Excitation of Rotational Bands in ^{40}Ca Observed in the Reaction ^{36}Ar(^{16}O, ^{12}C)

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Levels strongly populated in the reaction ^{36}Ar(^{16}O, ^{12}C)^{40}Ca are compared with predictions for the lowest (oblate) 4p-4h rotational band in ^{40}Ca.

The concept of a new collective coordinate, the quartet, has been introduced by Arima, Gillet, and Ginocchio[1] to describe four-nucleon correlations in levels of s-d and f-p shell nuclei. The quartet is defined as a two-proton–two-neutron substructure with $T=0$ and high orbital symmetry. In the (^{16}O, ^{12}C) stripping reaction such substructures could be transferred from their configuration in ^{16}O to the target nucleus without much intrinsic rearrangement, resulting in a relatively strong selective population of final states with significant quartet components. Large cross sections and selectivity have in fact been observed[2,3] in (^{16}O, ^{12}C) reactions on various isotopes of Ca and Ni. Together with a striking disappearance of excitation strength for low-lying final states with increasing neutron excess in the target isotope, these observations were taken as evidence for the existence of such quartet correlations and for their preferential excitation in four-nucleon-transfer reactions.[2] However, it was later shown[4,5] that most of the observations could already be accounted for by a consideration of the very drastic dependence of (^{16}O, ^{12}C) cross sections on kinematical variables such as Q value and momentum transfer. The Q-value dependence restricts the excitation of final states to a rather narrow energy window. The angular-momentum matching conditions result in a selectivity for final states of a specific spin.

In order to reinvestigate the nuclear-structure dependence in (^{16}O, ^{12}C) reaction cross sections at energies close to the Coulomb barrier, we have chosen the reaction ^{36}Ar(^{16}O, ^{12}C)^{40}Ca. In this reaction the "Q window" is situated around 8 MeV excitation energy, where an angular-momentum transfer of 6 to 8 units of $\hbar$ is favored.

The ^{40}Ca level scheme has been very carefully investigated both experimentally and theoretically. The most interesting feature of the low-excitation-energy spectrum is the mixing of deformed particle-hole excitations with simple shell-model configurations.[6] In the present investigation we attempt specifically to study the 4p-4h (four-particle, four-hole) excitation mode in ^{40}Ca because of its possible identity with a one-quartet, one-quartet-hole configuration, as suggested by calculations of Jaffrin.[7] Levels belonging to this mode should be strongly and selectively excited if quartets are in fact preferentially transferred in the (^{16}O, ^{12}C) reaction.

The experiments used the ^{16}O beam of the Heidelberg MP tandem Van de Graaff accelerator with an energy of 45 MeV. The (^{16}O, ^{12}C) reaction on ^{36}Ar has to be measured with a gas cell. This is a difficult task because of the high-energy loss of heavy ions in the target windows and in the gas itself. The gas cell must have very thin window foils (the high costs of isotopically pure ^{36}Ar are prohibitive for the use of windowless gas targets) and a geometry which minimizes the flight path of the ions in the gas.[8] On the other hand, particles scattered from the entrance foil must be prevented from reaching the detectors in order to avoid pileup. This requires a comparatively long flight path in the gas. A difficult compromise had to be reached resulting in an energy resolution of 450 keV for gas pressure below 80 Torr, which is about the optimum that can be obtained with this kind of heavy-ion gas target. The pressure of 80 Torr corresponds to an effective target thickness of about 20 μg/cm^2. With a solid angle of 2.5×10^{-4} sr (restricted to this value by the reaction kinematics), and the limitation to a beam current of 100 nA imposed by the entrance foil of the gas cell, it takes about 24 h to obtain one spectrum. Three spectra were taken at angles between 40° and 50° lab, which is sufficient for discrimination against lighter-target-gas contamination. Because of the high purity of the gas used, the spectra do not show any contaminations below 10 MeV of excitation energy. Contamination peaks above 10 MeV which might arise from ^{16}O and ^{14}N in the gas are estimated to be smaller than 10% of the measured cross section for levels of ^{40}Ca.

