Spectroscopy of $^{40}$Ca and negative-parity bands

S. Torilov$^{1,2}$, S. Thummerer$^2$, W. von Oertzen$^{1,2,a}$, Tz. Kokalova$^{1,2}$, G. de Angelis$^{2,4}$, H.G. Bohlen$^2$, A. Tumino$^{2,3}$, M. Axiotis$^4$, E. Farnea$^5$, N. Marginean$^4$, T. Martinez$^4$, D.R. Napoli$^4$, M. De Poli$^4$, S.M. Lenzi$^5$, C. Ur$^5$, M. Rousseau$^6$, and P. Papka$^6$

1 Freie Universit"at Berlin, Fachbereich Physik, Arnimallee 14, D-14195 Berlin, Germany
2 Hahn-Meitner-Institut Berlin, Glienicker Strasse 100, D-14109 Berlin, Germany
3 INFN-Laboratori Nazionali del Sud and Universit`a di Catania, Via S. Sofia 44, I-95123 Catania, Italy
4 INFN-Laboratori Nazionali di Legnaro, Legnaro, Italy
5 Dipartimento di Fisica and INFN, Padova, Italy
6 Institut de Recherches Subatomiques, IReS, Strasbourg, France

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Abstract. We have studied the reactions $^{28}$Si + $^{24}$Mg → $^{52}$Fe → $^{40}$Ca$^* + 3\alpha$ as well as the binary channel $^{52}$Fe → $^{40}$Ca$^* + ^{12}$C$^*$, in order to search for deformed states, which form rotational bands in $^{40}$Ca. We observe positive- and negative-parity bands. The negative-parity band is proposed to be a partner of an inversion doublet with the positive-parity states being based on 4p–4h configurations. The properties of the positive-parity states are discussed on the basis of the shell model and the parity doublet on the basis of a cluster model with intrinsic reflection asymmetric shapes.

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1 Introduction

States in nuclei in the vicinity of the $N = Z$ line are known to show strong clustering phenomena. In particular, several bands in $^{40}$Ca have been proposed to have structures, which are based on 4p–4h and 8p–8h excitations [1,2]. Such excitations can also be related to strong $\alpha$-particle clustering configurations [3–5]. The mentioned states are best populated in reactions in which clustering is already present in the target and the projectile.

A large number of states have been observed in $\alpha$-particle transfer reactions [3,6–8]. In particular, with the $^{36}$Ar($^6$Li, d) reaction the spin and parity of many low-lying states have been established [7,8]. The detailed $\gamma$-spectroscopy of nuclei around $^{40}$Ca has only been recently resumed using highly sensitive $\gamma$-detector arrays [9–12]. The most recent result on $\gamma$-spectroscopy of $^{40}$Ca has established deformed bands with 4p–4h and 8p–8h character [9,13].

To populate $^{40}$Ca for $\gamma$-spectroscopy we have chosen the $^{24}$Mg($^{28}$Si, $3\alpha$) reaction at a rather high incident energy of 139 MeV, in order to have the $3\alpha$ channel with enough counting rate in the compound decay channels. Such incident energy allows the observation of binary re-

actions with the emission of the $^{12}$C*(0$^+_2$) state, at an excitation energy of 7.654 MeV, which is at 379 keV above the $3\alpha$-threshold in $^{12}$C (see also refs. [14]). The $Q$-value of −7.8 MeV for the three $\alpha$-particles is the same as for the reaction $^{24}$Mg($^{28}$Si, $^{12}$C*(0$^+_2$))$^{40}$Ca. The latter can be observed in the silicon $\Delta E-E$ detector telescopes by the break-up of this excited state into $\alpha$-particles.

We report here on the results of the spectroscopy of the $^{40}$Ca-nucleus from the $^{24}$Mg($^{28}$Si, $3\alpha$)$^{40}$Ca reaction.

2 Experimental set-up and $\gamma$-spectra

The present experiment has been performed with the $\gamma$-detector array GASP and the charged-particle detector ball ISIS [15]. In the experiment absorber foils have been used inside the ISIS-ball to prevent the registration of the elastically scattered heavy ions in the silicon detectors. Only light particles up to $\alpha$-particles were registered.

