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Experimental g factors and $B(\mathrm{E2})$ values in Ar isotopes: Crossing the $N = 20$ semi-magic divide

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Abstract

Measurements of g factors and lifetimes of the 2_1^+ states in ^{36,38}Ar have been performed via α-transfer reactions using ^{32}S and ^{34}S ions in inverse kinematics combined with the techniques of transient magnetic fields and Doppler-shift-attenuation. The variations, with the neutron number, of the measured g factors and $B(\mathrm{E2})$ values of ^{36,38,40}Ar have been explained by large-scale shell model calculations. The good agreement achieved between experiment and theory demonstrates the impact of the effective nucleon–nucleon interactions and the magic $N = 20$ shell closure. The present new results are a very good show-case for the universal difference in sensitivity of excitation energies, magnetic moments and electromagnetic transition probabilities to nuclear wave functions behaviour as closed shells are approached, crossed, and left behind. Aspects of the collectivity of these nuclei are also discussed from the perspective of a simple vibrational model.

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1. Introduction

The argon isotopes ^{36,38,40}Ar, with $Z = 18$ protons and $18 \leqslant N \leqslant 22$ neutrons, lie near the doubly-magic ^{40}Ca ($N = Z = 20$) and are important benchmarks for testing the nuclear shell model.

In the self-conjugate ($Z = N = 18$) ^{36}Ar nucleus there are two proton holes and two neutron holes in the sd shell. The protons and neutrons occupy the same shell model orbitals and have a maximum spatial overlap. In [1,2] it is noted that such $N = Z$ nuclei could provide information on proton–neutron pairing correlations. The $T = 0$ low-lying states make it possible to consider isospin symmetry effects and to study isoscalar electromagnetic static and transition moments.

In the simplest picture, ^{38}Ar has two proton holes in the sd shell, with respect to the ^{40}Ca core, and possesses extra stability due to the neutron $N = 20$ shell closure. In [3] it is suggested that since the protons and the neutrons occupy the same orbitals, the large spatial overlap of their wave functions and proton–neutron correlations would favour excited particle–hole states for which protons and neutrons are equally strongly excited from the sd to the fp shell.

Finally, in ^{40}Ar, again has two sd shell proton holes but also two valence neutrons in the fp shell, beyond the neutron shell gap. Here, shell crossing from the sd to the fp shell could be enhanced [4].

All three nuclei exhibit changes in structure due to the variation of the neutron number near $N = 20$ and to the occupancy

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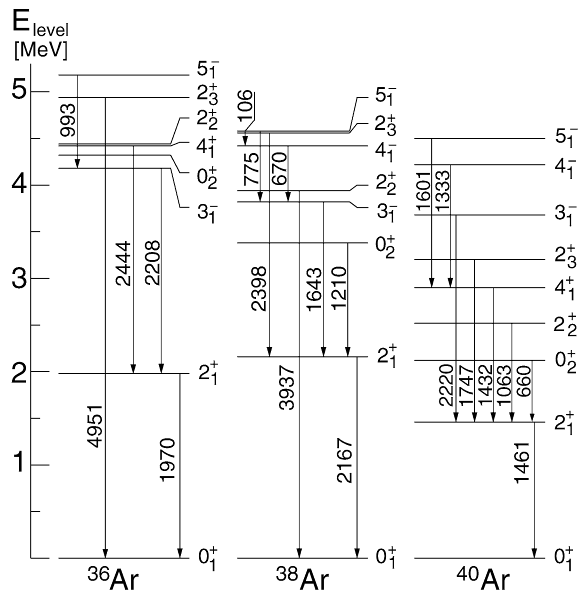

Fig. 1. Level schemes with relevant γ transitions in keV between comparable states. ^{36,38}Ar are part of the present work; the ^{40}Ar scheme has been added for comparison (see text).

of specific shell model orbitals. The level schemes of the three isotopes, relevant for the present investigations, are displayed in Fig. 1, showing characteristic changes in excitation energy of the corresponding nuclear states. For example, the 2_1^+ excitation energy is highest for the semi-magic ^{38}Ar nucleus.

In the present contribution, in which we consider primarily properties of the first excited 2^+ states of all three Ar isotopes, the interpretation of the nuclear structure focuses on two key questions: (i) can one consistently describe all three nuclei, ^{36}Ar, ^{38}Ar and ^{40}Ar, within the sd and/or the fp shell model configuration space; (ii) do particle–hole excitations from the sd shell play an increasingly important role when the number of neutrons increases? With respect to the latter issue it should be noted that recent investigations of 2_1^+ states in ^{42,44}Ca required large contributions of core-excited configurations to the nuclear wave functions in order to explain the experimental g factors and B(E2) values [5,6].

