Absolute measurement of the $5/2^+$ resonance of ^{36}Ar(p,γ)^{37}K at $E_\mathrm{p} = 918$ keV

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Abstract

The strength of the $5/2^+$ resonance of the reaction ^{36}Ar(p,γ)^{37}K at E_p = 918 keV was measured absolutely: $\omega\gamma = (258 \pm 24)$ meV. The new result is consistent with previous results. This resonance was used in several experiments as a calibration standard. Therefore we discuss our experimental uncertainties in detail which is important for the reliability of previous experiments and our new result.

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Recently, two resonances of the reaction ^{36}Ar(p,γ)^{37}K have been measured for different purposes. The low-energy resonance at $E_{\rm p} = 321$ keV is important for nuclear astrophysics because this resonance determines the reaction rate of the ^{36}Ar(p,γ)^{37}K reaction in hot and explosive hydrogen burning [1], and the measurement of the properties of the resonance at $E_{\rm p} = 1422$ keV helped to resolve a discrepancy found for Gamow-Teller strength distributions in $A = 37$ nuclei which were determined from β decay studies and from (p,n) cross section data [2]. However, all these resonance strengths have been determined relative to the $5/2^+$ resonance at $E_{\rm p} = 918$ keV (corresponding to $E_x = 2750.3$ keV in ^{37}K) which was measured absolutely by Goosman and Kavanagh in 1967 [3,4] using a gas cell filled with enriched ^{36}Ar and a NaI(Tl) detector in close geometry: $\omega\gamma = (208 \pm 30)$ meV. Unfortunately, no information on the uncertainties of about 15% is given in Ref. [3]. In a recent work de Esch and Van der Leun [5] used implanted ^{36}Ar targets and germanium detectors to determine spins, parities, branching ratios, and lifetimes of excited states in ^{37}K, but they did not try to determine absolute resonance strengths. Very recently, Hinnefeld *et al.* [6] have determined the resonance strength indirectly. They measured the total width of the resonance $\Gamma = (0.94 \pm 0.67)$ eV by the Doppler shift attenuation method, and they combined the total width Γ and the recently measured branching ratio $\Gamma_\gamma/\Gamma_{\rm p} = 0.69 \pm 0.15$ [7] to derive the resonance strength of $\omega\gamma = (680 \pm 490)$ meV. In this paper we present a direct and absolute measurement of the strength of the $5/2^+$ calibration resonance at $E_{\rm p} = 918$ keV.

The experiment was performed at the Van-de-Graaff accelerator, ATOMKI, Debrecen. The ^{36}Ar targets consisted of implanted ^{36}Ar into tantalum backings with a thickness of 0.4 mm. The targets were produced at the isotope separator of the University of Helsinki with an implantation energy of $E_{\rm imp} = 20$ keV and a charge density of $\rho_{\rm imp} = 11$ mC/cm^2 leading to an average implantation depth of 8.6 nm.

The number of implanted argon atoms was measured after the (p,γ) experiment by proton-induced X-ray emission (PIXE) at the PIXE setup of ATOMKI [8]. The X-rays were detected using a Si(Li) detector placed at an angle of 135° relative to the proton beam axis and covering a solid angle of 2.24×10^{-4}. The number of implanted ^{36}Ar atoms was determined from the comparison of measurements on the Ta backing with and without implanted ^{36}Ar atoms: $\rho(^{36}\mathrm{Ar}) = (1.33 \pm 0.09)\ \mu\mathrm{g/cm}^2$. The X-ray spectra were evaluated with the PIXYKLM code [9], which calculates the concentration and its uncertainty for the composite elements in μg/cm^2. The given overall uncertainty contains the uncertainties of beam current integration, detection solid angle, spectrum fitting procedure, and X-ray absorption in the Ar/Ta target. The efficiency determination of the Si(Li) detector was reported in Ref. [10], and the applicability of the PIXE method to thick targets was analyzed in Ref. [11]. The result for the target thickness is consistent with detailed analyses of the implantation of argon atoms in tantalum [12,13].

