High Resolution Study of the $^{24}\text{Mg}(\alpha, \gamma_0)^{28}\text{Si}$ Capture Reaction

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The $^{24}\text{Mg}(\alpha, \gamma_0)^{28}\text{Si}$ capture reaction has been studied for bombarding energies $4.4 \leq E_\alpha \leq 9.6$ MeV. Through angular distributions taken in steps of 60 keV the ground-state yield has been decomposed into its contributing $E1$ and $E2$ components. Excitation energies and widths of several narrow $1^-$ and $2^+$ levels were determined. Significant deviations of the phase factor $\cos \delta$ from the statistical expectation value were analysed in terms of a two-state interfering process and yielded as much as $(40 \pm 10)\%$ semidirect contributions to the $\alpha$-capture reaction.

Nuclear Reactions: $^{24}\text{Mg}(\alpha, \gamma_0)^{28}\text{Si}$, $E=4.4-9.6$ MeV; measured $\sigma(E, E_\gamma, \theta_\gamma)$. $^{28}\text{Si}$ deduced $E1$, $E2$ strengths. Enriched target. Analysed structure in phase factor $\cos \delta$ as interference phenomenon.

I. Introduction

The radiative capture of $\alpha$-particles has been proven to be an excellent tool for a measurement of $E2$ distributions in many even-even nuclei in the sd-shell. Extensively used in recent years to add information on the high-lying giant quadrupole resonance (GQR), this reaction has some features which help to compensate for the fact that only the $\alpha_0$-groundstate branch is observable. Besides having negligible direct-capture contributions and allowing for a high accuracy in the determination of absolute strengths, $\alpha$-capture offers two important advantages: i) the $E2$ yield can be determined virtually background free, since the only process simultaneously observed is $E1$ decay from high lying $1^-$ states whose amount can uniquely be fixed in a model independent way through angular distribution measurements; ii) the energy resolution obtained in capture reactions in principle is only limited by the target thickness and hence allows a careful study of the fine structure known to be superimposed on the GQR throughout the sd-shell.

Here we present high-resolution data of $\alpha$-capture into the low-energy tail of the GQR in $^{28}\text{Si}$. This nucleus has extensively been studied in recent years and is known to show a highly fragmented $E2$ distribution. The $E_x = 12.7-13.7$ MeV region far below the GQR was probed through $\alpha$-capture on thin ($\approx 10$ keV) $^{24}\text{Mg}$ targets and four narrow $2^+$ resonances with $\Gamma \approx 1$ keV and sizeable $E2$ strength were observed [1]. These measurements were extended to higher excitation energies with the main goal focussed onto the giant dipole resonance (GDR) [2]. Only a few angular distributions were measured, insufficient to reliably extract the $E2$ yield. A fluctuation analysis of the 90° yield curve taken for $E_\alpha(^{28}\text{Si}) = 14.6-22.6$ MeV in 30 keV steps yielded a fine structure width $\Gamma_c \approx 65$ keV. From inelastic alpha- [3, 4] and electron-scattering experiments [5] the GQR in $^{28}\text{Si}$ was found to be highly fragmented, centered around 19 MeV with a width of $\approx 6$ MeV and to contain some 30% of the energy weighted $E2$ sum rule strength. Recently a study of the GQR in $^{28}\text{Si}$ through $\alpha$-capture was reported [6] where angular distributions have been taken in steps ranging from 150 to 340 keV for bombarding energies $E_\alpha = 4.3-14.0$ MeV. A strongly fragmented $E2$ strength was observed consistent in absolute yield with the
results of a $^{28}\text{Si}(\alpha, \alpha'\gamma_0)^{24}\text{Mg}$ coincidence experiment [7]. The agreement in the observed structures was found to be remarkably good when allowing for some minor shifts partly due to the finite energy resolution which was given as 180 keV in the case of the coincidence experiment [7] and at best 150 keV in the $\alpha$-capture study [6]. Since for energies up to 18 MeV the level density is still reasonably small and individual levels are likely to be excited, structures with much narrower widths are expected in the capture reaction. The present investigation was undertaken to pin down the actual positions and widths of the various $2^+$ (and $1^-$) fragments contributing to the low-energy tail of the respective giant resonances with an energy resolution of better than 80 keV, which is roughly the estimated compound nuclear level width [2]. A check will be made whether the extracted results are consistent with the ones from inelastic scattering studies obtained with an equally good energy resolution as achieved in recent $(e, e')$ scattering experiments [5] and in part of the inelastic $\alpha$-scattering study by van der Borg et al. [4] where a magnetic spectrograph has been used. Attention will be given to the phase factor $\cos\delta$ which denotes the phase difference $(\Phi_1 - \Phi_2)$ of the interfering $p$-wave $E1$ and $d$-wave $E2$ capture amplitude. An analysis of the fine and gross structure in $\cos\delta$ will be attempted by assuming simple two-state interference and a comparison with the extracted cross sections for the $E1$ and $E2$ capture data be made.