In view of these fundamental questions, the g factors of the 2_1^+ states of ^{36,38}Ar have been measured for the first time, thus probing the proton and neutron configurations in the nuclear wave functions. In addition, the lifetimes of these and higher excited states have been remeasured, in order to obtain reliable B(E2) values for collectivity considerations. For the ^{40}Ar isotope, g factor information is already available from the literature, $g(2_1^+) = -0.1(1)$ [7], and its $g(2_1^+)$ factor was recently remeasured [8], confirming the earlier result. ^{40}Ar has been included in the overall shell model analysis of these nuclei in order to complete the picture near the $N = 20$ shell closure.

2. Experimental details

The experiment was a challenge due both to the impossibility of generating argon beams at tandem accelerators and the very low natural abundances of the two isotopes in question, ^{36}Ar (0.337%) and ^{38}Ar (0.063%). Therefore, the states of interest in both nuclei needed to be populated in an appropriate nuclear reaction. Earlier experiences with the technique of transient magnetic fields (TF) and the Doppler-shift-attenuation method (DSAM), for the measurement of g factors and lifetimes of short-lived nuclear states, respectively [9], have shown that α transfer at the Coulomb barrier to an easily available projectile offered such an appropriate reaction. For the Ar nuclei in question the α-transfer technique is particularly suitable since the required sulphur beams are easily available with high intensity at tandem accelerators. Using such a reaction, in inverse kinematics, ensured the same good physical conditions as in projectile Coulomb excitation experiments [10]. It should be noted that the α-transfer reaction was already successfully applied in some earlier measurements involving radioactive nuclei [11,12]. In these experiments it was demonstrated that the α-transfer reaction is a significant alternative to the Coulomb excitation of low-intensity radioactive beams, especially for neutron deficient beams.

In the present measurements isotopically pure ^{32}S and ^{34}S ion beams were accelerated to energies of 65 and 67 MeV, respectively, at the Cologne and Munich tandem accelerators, providing in each case intensities of ~ 25 enA on a multilayered target. The two targets used consisted of thin layers of 0.33 (0.40) $\mathrm{mg/cm^2}$ ^{nat}C on 3.23 (3.36) $\mathrm{mg/cm^2}$ Gd deposited on 1.7 (1.5) $\mathrm{mg/cm^2}$ Ta backed by 3.94 (4.27) $\mathrm{mg/cm^2}$ Cu. The targets were cooled to liquid nitrogen temperature and magnetized to saturation in an external field of 0.06 Tesla. The Ar isotopes were produced in the reactions ^{12}C(^{32}S,^{8}Be)^{36}Ar and ^{12}C(^{34}S,^{8}Be)^{38}Ar. In addition, Coulomb excitation of the sulphur projectiles also occurred. The nuclear-excited Ar and S ions moved in the direction of the primary beam at mean velocities of $3.8v_0$ and $3.5v_0$ ($v_0 = e^2/\hbar$), respectively, through the magnetized Gd layer for spin precession by TF. They were ultimately stopped in the copper backing which served as a hyperfine-interaction-free environment.

The de-excitation γ rays were measured with 12.7 cm × 12.7 cm NaI(Tl) scintillators in coincidence with the forward scattered ions, either carbon ions or 2α particles from the decay of ^{8}Be. Only in the case of ^{36}Ar were both ions allowed to pass through the target layers and an additional Ta foil. They were detected in a Si counter placed at 0° relative to the beam axis; the Ta foil between the target and the detector served as a beam stopper. In the case of ^{38}Ar, the carbon ions were stopped together with the beam in the same stopper foil. This precaution was required because the ^{34}S($2_1^+ \to 0_1^+$) γ line of 2.127 MeV from Coulomb excitation was too close to the ($2_1^+ \to 0_1^+$) line of 2.167 MeV in ^{38}Ar. These Doppler-broadened γ lines could barely be resolved with a Ge detector and certainly not with NaI(Tl) scintillators. Hence, a simultaneous measurement of the g factor of the ^{34}S(2_1^+) state was not possible in this experiment. This problem did not exist for ^{36}Ar and ^{32}S, where the corresponding lines were well resolved, so that the g factors of both nuclei could be measured simultaneously.

A Ge detector with 40% relative efficiency was placed at 0° to monitor contaminant lines and to measure the lifetimes of the excited states via DSAM. Some typical spectra obtained