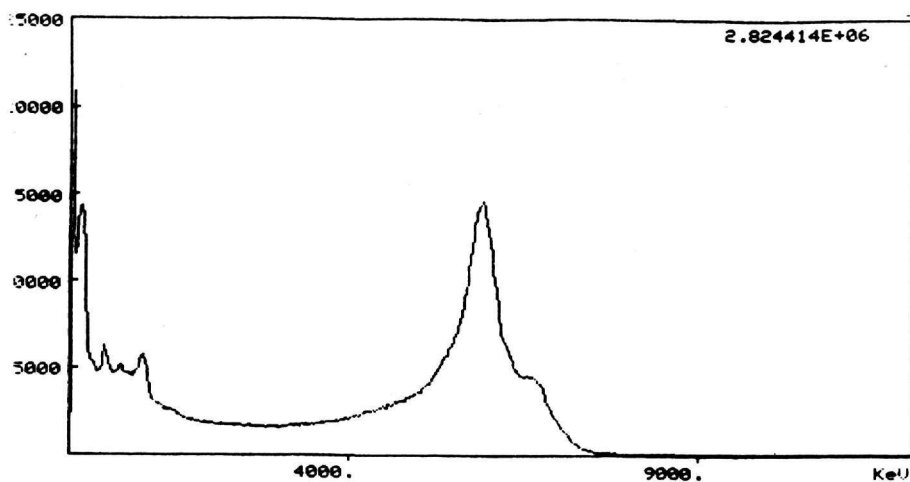

Fig. 3b : Sum spectrum at E_p = 876 keV.
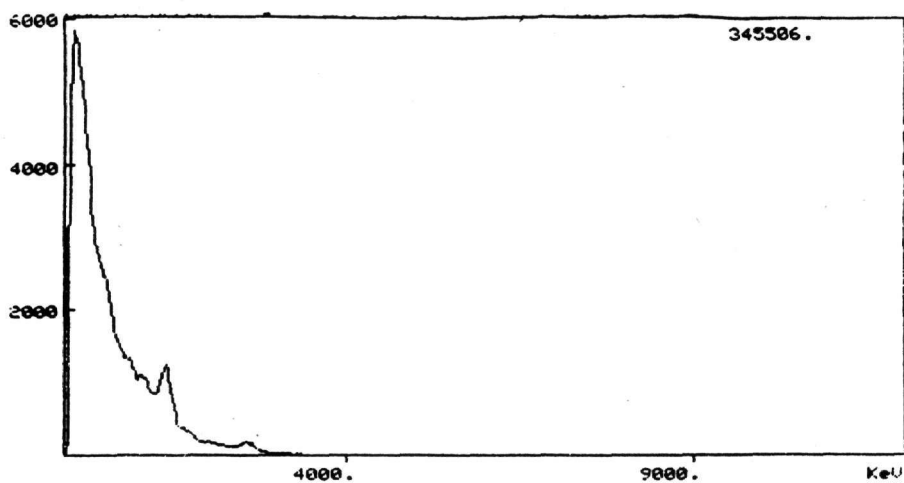
Fig 4 : Sum spectrum of the ^{63,65}Cu(p,γ)^{64,66}Zn reaction at E_p = 800 keV.

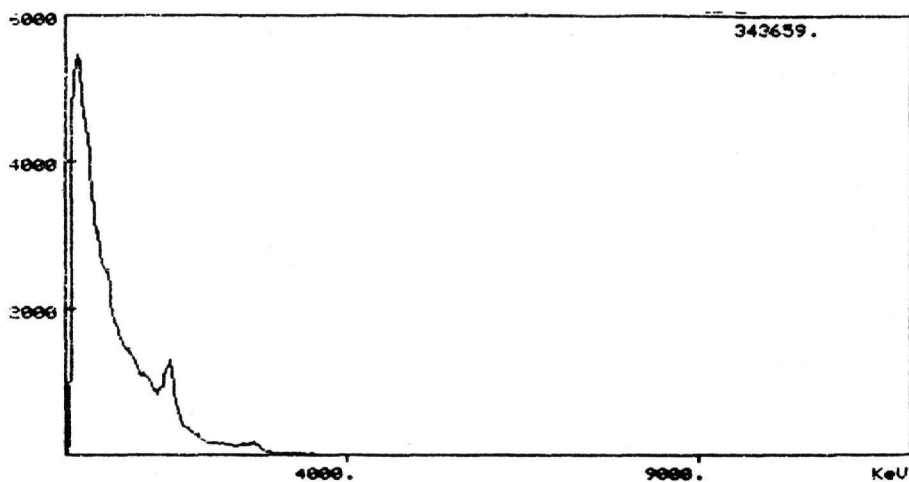Fig. 5 : Sum spectrum of cosmic background. Comparison with fig. 4 shows that the yield from Cu + p reaction is negligible.