The γ rays from the ^{36}Ar(p,γ)^{37}K reaction were detected in a high-purity Germanium (HPGe) detector with 40% relative efficiency. The absolute efficiency of the HPGe detector at $E_\gamma = 1332.5$ keV was determined from a calibrated ^{60}Co source with a quoted uncertainty of 0.7% (National Office of Measures, Hungary), and the energy dependence of the efficiency was measured using an uncalibrated ^{56}Co source which was produced at the cyclotron of ATOMKI. The HPGe detector was placed at an angle of $\theta_\gamma = 55^\circ$ relative to the proton beam axis. At this angle the $P_2(\cos\theta)$ contribution of the γ ray angular distribution vanishes, and the contribution of $P_4(\cos\theta)$ is negligible [3,5]. The $5/2^+$ resonance at $E_\mathrm{p} = 918$ keV mainly decays to the ground state of ^{37}K with a γ ray energy of $E_\gamma = 2750.3$ keV [1,3–5]. A typical γ ray spectrum in the $E_\mathrm{p} = 918$ keV resonance is shown in Fig. 1.

The tantalum backing was thick enough to stop the protons. Therefore the target was water-cooled to reduce the target deterioration during the experiment. A cooling trap was installed to minimize the carbon deposition on the implanted targets. The accumulated charge was measured with an estimated accuracy of $\pm 3\%$ by standard charge integration. A suppression voltage of -300 V was used to reduce the influence of secondary electron emission from the target. Typical beam currents were in the order of 5 μA.

The resonance was measured three times. In the first step the shape of the yield curve was measured in a relatively close geometry (distance between detector and target: $d_\mathrm{close} =$ 26.8 mm). In the second step we measured the γ ray yield in the maximum of the yield curve at a larger distance between detector and target ($d_{\mathrm{far}} = 66.8$ mm) with good statistics. At this distance d_{far}, the detection efficiency does not depend as sensitively on the geometry as at the close distance d_{close}. Finally, we moved back to the close distance and checked again the shape and position of the yield curve. No significant target deterioration was found during the experiment: both, the energy and the width of the yield curve could be measured again within their uncertainties. The yield curve is shown in Fig. 2.

The resonance strength was determined from two different procedures: (i) from the shape and the amplitude of the yield curve and (ii) from the maximum of the yield curve.

The resonance strength of a narrow resonance is given by the integration of the yield curve over the resonance [14]:

$$\omega\gamma \;=\; \frac{\mu E_{\mathrm{r,c.m.}}}{(\pi\hbar)^2}\,\frac{\int Y(E_{\mathrm{c.m.}})\,dE_{\mathrm{c.m.}}}{N_{\mathrm{T}}\mathcal{E}} \quad , \tag{1}$$

where μ is the reduced mass, Y the γ-ray yield per incident proton, N_T the number of target atoms per cm^2, and $\mathcal{E}$ the efficiency of the HPGe detector. The result for the resonance strength is $\omega\gamma = 254 \pm 25$ meV. This result is independent of the stopping power of the protons in the mixed Ar/Ta target.

From the one data point at the maximum of yield curve at the distance d_{far} the resonance strength was determined using the thick target yield formula with additional semi-thick target corrections:

$$\omega\gamma = \frac{2\epsilon}{\lambda_R^2}\cdot\frac{A_T}{A_P + A_T}\cdot Y_{\mathrm{thick}} \quad , \tag{2}$$

where λ_R is the proton wavelength at the resonance energy, A_P and A_T the mass numbers of projectile and target, Y_{thick} the thick target yield of the resonance, and ϵ the effective stopping power of the ArTa compound:

$$\epsilon = \epsilon_{\mathrm{Ar}} + \frac{N_{\mathrm{Ta}}}{N_{\mathrm{Ar}}}\cdot\epsilon_{\mathrm{Ta}} \quad . \tag{3}$$

The semi-thick target correction was made by

$$Y(\xi) = Y_{\mathrm{thick}}\cdot\frac{2}{\pi}\cdot\arctan\left(\frac{\xi}{\Gamma'}\right) \quad , \tag{4}$$

where ξ is the target thickness and Γ' the energy difference between the quarter and three quarter maximum of the leading edge of the measured yield curve. This procedure leads to a resonance strength of $\omega\gamma = 270 \pm 40$ meV.

