EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Shape of neutron-rich ^{42}Ar studied by low-energy Coulomb excitation

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M. Zielińska[1], A. Görgen[2], S. Bönig[3], J. Cederkäll[4], E. Clément[5], R. Chapman[6], G. de France[5], J.-P. Delaroche[7], D. DiJulio[4], A. Drouart[1], C. Fahlander[4], G. Georgiev[8], M. Girod[7], L. Grente[1], K. Hadyńska-Klęk[9], S. Ilieva[3], J. Iwanicki[9], G. Jaworski[9], W. Korten[1], J. Kownacki[9], T. Kröll[3], J. Ljungvall[8], P.J. Napiorkowski[9], J. Pakarinen[10], M. Palacz[9], M.-D. Salsac[1], M. Scheck[3], C. Sotty[8], B. Sulignano[1], Ch. Theisen[1], M. Thürauf[3], K. Wimmer[11], K. Wrzosek-Lipska[12]

[1] *CEA Saclay, IRFU/SPhN, Gif-sur-Yvette, France*
[2] *University of Oslo, Norway*
[3] *Technische Universität Darmstadt, Germany*
[4] *Department of Physics, Lund University, Sweden*
[5] *GANIL, Caen, France*
[6] *University of the West of Scotland, Paisley, UK*
[7] *CEA, DAM, DIF, Arpajon, France*
[8] *CSNSM, Orsay, France*
[9] *Heavy Ion Laboratory, University of Warsaw, Poland*
[10] *Department of Physics, University of Jyväskylä, Finland*
[11] *NSCL, MSU, East Lansing, USA*
[12] *Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Leuven, Belgium*

Spokesperson: M. Zielińska (magda.zielinska@cea.fr), A. Görgen (andreas.gorgen@fys.uio.no)
Contact person: E. Rapisarda (elisa.rapisarda@fys.kuleuven.be)

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Abstract: We propose to measure the spectroscopic quadrupole moment of the first 2^+ state and to verify the B(E2, $2_1^+ \to 0_1^+$) in the neutron-rich ^{42}Ar using low-energy Coulomb excitation. Our recent study of ^{44}Ar at SPIRAL yielded the first direct measurement of the nuclear shape in an excited state in this region of the nuclear chart, giving evidence for an onset of deformation already two protons and two neutrons away from doubly-magic ^{48}Ca. As the theoretical predictions of quadrupole moment in ^{42}Ar vary considerably and experimental data in this mass region are scarce, the results of the proposed measurement will provide a benchmark for theoretical nuclear models.

Requested shifts: 12 shifts

1 Motivation

The evolution of the nuclear shell structure far from stability is one of the fundamental and still open questions in nuclear structure physics. The erosion of the shell closure in exotic nuclei was first discovered in the so-called “island of inversion” at $N = 20$, where the ground states of neutron-rich Na, Mg and Ne isotopes are dominated by deformed intruder configurations [1]. While the $N = 20$ shell closure disappears rather abruptly between ^{34}Si and ^{32}Mg, evidence has been gathered recently for a more gradual erosion of the neutron shell closure in the proton-deficient $N = 28$ isotones below ^{48}Ca. Neutron single-particle energies have been determined via the $d(^{46}\mathrm{Ar},\, ^{47}\mathrm{Ar})p$ reaction, indicating a moderate reduction of the $N = 28$ gap already for ^{46}Ar [2]. A rather low-lying and collective 2_1^+ state in ^{44}S [3] and the presence of an isomeric 0_2^+ state at low excitation energy [4] suggest the presence of deformation and shape coexistence in this nucleus. Finally, the very low lying 2_1^+ state at only 770 keV in ^{42}Si [5] provides evidence for the complete collapse of the neutron shell closure at $Z = 14$, contrary to earlier claims of a doubly-magic character of this nucleus [6].

