Evidence for a 2^+ Resonance in ^{4}He at 40 MeV

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The fore-aft asymmetry in the angular distribution of the reaction ^{3}H(p,γ_0)^{4}He has been measured as a function of energy for protons from 17 to 31 MeV. The same quantity was also measured using the reaction ^{4}He(e, ^{3}H)pe'. These asymmetry data were fitted with an expression which consisted of a term which varied slowly with energy plus a 2^+ resonance having parameters of $\Gamma_{c.m.} = 3.5$ MeV and E_x(res) = 40.2 MeV.

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Previous photonuclear and capture measurements have indicated the presence of broad 1^- and 2^+ resonances in ^{4}He below 35 MeV.[1,2] Such states, typically 10–15 MeV wide, can be accounted for by shell-model calculations[3,4] and are characterized by a high degree of spatial symmetry. Any such states located at higher energies would be expected to be even broader. The appearance of narrow (a few megaelectron volts) resonances at high excitation energies in the photonuclear channels would therefore be surprising and would raise the question as to what symmetry properties were responsible for the increased lifetime of these states. Although previous experimenters have sought to establish the existence of narrow resonance structures in the photonuclear cross sections of ^{4}He, none has been able to provide convincing evidence.[2] This Letter reports evidence from capture and photonuclear reaction measurements which indicates the existence of a 2^+ resonance at 40.2 MeV in ^{4}He which has a width of about 3.5 MeV. It will be argued that this resonance establishes the importance of unusual (lower-symmetry) components in the ^{4}He wave function near 40 MeV.

The Triangle Universities Nuclear Laboratory (TUNL) cyclograaff facility[5] was utilized to measure the reaction ^{3}H(p,γ_0)^{4}He for proton energies of 17 to 31 MeV. The target was a 5-μm tritiated titanium foil obtained from Oak Ridge National Laboratory. The measured tritium thickness was approximately 250 μg/cm^2. The γ rays were detected with the TUNL 25.4-cm$\times$25.4-cm NaI spectrometer.[6] Measurements were made at center-of-mass angles of 55°, 90°, and 125° in 1.0-MeV steps from $E_p = 8$ to 26 MeV, and in 0.5-MeV steps from 26 to 31 MeV. Two solid-state detectors were employed as monitor detectors utilizing the reaction ^{3}H(p,p). The γ-ray spectra were integrated with use of a standard line-shape fitting program, and the sums were normalized to the monitor detector sums. Timing requirements, provided by the pulsed beam from the cyclotron, significantly reduced the cosmic-ray background in the spectra. In addition a spectrum was taken at each energy and angle with a titanium foil identical to the one of the tritium target, but without tritium, to check for the effects of possible contaminants. Such effects were found to be negligibly small.

The results are shown in Fig. 1 where we have plotted the fore-aft asymmetry, a_s, for the reaction $^3\mathrm{H}(p,\gamma_0)$ as a function of excitation energy, E_x, in ^{4}He. The quantity a_s is given by

$$a_s = \frac{Y(55^\circ) - Y(125^\circ)}{\cos(55^\circ)[Y(55^\circ) + Y(125^\circ)]},$$

where $Y(\theta)$ is the center-of-mass yield for the center-of-mass angle θ. The TUNL data are the combined results of two separate experiments. The error bars shown are statistical only.

The results for a_s [for the reaction $^3\mathrm{H}(p,\gamma_0)$] obtained from the reaction $^4\mathrm{He}(e,{}^3\mathrm{H})pe'$ are also shown in Fig. 1. This reaction was measured using the positive-ion spectrometer facility at the University of Saskatchewan.[7] The energy region covered corresponds to 35.7 to 43.7 MeV excitation energy in ^{4}He in 1.0-MeV steps. The spectrometer can be located at continuous angles in the laboratory, allowing cross sections to be measured at 55° and 125° in the center-of-mass system. Tritons were distinctly identified in the spectrometer, thus insuring that only the two-body breakup channel was measured.