Our final result for the resonance strength is the weighted average of our two determinations: $\omega\gamma = (258 \pm 24)$ meV, taking into account that the uncertainties of the two determinations are independent with the exception of the PIXE result and the strength of the calibrated ^{60}Co source. This result is slightly higher than the previous result $\omega\gamma = (208 \pm 30)$ meV of Goosman and Kavanagh [3]. Our result already includes a small correction due to the weak branching (1.4%) of this $5/2^+$ resonance to the $7/2^-$ excited state at $E_x = 1380$ keV in ^{37}K [2,4,5].

The main uncertainties of our experiment are the number of Ar atoms in the target, the effective stopping power of the mixed Ar/Ta target (only in the second determination of the resonance strength), and the efficiency of the HPGe detector. The number of ^{36}Ar atoms was measured by PIXE with an accuracy of 6.5% (see above). The stopping power is dominated by the stopping of tantalum because (i) $Z(\mathrm{Ta}) = 73 >> Z(\mathrm{Ar}) = 18$, and (ii) the number of Ta atoms is a factor of 8.3 $\pm$ 10% higher than the number of Ar atoms. The stopping power of tantalum was taken from the Ziegler tables [15], and the value was corrected by 6% because of the additional stopping power of argon. The overall uncertainty of the effective stopping power (including the argon contribution) was estimated as 11%. The relative detector efficiency was determined from many γ ray lines from the ^{56}Co source with energies above and below the relevant γ ray energy of $E_\gamma = 2750.3$ keV. The uncertainty of the efficiency $\mathcal{E}(2750.3\text{ keV})$ is given by the uncertainties of the parameters a and b in the following equation:

$$\log \mathcal{E} = a \cdot \log E_\gamma + b \tag{5}$$

For our detector in the far geometry we obtained $\mathcal{E}_{\mathrm{far}}(2750.3\text{ keV}) = 1.92 \cdot 10^{-3} \pm 5.5\%$, and in the close geometry $\mathcal{E}_{\mathrm{close}}(2750.3\text{ keV}) = 5.39 \cdot 10^{-3} \pm 6.7\%$, including the minor uncertainty from the calibrated ^{60}Co source. Because of the relatively small distances d_{close} and d_{far}

cascade summing effects from coincident γ rays in the decay schemes of ^{56}Co and ^{60}Co had to be taken into account. The total uncertainty of each of our two results is given by the quadratic sum of the above uncertainties. Finally, after averaging both results, we end up with an overall uncertainty of 9.5% which is slightly smaller than the 14.4% uncertainty of Ref. [3] which was not discussed at all.

In conclusion, we have measured the resonance strength of the $5/2^+$ resonance of the reaction ^{36}Ar(p,γ)^{37}K at E_p = 918 keV absolutely. The average of our new result $\omega\gamma = (258 \pm 24)$ meV and the previously used strength of Goosman and Kavanagh $\omega\gamma = (208 \pm 30)$ meV [3] gives $(\omega\gamma)_\mathrm{average} = (238 \pm 19)$ meV which is consistent with the results of both experiments within their uncertainties, and the overall uncertainty of the resonance strength is reduced from about 15% to less than 10%. We did not include the result of Ref. [6] into the average value because of their large (72%) uncertainties.

The experimental results of Refs. [1,2] should be normalized to the new resonance strength of the $5/2^+$ calibration resonance. The final results are summarized in Table I. We obtain for the resonance strength of the resonance at 321 keV $\omega\gamma = (7.0 \pm 1.0) \times 10^{-4}$ eV instead of $\omega\gamma = (6.1 \pm 1.4) \times 10^{-4}$ eV [1], and for the resonance at 1422 keV $\omega\gamma = (6.9 \pm 1.0) \times 10^{-4}$ eV instead of $\omega\gamma = (6.0 \pm 1.5) \times 10^{-4}$ eV [2]. However, the main conclusions of Refs. [1,2,6] remain unchanged and are confirmed by this experiment.

