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First g-factor measurements on semi-magic ^{36}S and their implications for the rigidity of the $N = 20$ shell closure

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Abstract

The g-factor of the very short-lived ($\tau = 0.12(1)$ ps) 2_1^+ state at 3.290 MeV in ^{36}S, $g(2_1^+) = +1.3(5)$, has been determined for the first time by utilizing the Coulomb excitation of ^{36}S beams in inverse kinematics combined with the transient field technique. In addition, for the 3_1^- state (with $\tau = 0.9(1)$ ps) at 4.192 MeV, a value of $g(3_1^-) = +0.8(5)$ was obtained. In the same experiment, the g-factor of the 2_1^+ state in ^{40}Ar has been remeasured using the α-transfer reaction on the same carbon target. Lifetimes of several excited states in both ^{36}S and ^{40}Ar were also redetermined using the Doppler-shift-attenuation method. The new experimental g-factors and deduced $B(\mathrm{E2})$ values were compared with results of shell-model calculations with the WBT effective interaction and the $sdfp$ shell model space. Comparisons with previous results for ^{32,34,38,40}S and ^{36,38,40}Ar shed light on how the properties of the Ar and S isotopes change as the $N = 20$ shell closure is approached, crossed, and left behind.

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1. Introduction

Newly available intense radioactive ion beams for nuclear spectroscopy make it possible to study whether and how single particle energies of protons and neutrons change as one moves away from the stability line. Such changes would markedly alter which proton and neutron configurations play important roles in the nuclear wave functions of unstable nuclei. In a chain of isotopes of a given element, such changes could be related to differences, with the varying neutron number, N, in the strength of the pn-interaction. This interaction will be particularly strong when the protons and neutrons occupy the same orbitals, resulting in a large spatial wave functions' overlap. Comparing the properties of isotope chains of neighbouring elements could elucidate the effects of changing the number of protons, Z.

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Several g-factor measurements have been recently performed on various even–even sd and fp shell nuclei. Nuclear magnetic moments are particularly sensitive to the specific proton and neutron configurations in the wave functions due to the proton's and neutron's strikingly different spin and orbital g-factor values.

The g-factor measurements on the first 2^+ states of the calcium ($Z = 20$) isotopes ^{42,44,46}Ca implied substantial proton and neutron excitations across the N, $Z = 20$ shell gaps [1–3]. The observed positive $g(2_1^+)$ values for ^{42,44}Ca strongly suggested such cross-shell proton excitations. However, the observed negative $g(2_1^+)$ value for ^{46}Ca implied that these excitations become more hindered towards the $N = 28$ shell closure.

The argon ($Z = 18$) isotopes with two proton holes in the sd shell [4,5] behave differently. The observed continuous decrease of the $g(2_1^+)$ factors, from ^{36}Ar ($N = 18$) via ^{38}Ar ($N = 20$) to ^{40}Ar ($N = 22$), were explained by shell-model calculations without requiring cross-shell excitations of protons and neutrons.

Are these differences in the importance of cross-shell excitations between the Ar and Ca isotopes solely due to their differing by two protons? To further clarify the role of the cross-shell excitations, measurements and shell-model calculations were carried out for the sulphur ($Z = 16$) isotopes with even two less protons than Ar.

Reliable data on g-factors and B(E2) values have existed for a while for the first 2^+ states of the stable ^{32,34}S isotopes [4,6]. Recently, g-factor data were obtained for the neutron-rich radioactive ^{38,40}S [7,8]. This information helps to elucidate subtle changes in the nuclear structure of the even sulphur isotopes as the neutron number varies from $N = 16$ to $N = 24$ while crossing the $N = 20$ and approaching the $N = 28$ spherical shell closures. Thus, one can now study the possible onset of deformation and increase of collectivity as one nears the neutron drip-line.

However, one very important piece of information had been missing: the $g(2_1^+)$ factor of ^{36}S. The high excitation energy (3.29 MeV) of this 2_1^+ state and its very short lifetime (0.12(1) ps) both make a significant g-factor measurement very difficult.

The present Letter reports on a first measurement of the $g(2_1^+)$ factor of ^{36}S. We also redetermined this state's lifetime and remeasured the g-factor and lifetime of the ^{40}Ar(2_1^+) state. The new and the previous data for the neighbouring isotopes are discussed within the framework of large-scale shell-model calculations.