The spectroscopy of neutron-rich nuclei in this mass region is very challenging. $B(E2)$ values have been measured via intermediate-energy Coulomb excitation for ^{44}Ar [7], ^{46}Ar [7, 8], $^{38-42}$S [7] and ^{44}S [3]. For ^{42}Ar lifetimes of several low-lying states were measured in the seventies using DSA method in the ^{40}Ar(t,pγ) reaction [9]. A cryogenic ^{40}Ar was used and the stopping powers were calculated from the model of Lindhard et al. [10] and it is difficult to judge to what extent it influenced the results; an additional uncertainty of 15% was ascribed to all lifetime values to account for this. Lifetimes in ^{44,46}Ar have been recently measured using the recoil distance technique after deep-inelastic reactions [12]. The result for the lifetime of the 2_1^+ state in ^{44}Ar is in agreement with both our result from low-energy Coulomb excitation [11] and an earlier intermediate-energy experiment [7]. On the other hand, the lifetime of the 2_1^+ state in ^{46}Ar [12] is more than two times shorter than the one obtained from intermediate-energy Coulomb excitation [7]. Our study of ^{44}Ar [11] using low-energy Coulomb excitation resulted in the first direct measurement of the spectroscopic quadrupole moment for an excited state in this region of the nuclear chart, and also the first case where $B(E2)$ values beyond the first 2^+ state were extracted. Recently, an experiment to study ^{46}Ar by a two-neutron transfer reaction ^{44}Ar(t,p)^{46}Ar has been performed at ISOLDE (IS499) and the data are currently under analysis.

Theoretical calculations support the observation of an eroding shell closure and the development of deformation for the neutron-rich $N = 28$ isotones. A comparison of various theoretical calculations with the available experimental data for $B(E2)$ values and quadrupole moments in the neutron-rich Ar isotopes and proton-deficient $N = 28$ isotones is shown in Fig.1. Both shell model and HFB calculations beyond the mean-field approach can be applied in this mass region. As can be seen in Fig.1, the predictions of the different calculations vary considerably, in particular for the spectroscopic quadrupole moments, for which only one experimental value is known (^{44}Ar).

Calculations using the angular momentum projected generator coordinate method with the axial quadrupole moment as generator coordinate and the Gogny D1S interaction (labelled GCM-1D in figure 1) predict coexistence of oblate and prolate shapes in this mass region, with oblate shapes slightly favored for ^{44,46}Ar, ^{44}S, and ^{42}Si [11, 13]. Triaxial

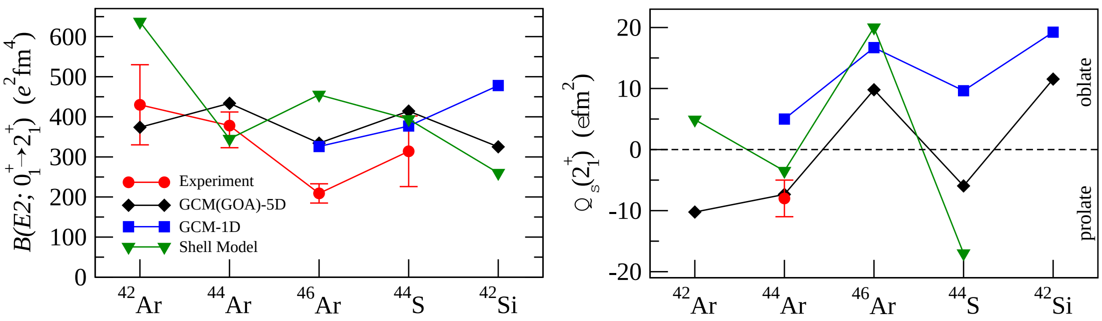

Figure 1: Spectroscopic quadrupole moments ($e$fm^2) and B(E2; $0_1^+ \to 2_1^+$) values (e^2fm^4) for the chain of Ar isotopes between ^{42}Ar and ^{46}Ar and for the $N = 28$ isotones from ^{46}Ar to ^{42}Si. Note that the experimental B(E2) value for ^{46}Ar comes from the intermediate-energy Coulex [7] and the recent lifetime measurement gives a higher value of 570 e^2fm^4 [12].

configuration mixing calculations [11] using the Generator Coordinate Method with Gaussian Overlap Approximation and Gogny D1S interaction (labelled GCM(GOA) in Fig.1) predict a very similar trend for the quadrupole moments, but shifted towards prolate shapes. One is tempted to conclude that the mixing of oblate and prolate shapes results in a sizeable triaxiality, which would shift the quadrupole moments to smaller values. The good agreement for the $Q_s(2_1^+)$ state in ^{44}Ar supports this interpretation. The fact that the measured value of the diagonal $E2$ matrix element represents only about 50% of the value expected for an axially symmetric prolate rotor gives further support for a triaxial shape of ^{44}Ar. While most of the theories agree rather well with the experimental results obtained for ^{44}Ar, a clear distinction can be achieved by a higher precision measurement of the $B(E2; 0_1^+ \to 2_1^+)$ and a first determination of the spectroscopic quadrupole moment $Q_s(2_1^+)$ in ^{42}Ar.
Shell model calculations for this mass region depend strongly on the local adjustment of the effective interaction. Slight modifications in the monopole term of the interaction, for example, changed the shell model predictions for the character of ^{42}Si from doubly-magic [14] to dominated by a $2p - 2h$ intruder configuration [15]. While the shell model predictions for the quadrupole moments in ^{44,46}Ar agree qualitatively with those of the GCM(GOA) calculation, the predictions for ^{42}Ar have opposite signs. Large differences exist also between the predictions for the $B(E2; 0_1^+ \to 2_1^+)$ value in ^{42}Ar. The experimental $B(E2)$ value lacks the necessary precision to draw conclusions.

