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Resonances in the ^{40}A (p, γ) ^{41}K Reaction

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Abstract. Two resonances in the ^{40}A (p, γ) ^{41}K reaction have been investigated using good energy resolution and a differentially pumped gas target. The following resonance energies were measured: 1086 ± 1 keV and $1101{,}8 \pm 0{,}3$ keV. Gamma-ray spectra were obtained for both resonances and the partial widths of several transitions were determined.

Due to their narrow widths, resonances in the ^{40}A (p, γ) ^{41}K reaction are well suited for precise energy standards to be used in calibrating low energy proton accelerators. In the present work, two prominent resonances near 1,1 MeV were investigated using good energy resolution. A differentially pumped gas target eliminated surface contamination effects which often limit the accuracy of measurements made with solid targets. The energy resolution employed made it necessary to take into account the effect of the non-zero minimum energy loss of a proton interacting with a target atom. In addition to the determination of the resonance energies, the gamma-ray spectra were measured at both resonances, and the partial widths of several transitions were determined.

A uniform field, 180° analyzing magnet[1]) was used to determine the absolute energy of the proton beam. The full-width energy resolution was 400 eV. The differentially pumped Argon target was maintained at a pressure of 0,6 Torr. Natural Argon (99,6% ^{40}A) was used for most of the work; however, several measurements were made with 99,93% ^{40}A. The target volume was cooled to liquid air temperature in order to increase the target density without exceeding the available pumping capacity. The protons lost 3 keV in the 5 cm long target. A 3×3 inch NaI (T1) crystal was positioned directly behind the target.

The excitation curve for the more intense resonance is shown in figure 1. Background measured without target gas has been subtracted, and a correction has been made for the variation of the gamma detector efficiency due to the motion of the resonance position within the target. The remaining small background is due to a weak resonance at lower energy and it is assumed that this background is constant over the energy range shown in figure 1.

In order to calculate the shape of the excitation function including the effect of finite proton energy loss[2]), we have made use of a simple model in which it is assumed that the probability $f(\varepsilon)$ for an electronic collision with an energy transfer between ε and $\varepsilon + d\varepsilon$ is zero for ε less than the first excitation level of the atom. For higher ε up

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to the maximum energy transfer in a head on collision, $f(\varepsilon)$ is proportional to ε^{-2}. The normalization is chosen so that the integral of $f(\varepsilon)$ over all ε is equal to one. The proton energy distribution after n collisions can then be calculated by repeated integration of the relation

$$N_n(E) = \int_{E_{min}}^{E_{max}} f(\varepsilon)\, N_{n-1}(E + \varepsilon)\, d\varepsilon$$

in which the initial energy distribution $N_0(E)$ is triangular in shape and determined by the entrance and exit slits of the analyzing magnet[3]). Since only a very small fraction of the incident protons interacts with the target nuclei, the total energy distribution $N(E)$ of the protons is just the sum over all n of the individual distributions. For energies not too different from the incident proton distribution, it is sufficient to consider only a finite number of collisions in order to obtain $N(E)$ to a reasonable accuracy. The excitation function is the integral of $N(E)$ times the Breit-Wigner resonance factor integrated over all energies.

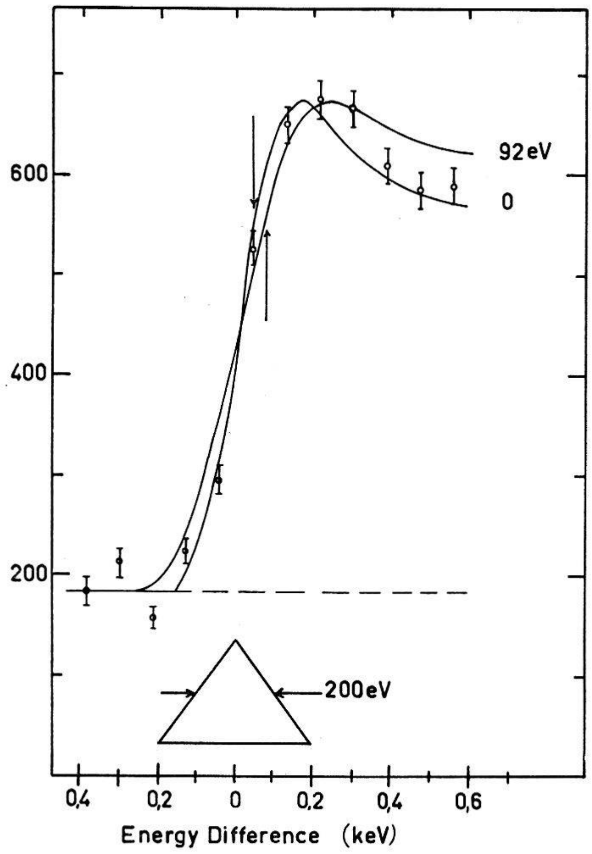

Fig. 1.

Excitation functions and experimental data for the 1102 keV resonance. The curves have been calculated for resonance widths of 0 and 92 eV. The arrows indicate the resonance energy for the two curves.

The curves shown in figure 1 were calculated on an IBM 7070 computer for 45 collisions with E_{max} equal 2,2 keV, E_{min} equal 11,5 eV, and the full energy width of $N_0(E)$ equal to 400 eV. The computation was made for level widths of 0 and 92 eV. The error made in limiting n_{max} to 45 is less than 1% in the energy range shown.