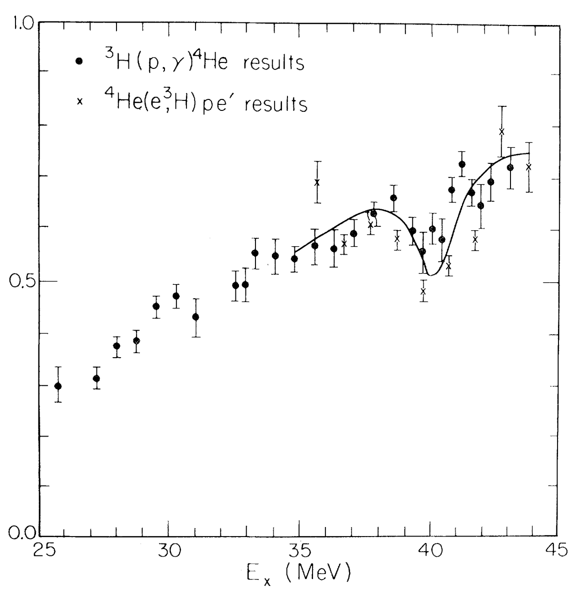

FIG. 1. The measured fore-aft asymmetries in the center-of-mass system are shown as a function of excitation energy in ^{4}He. The data of both reaction studies are shown. The error bars represent the statistical errors only. The solid curve is the result of a fit described in the text.

Since this experiment determined the fore-aft asymmetry from the ratio of the difference to the sum of the cross sections measured at two angles, no virtual photon spectrum had to be used in the analysis. The only assumption made in the analysis was that the electrons predominantly scatter in the forward direction, thus allowing an excitation energy to be calculated assuming two-body kinematics. Since the electrodisintegration cross section is weighted by $1/q_\mu^4$, where q_μ is the four-momentum transferred to the nucleus by the electron, this approximation is quite reasonable.[8] The asymmetry found by measuring the reaction $^4\mathrm{He}(e,{}^3\mathrm{H})e'p$ can therefore be directly related to that which would be measured for the reaction $^4\mathrm{He}(\gamma,{}^3\mathrm{H})p$ and the corresponding inverse reaction $^3\mathrm{H}(p,\gamma_0){}^4\mathrm{He}$.

The asymmetry data of Fig. 1 show a "dip" at $E_x \simeq 40$ MeV which is superimposed upon a gradually increasing "background" from 26 to 44 MeV excitation energy. No convincing evidence for any narrow resonance structures is observed below this energy. The asymmetry (a_s) in the angular distribution must arise from $E1$–non-$E1$ interference. Since $M1$ radiation is expected to be small,[9] we attempted to fit the data by assuming that it is due to $E1$-$E2$ interference effects. The asymmetry can be written in terms of an $E1$ and an $E2$ amplitude and their relative phase as

$$a_s = \frac{4.365 A_{E1} A_{E2} \cos(\varphi_{E1} - \varphi_{E2})}{0.75 A_{E1}^2 + 1.25 A_{E2}^2},$$

where the ($S=0$) $E1$ and $E2$ amplitudes have been normalized so that $\sigma_T = 4\pi A_0 = 4\pi[0.75 A_{E1}^2 + 1.25 A_{E2}^2]$, and where φ_{E1} and φ_{E2} are the respective phases associated with the $E1$ and $E2$ amplitudes. The $E1$ amplitude used to evaluate this expression was obtained from the measured 90° capture cross section which is shown in Fig. 2; the data of Meyerhof, Suffert, and Feldman[10] have been included in this figure. The complex $E2$ amplitude was written as a direct plus a resonance term. The direct $E2$ term was calculated using a Wood-Saxon potential to generate the bound-state wave function and a Coulomb potential to generate the continuum wave function. Note that the resonance could not be added to the 1^- ($E1$) channel. In fact, a 1^- ($E1$) resonance of sufficient strength to fit the dip in the asymmetry data gave a resonance shape in the 90° cross section with a peak cross section about twice as large as the smoothly varying yield shown in Fig. 2. In this model $E1$–direct-$E2$