The ^{36}Ar gas was isotopically enriched to 99%. The beam was stopped inside the gas cell. Absolute normalization of the spectra was achieved by measuring the Rutherford scattering from a 2% admixture of xenon to the Ar isotope.

The outgoing particles were detected with a ΔE-E semiconductor telescope, the ΔE and E counter positioned about 50 cm apart from each other. In addition to the ΔE and E information we measured the time of flight T of the outgoing particles between the detectors. Each triple event consisting of $\Delta E + E$, E, and T was stored through a buffer on magnetic tape. The data were analyzed off-line. This three-dimensional analysis guarantees a perfect resolution of outgoing masses and charges both, and essentially background-free spectra.

A spectrum of the reaction $^{36}Ar(^{16}O, ^{12}C)^{40}Ca$ obtained at a lab angle of 40° is shown in Fig. 1. The energy calibration is uncertain to about ± 100 keV as a result of nonlinearities of energy loss in the gas and in the window foils. The most remarkable features of the spectra are (1) selective excitation of levels (or groups of levels, within the limits of energy resolution) in ^{40}Ca centered at excitation energies of 3.9, 5.2, 6.9, 9.9, and 12.4 MeV. (2) No peak is observed at $E_x = 4.4$ MeV corresponding to the 5^-, 4.49-MeV level in ^{40}Ca or to an outgoing ^{12}C in the 2^+, 4.43-MeV state. (3) The envelope of the spectra shows an approximately Gaussian shape as is expected from the Q-value dependence. Excitation of the ground state is strongly inhibited by the position of the kinematical window.

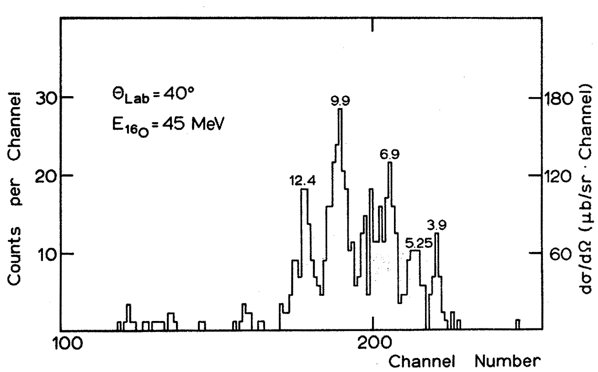

FIG. 1. Spectrum of the reaction $^{36}Ar(^{16}O, ^{12}C)^{40}Ca$. Absolute cross sections are given on the right-hand ordinate in μb/sr channel.

Three rotational bands have been suggested in ^{40}Ca, two based on a $K^\pi = 0^+$ state, one beginning with $K^\pi = 2^+$.[9] The lowest $K^\pi = 0^+$ band comprises the levels at 3.35 MeV (0^+), 3.9 MeV (2^+), and 5.28 MeV (4^+). It is generally agreed that these levels are built up mainly by the promotion of four particles from the s-d shell to the f-p shell. Thus, the wave functions contain large 4p-4h components. The higher members of this band have never been identified.

Whereas in the present experiment we should strongly excite this band as well as the $K^\pi = 2^+$ band, which is also supposed to have 4p-4h structure, we should probably not so strongly excite the second $K^\pi = 0^+$ band. The wave functions of this band are believed to contain large 8p-8h components.[9,10] Thus, these levels can in our case only be excited through the weak 4p-4h components in the ^{36}Ar ground-state wave function.