A recent two-step fragmentation experiment [22] determined the excitation energy of the first excited 2^+ state in ^{36}Ca, the mirror nucleus to ^{36}S. Comparing the properties of these two 2_1^+ mirror states will further test the isospin symmetry of shell gaps at the driplines.

2. Experimental details

All the measurements required intense beams of ^{36}S. Due to its low natural abundance of 0.02%, highly enriched ^{36}S was needed for the ion source of the Cologne accelerator. With enrichments to between 10–20%, pure ^{36}S ion beams were accelerated to 70 MeV, providing intensities of (20–30) e nA on a multi-layered target. The target consisted of 0.19 mg/cm^2 natural C on 3.03 mg/cm^2 Gd which was deposited on 1.0 mg/cm^2 Ta backed by 2.0 mg/cm^2 Cu (see also [9]). It was cooled to liquid nitrogen temperature and magnetized to saturation by an external field of 0.06 Tesla.

In their collisions with the carbon nuclei, the ^{36}S projectiles were either Coulomb excited to the states of interest in ^{36}S or else, via the α-transfer reaction ^{12}C(^{36}S, ^{8}Be)^{40}Ar*, excited states in ^{40}Ar were reached. Due to the inverse kinematics in both reactions, the ^{36}S and ^{40}Ar ions moved in the original direction of the primary beam, at mean velocities v_{ion} of $4.1v_0$ and $4.6v_0$ ($v_0 = e^2/\hbar$), respectively, through the magnetized Gd layer for spin precessions in the transient field (TF). These ions were ultimately stopped in the hyperfine-interaction-free Cu layer. The carbon layer's thickness was optimized for the short-lived 2_1^+ state in ^{36}S so that the nuclear decay in the carbon layer was restricted to $\sim 30\%$.

To calibrate the TF, the same target was bombarded with a 108 MeV ^{48}Ti beam under experimental conditions identical to those used with the sulphur beam. For ^{48}Ti, the first 2_1^+ state at 984 keV with $g(2_1^+) = +0.392(19)$ [10], was Coulomb excited and its spin precession measured.

In all these experiments the de-excitation γ rays were measured (with four 12.7 cm × 12.7 cm NaI(Tl) scintillators and with a Ge detector of 40% relative efficiency) in coincidence with the forward scattered carbon ions or with the two α particles originating from the decay of a recoiling ^{8}Be. The particle detector, a commercial Si counter, of 300 mm^2 area and nominal 100 μm thickness, was placed at 0° relative to the beam axis. A Ta foil behind the target served as a beam stopper. The foil thickness was adjusted to stop only the beam ions; the lighter particles could pass through and be detected. The Ge detector was used to monitor contaminant lines and also to measure the lifetimes of excited states via the Doppler-Shift-Attenuation Method (DSAM). The relevant low-lying energy level schemes of ^{36}S and ^{40}Ar are displayed in Fig. 1. Typical γ-coincidence spectra of ^{36}S and ^{40}Ar, gated with the relevant particles, are shown in Figs. 2 and 3. The Doppler-broadened line-shape of the $(2_1^+ \to 0_1^+)$ 1461 keV line of ^{40}Ar is displayed as an insert in Fig. 3, together with the DSAM fit to the lifetime of the 2_1^+ state (see below). In all the cases, the particle-γ-angular correlations $W(\Theta_\gamma)$ or the anisotropies $W(50°)/W(80°)$ have been measured in order to determine the slope $S \equiv [1/W(\Theta_\gamma^{\mathrm{rest}})] \cdot [dW(\Theta_\gamma^{\mathrm{rest}})/d\Theta_\gamma^{\mathrm{rest}}]$ in the rest frame of the γ-emitting nuclei at laboratory angles of $\Theta_\gamma^{\mathrm{lab}} = \pm 65°$ and $\pm 115°$ with the beam direction (see Table 1). The precession angles, Φ^{exp}, were determined in the conventional way, utilizing the counting rate double ratios R for the 'up' and 'down' directions of the external magnetizing field (see [11]). The precession angles are given by

$$\Phi^{\mathrm{exp}} = \frac{1}{S}\frac{\sqrt{R}-1}{\sqrt{R}+1} = g\frac{\mu_N}{\hbar}\int_{t_{\mathrm{in}}}^{t_{\mathrm{out}}} B_{\mathrm{TF}}\big(v_{\mathrm{ion}}(t)\big)e^{-\frac{t}{\tau}}\,dt. \tag{1}$$