To keep the beam time necessary for the angular distribution studies within reasonable limits a six-detector set-up described in Sect.II has been used which allowed the study of the fine structure in the $E2$ distribution as well as in $\cos\delta$ with an energy resolution exceeding that of the compound nuclear level width $\gamma$. The data analysis as well as the results are presented in Sect.III. In Sect.IV the various narrow $2^+$ and $1^-$ states observed in the present study will be discussed in comparison with recent high-resolution data from inelastic scattering experiments. The observed energy dependence of the phase factor $\cos\delta$ which shows strong indications of intermediate structure effects will be discussed in detail and comparisons be made with the results of recent $(\alpha, \alpha'\gamma_0)$ coincidence studies.

II. Experimental Set-Up

The $^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$ reaction was studied in the energy range $4.4 \leq E_\alpha \leq 9.6$ MeV. An $\alpha$-particle beam of approximately 0.5 $\mu$A supplied by the Dynamitron tandem accelerator of the Ruhr-Universität Bochum impinged on thin, highly enriched (99.94%) $^{24}\text{MgO}$ targets on 0.1 mm Ta backings. The target thickness was determined by use of the $^{24}\text{Mg}(p, \gamma)^{25}\text{Al}$ resonance reaction at $E_p = 223$ keV to be $(120 \pm 13)$ $\mu$g/cm$^2$, corresponding to an effective thickness of 80 (60) keV for $\alpha$-particles of 6 (9) MeV, respectively. The carbon build-up was suppressed by use of a liquid nitrogen trap in front of the target.

The capture $\gamma$-rays were observed in a total of six NaI(Tl) crystals ranging in size from 11.4 cm $\times$ 12.7 cm to 7.6 cm $\times$ 7.6 cm. The energy resolution for each of the detectors was around 10% for $\gamma$-ray energies of 16 MeV. The maximum bombarding energy used in the present study was limited to slightly above 9 MeV corresponding to $E_\gamma \approx 18$ MeV. Typical spectra are shown in Fig. 1; the resolution even at the highest energy is sufficient to separate the transition to the groundstate ($\gamma_0$) from the one to the first excited state ($\gamma_1$) at 1.78 MeV. The groundstate yield was deduced by adding up the events within a suitably placed window, having lower ($E_\gamma < E_{\gamma_0} - 0.511$ MeV) and upper ($E_\gamma > E_{\gamma_0}$) limits of $E_\gamma = 0.98 E_{\gamma_0}$ and $E_\gamma = 1.06 E_{\gamma_0}$, respectively, as given by the shaded areas in Fig. 1. Here $E_{\gamma_0}$ corresponds to the calculated energy of the single-escape peak $E_{\gamma_0} = E_{\gamma_0} - 0.511$ MeV of a $\gamma$-transition of energy $E_{\gamma_0}$, which is the actual energy of the "$\gamma_0$-peak" given in Fig. 1, as line-shape studies of all detectors have shown.

Angular distributions of the groundstate transition $\gamma_0$ were taken in $\Delta E \approx 60$ keV steps for bombarding energies $6.4 \leq E_\alpha \leq 9.1$ MeV. Six NaI(Tl) crystals were kept fixed at 48°, 60°, 69°, 90°, 120° and 135°. The largest crystals were placed at 48° (10.2 cm $\times$ 12.7 cm) and 135° (11.4 cm $\times$ 12.7 cm), where a maximum of the $E2$ yield is expected as well as at 90° (10.2 cm $\times$ 10.2 cm), where the $E1$ yield peaks. The relative detector efficiencies were determined with the same set-up through use of the $^{11}\text{B}(p, \gamma)^{12}\text{C}$