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From (a) and (b) $\Longrightarrow$

$$\Delta_t = 21.5 \pm 0.7 \ \mu gr/cm^2 \ or$$

$$\Delta_t = 4.12 \pm 0.13 \ keV$$

Finally, the efficiency of our detector, for that particular window of integration and for each one of the three branches, was calculated with simulation programs using the GEANT code. The results are summarized in the following table

Table 1

Branch	Branching ratio	Efficiency (2.8-9.0 MeV)
α_2	$73.34 \pm 3.7\%$	0.54
α_3	$20.7 \pm 1.3\%$	0.57
α_4	$6.0 \pm 0.3\%$	0.56

The total efficiency is the linear combination of all the weighted independent efficiencies :

$$eff = \Gamma(\alpha_2) \cdot eff(\alpha_2) + \Gamma(\alpha_3) \cdot eff(\alpha_3) + \Gamma(\alpha_4) \cdot eff(\alpha_4) \Longrightarrow$$

$$eff = 0.55 \pm \delta eff \quad , \quad \delta eff = 5\% \cdot eff$$

4 Analysis and results

The reaction yield (per incident projectile) for a small target thickness compared to the resonance width is given [6] by :

$$Y = \sigma \cdot N^* \cdot eff \cdot dx \qquad (1)$$

where Y : the reaction yield

eff : the efficiency of the detection system

σ : the cross section of the reaction

N^* : target nuclei per unit volume

dx : target thickness

If the condition for a thin target is not fulfilled, the reaction yield per incident projectile is obtained by integrating the thin target yield over the target thickness :

$$Y_{eff}(E_0) = \int \sigma(E) \cdot dx = \int_{E_0-\Delta}^{E_0} \frac{\sigma(E)}{S(E)} \cdot dE \qquad (2)$$

where $Y_{eff}(E_0) = Y(E_0)/N^* \cdot eff$, and S(E) the stopping power of the target. In addition, one must consider the energy spread of the incident projectiles. Their energy distribution is given by $g(E, E_0)$, which can be sufficiently approximated in many cases with a Gaussian function :

$$g(E, E_0) = \frac{1}{\sqrt{2\pi}\delta_b} \cdot \exp\left(-\frac{(E-E_0)^2}{2 \cdot \delta_b^2}\right) \qquad (3)$$

where the FWHM of the distribution is given by :

$$\Delta_b = 2.355 \ \delta_b$$

Neglecting the effects of beam energy straggling inside the target, the reaction

yield $Y_{eff}(E_0)$ has to be folded with this energy distribution :

$$Y_{eff}(E_0) = \int_{E_0-\Delta}^{E_0} \int_0^\infty \frac{\sigma(E')}{S(E')} \cdot g(E', E_0) \cdot dE' \cdot dE \qquad (4)$$

The cross section of a narrow and isolated resonance is given by the Breit - Wigner formula :

$$\sigma(E) = \sigma \cdot \frac{\lambda^2}{4\pi} \cdot \frac{(2J+1)}{(2J_1+1) \cdot (2J_2+1)} \cdot (1 + \delta_{12}) \cdot \frac{\Gamma_a(E) \cdot \Gamma_b(E)}{(E-E_R)^2 + (\Gamma/2)^2} \qquad (5)$$

With the approximation $\Gamma_a(E) = \Gamma_a(E_R)$ and $\Gamma_b(E) = \Gamma_b(E_R)$, (5) $\Longrightarrow$

$$\sigma(E) = \sigma_R \cdot \frac{E_R}{E} \cdot \frac{(\Gamma/2)^2}{(E-E_R)^2 + (\Gamma/2)^2} \qquad (6)$$

(3), (6), $\Longrightarrow$

$$Y_{eff}(E_0) = \sigma_R \cdot A \qquad (7)$$

where

$$A = \int_{E_0-\Delta}^{E_0} \int_0^\infty \frac{1}{S(E')} \cdot \frac{E_R}{E} \cdot \frac{(\Gamma/2)^2}{(E-E_R)^2 + (\Gamma/2)^2} \cdot g(E', E_0) dE' \cdot dE$$

The quantity A can be calculated with numerical methods, because all the parameters are known.

The result of the present work for the cross section is :

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$$\sigma_R(\text{tot}) = 470 \pm 40 \text{ mb or}$$

$$\sigma_R(\alpha_2) = 350 \pm 30 \text{ mb}$$

5 Discussion

The comparison between the deduced value for σ_R and the previous ones is summarized in Table 2 :

Table 2

Previous measurements		Present work	$\delta\sigma_R/\sigma_R$
[2]	$\sigma_R(\alpha_2) = 440 \pm 13$mb	350 ± 30 mb	-20%
[3]	$\sigma_R(tot) = 560 \pm 80$mb	470 ± 40mb	-16%
[4]	$\sigma_R(tot) = 540 \pm 80$mb	470 ± 40mb	-13%

The results of our analysis give systematically lower values for σ_R. than the ones presented in previous publications. In the analysis presented here two effects have been neglected. First, the beam straggling effect inside the target, and second, the check of the real target stoichiometry, which may be different from the theoretical one after the evaporation. These effects will be taken into account in the near future, and the final results for the 872 keV resonance will be extracted.

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