In the following we want to demonstrate that the most remarkable excitations in our spectra can already be explained by assuming that the members of the lowest $K^\pi = 0^+$ band receive large parts of the total cross section. This would be analogous to observations in the α transfer leading to ^{16}O, where the 4p-4h, $K = 0$ rotational band is preferentially excited.[11]

In Fig. 2 we show the strongly excited final states or groups of final states as seen in the reaction $^{36}Ar(^{16}O, ^{12}C)^{40}Ca$. They are compared with the predictions of a rigid-rotator model for a band based on the 3.35-MeV (0^+) level, and with calculations by Jaffrin[7] for a one-quartet, one-

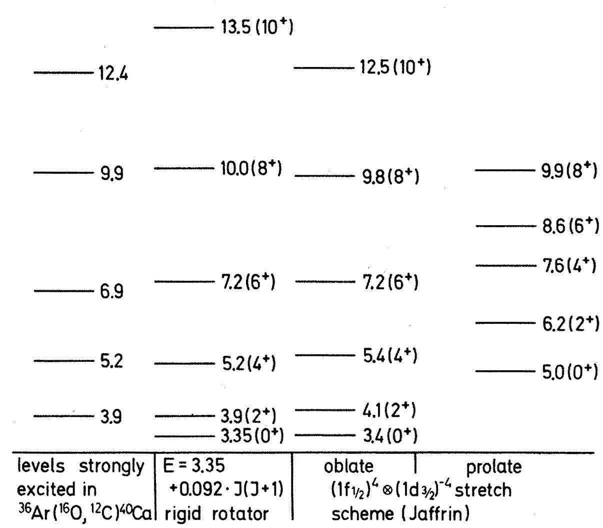

FIG. 2. Comparison of the levels strongly excited in ^{40}Ca with predictions of a rigid-rotator model and with stretch-scheme calculations of Jaffrin (Ref. 7).

quartet-hole configuration in the stretch-scheme approximation. The agreement between experimentally observed levels and theoretical predictions for an oblate band is quite remarkable. We may therefore tentatively identify the 6.9-MeV level in ^{40}Ca with the 6^+ member of the $(1f_{7/2})^4$-$(1d_{3/2})^{-4}$ quasirotational band, with the band head at 3.35 MeV excitation energy.

From the fact that the 4.49-MeV (5^-) level is very weakly populated in accordance with recent ^{36}Ar(^{7}Li, t)^{40}Ca[12] and ^{32}S(^{12}C, α)^{40}Ca[10] studies, it is concluded that the excitation of collective negative-parity states through a mixed-shell configuration assumed by the four transferred particles is weak. Thus, the peak at 3.9 MeV should contain only small contributions from the excitation of the 3^-, 3.73-MeV level. The peak near 5.28 MeV in our spectra is somewhat broader than the peak at 3.9 MeV. This suggests that contributions to this "bump" result not only from the 4^+, 5.28-MeV state, but also from the bandhead of the first $K=2^+$ band at 5.25 MeV and from the 0^+, 2^+ states of the second $K=0^+$ band at 5.21 and 5.63 MeV, respectively. This result may be an indication of band mixing as proposed by Gerace and Green.[13]

If the sharp peak observed at 6.9 MeV excitation energy is really the 6^+ member of the lowest $K^\pi=0^+$ rotational band, one expects to find a strong $E2$ de-excitation γ ray to the 4^+, 5.28-MeV level. In fact, three states have been observed to decay strongly to the 4^+, 5.28-MeV level[9,14]: the states at 6.93, 7.4, and 7.68 MeV. States at 7.4 and (or) at 7.68 MeV are not seen in the reactions ^{36}Ar(^{7}Li, t)^{40}Ca[12] and ^{32}S(^{12}C, α)^{40}Ca,[10] whereas a level at 6.9 MeV is strongly excited in both cases. Further, the $(p, p'\gamma)$ experiments of Ref. 14 show that the level at 6.93 MeV in ^{40}Ca, which decays strongly to the 4^+, 5.28-MeV state, is identical neither with the 2^+ state at 6.91 MeV suggested[9] to result mainly from 2p-2h excitations, nor with the 3^-, 1^- states at 6.93 and 6.95 MeV, respectively. Minor contributions from these latter levels to the peak at 6.9 MeV cannot be excluded. However, our observations as a whole lend further support to the assumption that the 6^+ member of the lowest $K^\pi=0^+$ rotational band is situated around 6.9 MeV in ^{40}Ca.