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TABLES

TABLE I. Propoerties of ^{36}Ar(p,γ)^{37}K resonances. The partial widths of the 918 keV resonance are derived from the adopted resonance strength and the recently measured branching ratio $\Gamma_\gamma/\Gamma_\mathrm{p} = 0.545 \pm 0.030$ (weighted average from [16,7,17]). The total width $\Gamma = 348 \pm 28$ meV corresponds to a lifetime of $\tau = 1.89 \pm 0.15$ fs which is in agreement with the upper limit $\tau < 3$ fs [5] and in rough agreement with $\tau = 0.7 \pm 0.5$ fs [6].

E_p (keV)	E_x (keV)	J^π	$\omega\gamma^\mathrm{a}$ (meV)	$\omega\gamma^\mathrm{b}$ (meV)	$\omega\gamma$ (meV)	Γ_p (meV)	Γ_γ (meV)	Γ (meV)
918	2750	$5/2^+$	208 ± 30	258 ± 24	$238 \pm 19^\mathrm{c}$	225 ± 20	123 ± 10	348 ± 28
321	2170	$3/2^-$	0.61 ± 0.14		$0.70 \pm 0.10^\mathrm{d}$			
1422	3240	$(5/2, 7/2)^+$	0.60 ± 0.15		$0.69 \pm 0.10^\mathrm{d}$			

[a]from Refs. [3,1,2]

[b]this work

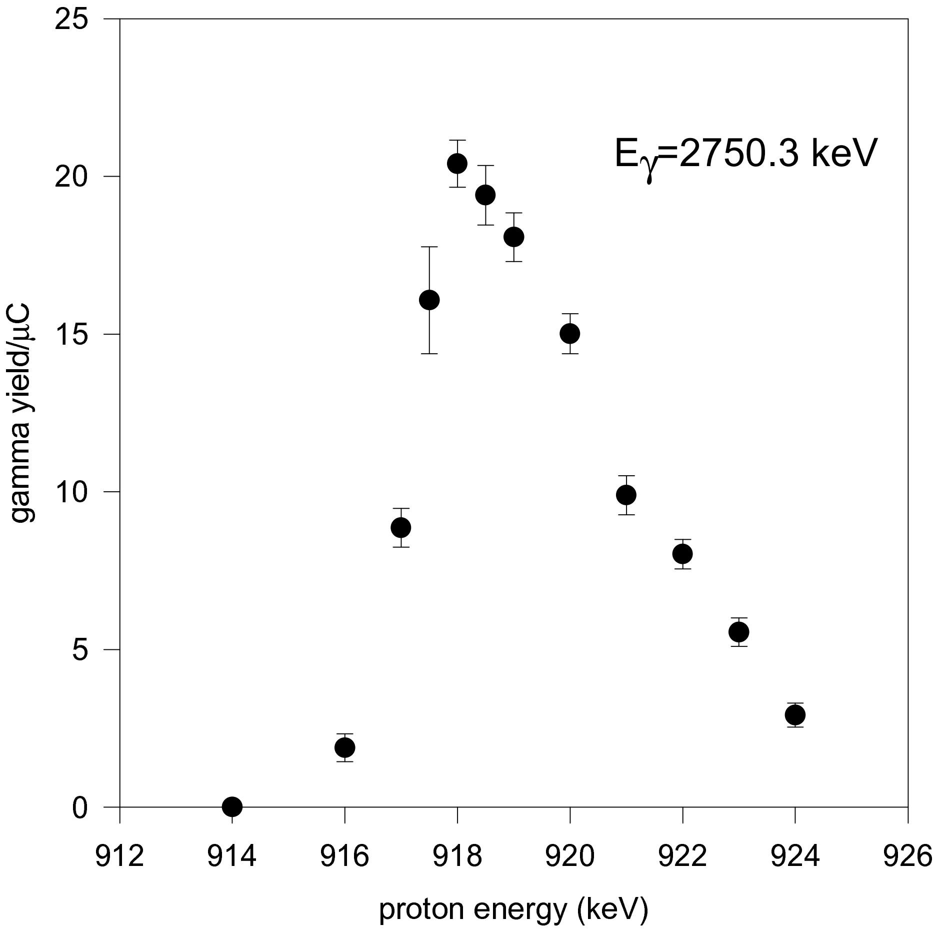
[c]weighted average from this work and Ref. [3]

[d]adopted strengths: from Refs. [1,2] normalized to the new adopted strength of the 918 keV resonance given in the first line.