The calculated curves have been normalized to the maximum counting rate above background and have been positioned such that their midpoints coincide with the experimentally determined midpoint. The resonance energy lies 40 eV above the midpoint of the $\Gamma = 0$ curve and 70 eV above the midpoint of the $\Gamma = 92$ eV. From the good agreement between the data and the $\Gamma = 0$ curve, it appears that the level width is less than 100 eV. The resonance energy determined in this measurement is 1101,8 $\pm$ 0,3 keV. All errors are small compared to the 0,2 keV uncertainty resulting from the determination of the proton radius of curvature in the analyzing magnet. The energy of the second resonance determined relative to the first resonance is 1086 $\pm$ 1 keV (data not shown). The resonance energies reported by other groups[4][5][6] are in good agreement with the present more accurately determined values.

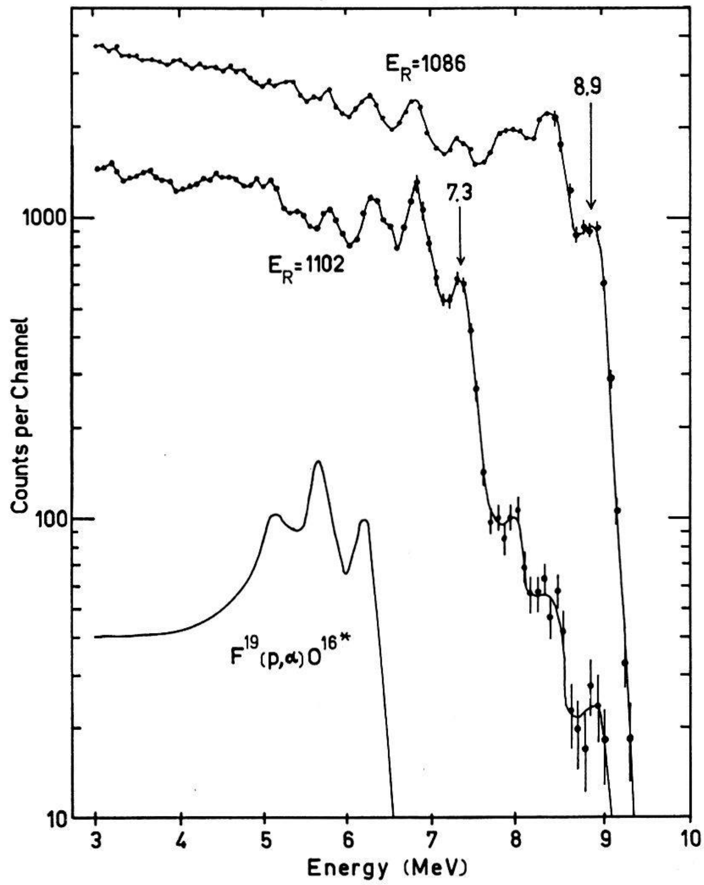

Fig. 2.

Gamma-ray spectra for the 1086 keV and 1102 keV resonances. Also shown is a comparison spectrum of the 6,13 MeV gamma ray resulting from the ^{19}F $(p, \alpha\gamma)$ ^{16}O reaction. A proton charge of 2250 μC was collected on the target for the spectrum of the 1086 keV resonance and 360 μC for that of the 1102 keV resonance.

The gamma-ray spectra above 3 MeV are shown in figure 2. It is seen that the two spectra are markedly different. The 1086 keV resonance shows a strong ground-state transition while the ground-state transition of the 1102 keV resonance is much weaker. From the absolute yield of a particular gamma-ray, one can determine $\omega \Gamma p \Gamma \gamma / \Gamma$ where ω is the statistical weight factor $(2J + 1)/[(2s + 1)(2i + 1)]$ which is $J + 1/2$ for the present case, Γp is the proton width, $\Gamma \gamma$ is the gamma-ray partial width for the observed transition and Γ is the total width of the level. For the ground-state transition of the 1086 keV resonance and the 7,3 MeV transition of the 1102 keV resonance, the values of $\omega\,\Gamma p\,\Gamma\gamma/\Gamma$ are 1,5 eV and 2 eV, respectively. This indicates that the proton width is greater than or equal to 1,5 eV$/(J + {}^1/_2)$ and 2 eV$/(J + {}^1/_2)$ for the two levels. These proton widths exceed the Wigner-single -particle limit[7]) for incoming protons with $l \geqslant 3$. Thus, the spin and parity of either level is limited to the values $(7/2)^-$ or less than or equal to $(5/2)^+$. Similarly, the gamma -ray partial width for the ground-state transitions of the 1086 keV resonance is greater than or equal to 1,5 eV$/(J + {}^1/_2)$. This is more than 50 times the Weisskopf -width for an $M2$ transition of 8,9 MeV and indicates that the transition can be only E 2, M 1, or E 1. Since the ground state of ^{41}K is $(3/2)^+$, the spin and parityof the 1086 keV resonance can be $(7/2)^+$ or less than or equal to $(5/2)^+$. The $(7/2)^+$ value is excluded by the proton width, and therefore only the values less than or equal to $5^+/2$ are possible for the spin and parity of the 1086 keV resonance. The width of the ground-state transition from the 1102 keV resonance is less than or equal to

$$0{,}1\ \mathrm{eV}/(J + {}^1/_2).$$

Although this would be a very weak E 1, M 1 or E 2 transition, one can draw no conclusions regarding the type of transition as all multipolarities are possible. The 7,3 MeV gamma ray observed in both spectra of figure 2 is the upper member of the cascade through the state at 1,56 MeV. The lower member of the cascade is easily identified in the low energy gamma-ray spectra (data not shown). The partial width of the 7,3 MeV transition from either resonance level is consistent with only an E 1, M 1 or E 2 transition; however, since the spin and parity of the 1,56 MeV state is unknown, the partial widths of the 7,3 MeV transitions furnish no information about the spin and parity of the resonance levels.

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