From the agreement between theoretical predictions and experiment, one may tentatively assign the spins 8^+ and 10^+ to the strong peaks at 9.9 and 12.4 MeV excitation energy. This assignment, however, remains rather speculative because of the lack of other experimental information on levels in this excitation energy region.

From a comparison of the supposed rotational band with the Jaffrin calculations, it can further be seen that agreement between the experimental results and the stretch-scheme predictions is far better for oblate than for prolate deformations. This is in contradiction to a recent investigation by Towsley, Cline, and Horoshko,[15] who had to assume a prolate deformation for the 4p-4h band in ^{40}Ca in order to explain the negative quadrupole moment of the first 2^+ state in ^{42}Ca. Calculations in the Strutinsky model, however, have also suggested that the lowest deformed state in ^{40}Ca should be oblate.[16]

In conclusion, we may say that the reaction ^{36}Ar(^{16}O, ^{12}C)^{40}Ca shows a high degree of selectivity over the whole range of excitations accessible in ^{40}Ca because of the kinematical window, suggesting a direct transfer of four correlated particles to be the dominating reaction mechanism.

Our experimental results are in agreement with the assumptions that the reaction ^{36}Ar(^{16}O, ^{12}C) populates preferentially the members of one single deformed (quasi-)rotational band based on the 3.35-MeV (0^+), 4p-4h state in ^{40}Ca and extending up to a tentatively assigned 10^+ level at 12.4 MeV excitation energy. This band coincides with the lowest oblate one-quartet, one-quartet-hole band predicted in the stretch scheme.

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Optical-Model Information Provided by Scattering from Aligned Targets*

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Data on the scattering of α particles from aligned ^{165}Ho was recorded over the energy range $14 \leq E_\alpha \leq 23$ MeV. Optical-model calculations are presented. It is shown that the data provide a clear resolution of the optical-model ambiguities found in previous analyses of α scattering from rare-earth nuclei.

The parameter ambiguities which arise in optical-model fits to scattering data for strongly absorbed particles are well known and have been discussed by several authors.[1,2] At low bombarding energies where only the tail of the nuclear potential is probed, the principal source of ambiguity results from changes in the parameters which leave the potential in this region unaltered. The tail region itself, however, is well determined.[1,3] At higher energies ambiguities of a discrete nature are found as well as a continuous VR^n ambiguity.[4,5] It has been shown[6] that at very high energies, near 80 MeV in the case of ^{24}Mg, only the continuous type of ambiguity remains. In this case, a good fit to the data can be obtained with almost any strength potential by suitable adjustment of the other parameters. These characteristics are consistent with the assumption that the scattering is only sensitive to a portion of the nuclear surface.

The resolution of these ambiguities has been the subject of much investigation. Initially, it was believed that including inelastic scattering data with a coupled-channel analysis would be of value. Austern and Blair[7] have shown, however, that optical potentials which reproduce the elastic scattering must be expected to reproduce the inelastic angular distributions. Several authors[8] have demonstrated that partial resolution of the ambiguities is obtained by including large-angle scattering data. Simultaneous fitting of data from several target nuclei at various energies, constraining the parameters to vary smoothly, offers another means of reducing the ambiguities.[4,5]

In the present Letter we propose that scattering data from aligned targets offer additional information which can lead to better determination of the optical parameters. The potential for a permanently deformed nucleus can be written in the form

$$V(r,\theta) = -(U+iW)[1+\exp(\{r-R_0[1+\beta Y_2^0(\theta)]\}/a)^{-1} + V_c(r,\theta), \tag{1}$$

where $V_c(r,\theta)$ is the potential due to the charge distribution and β is the nuclear deformation parameter.