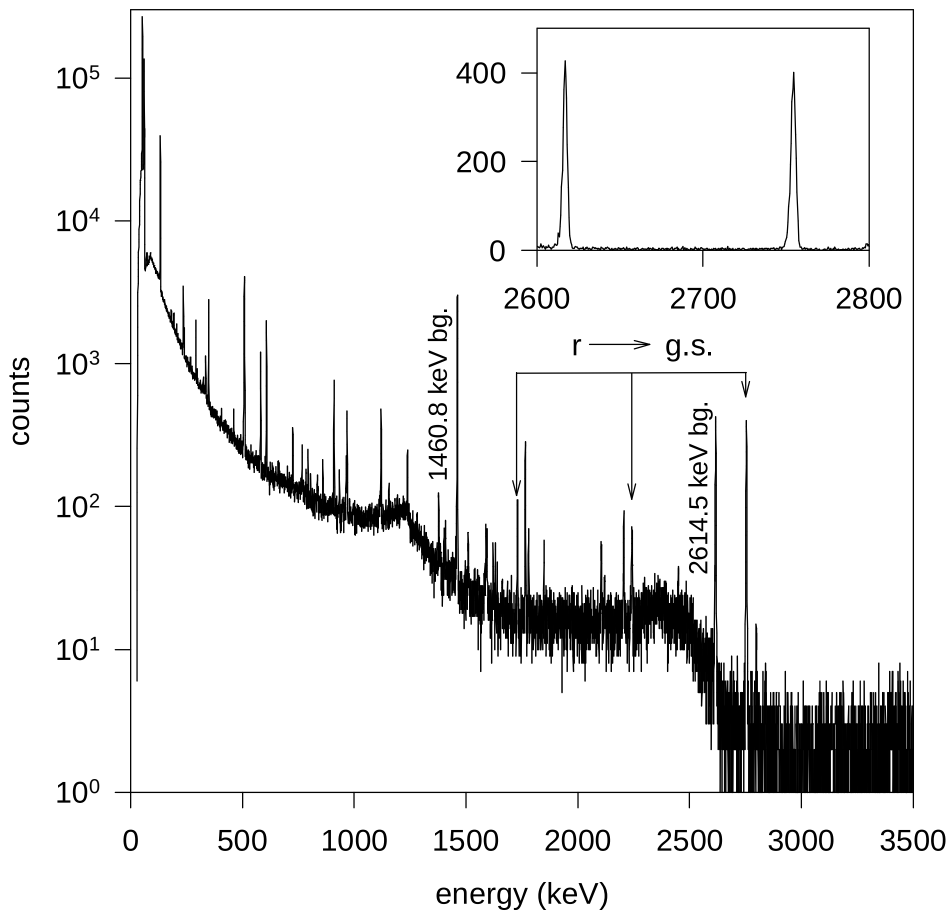
FIGURES

FIG. 1. Typical γ ray spectrum of the $E_\mathrm{p} = 918$ keV resonance in the reaction ^{36}Ar(p,γ)^{37}K. Note the logarithmic scale of the full spectrum and the linear scale of the inset at the relevant transition energy $E_\gamma = 2750.3$ keV.

FIG. 2. Yield curve of the reaction ^{36}Ar(p,γ)^{37}K measured at the $E_\mathrm{p} = 918$ keV resonance.



Eγ=2750.3 keV
gamma yield/μC
proton energy (keV)
0
5
10
15
20
25
912
914
916
918
920
922
924
926



counts
energy (keV)
1460.8 keV bg.
2614.5 keV bg.
r → g.s.