The detection of heavier (unbound) fragments becomes possible for states with very small decay energies through the decay into $\alpha$-particles as for $^8$Be(0$^+_1$) and $^{12}$C*(0$^+_2$). The relevant individual energies of the $\alpha$-particles in their center-of-mass frame are so small that the decay cone for the two and three $\alpha$-particles is in the range of 10°–15°, which thus fits well into the opening angle (29°) of one
ISIS $\Delta E$-E telescope. Thus, we are able to detect simultaneously the $\alpha$-particles from the compound decay as well as the spontaneous decay of a weakly bound state by the double and triple pile-up lines. Details on the observation of the $^8$Be$(0^+_3)$ and the $^{12}$C$(0^+_2)$ are reported in ref. [14] (see also ref. [16]). The $^{24}$Mg targets were self-supporting foils of 0.5 mg/cm$^2$ thickness. At the incident $^{28}$Si beam energy of 139 MeV, we have a large contribution of the compound reaction in the 3$\alpha$ channel. We cite the measured total count rates $N(M\alpha)$ for the multiplicities in the 1$\alpha$ up to 4$\alpha$ channels:

$N(1\alpha) = 8.7 \cdot 10^7,$

$N(2\alpha) = 1.5 \cdot 10^7,$

$N(3\alpha) = 0.9 \cdot 10^6,$

$N(4\alpha) = 0.018 \cdot 10^6.$

The counts for the binary emission process with $^{12}$C$^+$ are 0.4 $\cdot$ 10$^6$. The relative yields cited correspond to a total geometrical efficiency $\epsilon$ of the ISIS-detector ball of $\approx 0.35$ for singles (see also ref. [14]). We are able to use both the 3$\alpha$ channel as well as the $^{12}$C$^+(0^+_2)$ channel for the Doppler-shift correction of the $\gamma$-spectra and for the selection of the $^{40}$Ca channel; subsequent decays, however, are not selected by this particle trigger, and can only be removed by $\gamma$-gating.

### 2.1 Discussion of the charged-particle and $\gamma$-spectra

The relatively high velocity of the compound nucleus and the larger mass emitted mean that the $\gamma$-spectra must be corrected for Doppler-shifts on an event-by-event basis.

**Fig. 1.** Plot of $\Delta E$-$E$ signals as observed with the ISIS charged-particle detector system. The events with the emission of single $\alpha$'s, $^8$Be and with $^{12}$C$(0^+_2)$ are indicated.

**Fig. 2.** Doppler-corrected $\gamma$-spectrum selected with the 3$\alpha$ channel, and the $^{12}$C$(0^+_2)$ channel, respectively. Solid lines mark the $\gamma$-transitions for $^{40}$Ca. Dashed lines are the $\gamma$-transitions for $^{39}$K.

The recoil velocities have been obtained using the momentum vectors of the coincidently registered charged particles. We show in fig. 1 the plot of the charged-particle identification as observed with the ISIS-ball (mainly the first ring with six telescopes contributes in the chosen kinematic conditions). The $\gamma$-spectra of $^{40}$Ca can thus be obtained with three different charged-particle triggers:

a) 3$\alpha$-particles,
b) $^8$Be + $\alpha$-particle emission, and
c) $^{12}$C$^+(0^+_2)$ emission.

For all three cases a satisfactory Doppler-shift correction was obtained corresponding, for a 1 MeV $\gamma$-transition, to a FWHM of approximately 10 keV.

The energy spectra of the $\alpha$-particles, the $^8$Be- and the $^{12}$C$^+(0^+_2)$ clusters are shown in ref. [14]. We show in fig. 2 the $\gamma$-spectra obtained with two different particle gates, the 3$\alpha$ trigger and the $^{12}$C$^+(0^+_2)$ trigger. In these figures we observe also transitions from other nuclei. After selection of the $^{12}$C$^+(0^+_2)$ channel we observe a strong increase of $^{39}$K as well as of $^{36}$Ar transitions (4$\alpha$-particles emission). The main part next to $^{40}$Ca corresponds to $^{39}$K, with an additional proton emission. One can see that these peaks are much stronger than those of $^{40}$Ca for $^{12}$C$^+$ emission. One can deduce from the results shown in fig. 2 and fig. 3 that the intensity of the $\gamma$-transitions in $^{40}$Ca after 3$\alpha$ emission are approximately 12 times larger than after a $^{12}$C$^+(0^+_2)$ emission.

Further $\gamma$-spectra were obtained by setting $\gamma$-gates in the higher excitation energy for the establishment of the