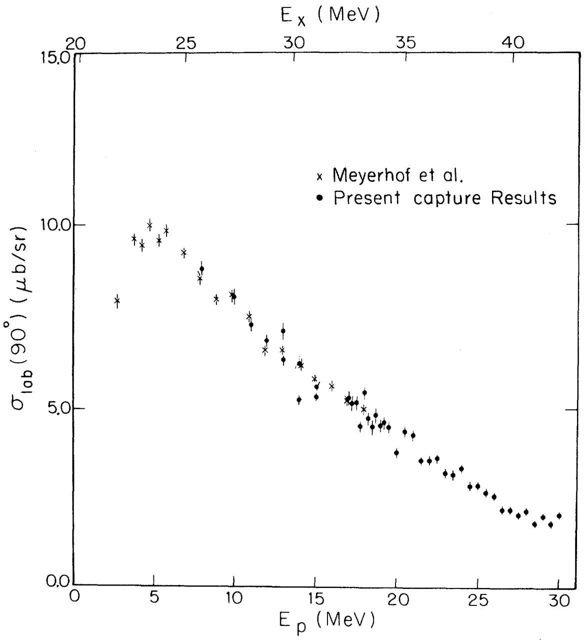

FIG. 2. The experimentally determined cross section for the reaction $^3H(p,\gamma_0)^4He$ at $\theta_{lab}=90°$ as a function of incident proton energy. The data of the present work are shown along with the data of Ref. 10. The error bars represent the statistical uncertainties associated with the data points.

interference produces the smoothly varying background seen in the data. The $E1$–direct-E_2 phase was determined as a function of energy so as to give a good approximation to this smoothly varying background. The phases determined in this manner were consistent with those obtained at lower energies by use of the reaction[11] $^3H(p_{pol}, \gamma_0)^4He$.

The fit parameters used in the resonance region were $\Gamma_{c.m.}$, E_x(res), $\omega\gamma$, and η, where $\omega\gamma$ represents the resonance strength,[12] and η represents the phase of the resonance relative to the $E1$ term. Our "best-fit" results are shown in Fig. 1. The parameters found for the 2^+ resonance are $\Gamma_{c.m.}=3.5\pm1.5$ MeV, $E_x(\text{res})=40.2\pm0.5$ MeV, $\omega\gamma=2.1\pm1.0$ eV, and $\eta=-169°\pm10°$.

The $2\hbar\omega$ shell-model spectrum of ^4He can be examined for candidates which might represent this resonance. This spectrum has thirteen 2^+ states[13] which may be considered for identification with the observed resonance. In this discussion we classify these basis states according to $LST\ \{f\}\ J^\pi$, where $\{f\}$ is the supermultiplet partition. We employ the following two assumptions: (1) The ground states of (^3He, ^3H) and ^4He are states of maximum orbital symmetry, partitions {3} and {4}, respectively; (2) the $E2$ transition operator is spin independent. With these assumptions, of the thirteen basis states, only two, 200 {4} and 201 {31}, have allowed $E2$ transitions to the ground state of ^4He, 000 {4} 0^+. These two states are strongly coupled to the nucleon channels and are thus expected to account for the gross features of the $^3H(p,\gamma)^4He$ $E2$ capture cross section from threshold to about 50 MeV proton energy. They correspond to single-particle resonances which yield a slowly varying cross section as would be obtained from a direct-capture calculation. They are too broad ($\Gamma\sim15$ MeV) to be identified with the presently observed "narrow" resonance at 40 MeV.

Since $E2$ decay to the ground state is forbidden for all other $2\hbar\omega$ 2^+ shell-model states, the wave function for the 40-MeV resonance must contain an admixture of the 200 {4} and/or 201 {31} states. The dominant $E2$ forbidden component of this wave function could include contributions from any of the other $2\hbar\omega$ 2^+ states that are compatible with the small total width of the resonance. Five of these states, 210 {31}, 211 {31}, 020 {22}, 220 {22}, and 200 {22}, are strongly coupled to either the nucleon channels or the $d+d$ channel and thus would have widths of 15 MeV or more at 40 MeV excitation. These states are also too broad to be identified with the 40-MeV resonance. Continuum-shell-model[4] and resonating-group[14] calculations corroborate these conclusions about the broad 2^+ resonances of ^4He.

Within the framework of the preceding assumptions, we conclude that the wave function for the 40-MeV 2^+ resonance is dominated by a state(s) from a supermultiplet partition(s) less spatially symmetric than those usually associated with the nucleon and electromagnetic channels. These arguments demonstrate the importance of the 40-MeV resonance to an understanding of the structure and decay modes of four nucleons.

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