2 Experimental method

Coulomb excitation of the radioactive ^{42}Ar beam post-accelerated to 2.85 MeV/A will be performed on a ^{194}Pt target of about 2 mg/cm^2 thickness. The choice of target with a high atomic number is motivated by the strong dependence of the second order reorientation effect on Z; using a heavy target will increase the sensitivity to the quadrupole moment. At the same time, simultaneous target excitation will be observed that will be used for

normalization purposes. The electromagnetic structure of ^{194}Pt is very well known from Coulomb excitation and lifetime studies [16].
We will use the standard set-up for Coulomb excitation experiments at REX-ISOLDE. The de-excitation γ rays will be observed in the MINIBALL array containing 8 triple clusters of 6-fold segmented Ge detectors [17], which has an efficiency of 7% for 1.3 MeV photons. Both scattered projectiles and target recoils will be detected using the DSSD CD detector. To limit the number of elastically scattered Ar ions hitting the detector, three inermost rings will be shielded and so the particles willl be detected in the angular range of 25° - 53°. which corresponds to center-of-mass angles of $30° < \theta_{CM} < 63°$ in case of scattered beam detection, and $72° < \theta_{CM} < 130°$ when recoiling target nuclei are detected.
The beam composition (in particular isobaric Ca contamination is expected) will be determined using the ionisation chamber at the MINIBALL beam dump. The IS499 experiment reported a pure ^{44}Ar beam.

3 Rate estimate

The ^{42}Ar beam can be delivered to REX from a UC$_x$/graphite target with the VADIS ion source. For the same configuration, $5 \cdot 10^6$ pps of ^{44}Ar were obtained at ISOLDE per 1 μC of the proton beam (IS499). The expected intensity of ^{42}Ar is of at least 10^7 pps per μC. Assuming REX efficiency of 5% one can expect $5 \cdot 10^5$ pps at MINIBALL.
The expected yields of γ rays de-exciting the 2_1^+ state at 1208 keV have been estimated using the GOSIA code [18], assuming $\langle 2_1^+ \| \mathrm{E2} \| 0_1^+ \rangle$ equal to 0.20 eb (calculated from the known lifetime [9]). For the quadrupole moment of the 2_1^+ state values of ± 0.1 eb were assumed, corresponding to theoretical predictions shown in Fig. 1; it should be noted that this is much lower than what would be expected for an axial rotor (0.24 eb). Possible influence of higher-lying states in ^{42}Ar on the $2_1^+ \to 0_1^+$ gamma-ray yield was also investigated. Their lifetimes are known from Ref. [9], and although there may be some doubts concerning the reliability of this measurement, the orders of magnitude should be correct. The calculations have shown that including coupling to higher-lying states in ^{42}Ar changes the population of the 2_1^+ by less than 1% in the considered range of scattering angles.
With a beam intensity of 2 10^5 pps (which was the intensity of ^{44}Ar obtained in the IS499 measurement) and a ^{194}Pt target of 2 mg/cm^2 thickness, taking into account a MINIBALL efficiency of 7% at 1.3 MeV, we expect a rate of 480 counts/day in the $2_1^+ \to 0_1^+$ transition (worst-case scenario, e.g. prolate shape of ^{42}Ar assumed). In our Coulomb excitation measurement on ^{44}Ar the statistics of 4000 counts in the $2_1^+ \to 0_1^+$ line has been sufficient to determine both the B(E2, $2_1^+ \to 0_1^+$) (with a precision of 15%) and the quadrupole moment of the 2_1^+ state (with a precision of 35%). We estimate that a yield of 2000 counts in the $2_1^+ \to 0_1^+$ transition should allow subdividing the total statistics into four angular ranges and obtaining precision of B(E2, $2_1^+ \to 0_1^+$) below 10% and a similar accuracy for the quadrupole moment as in the case of ^{44}Ar. The lower statistics necessary to reach this goal is related to the strong dependence of the reorientation effect on Z: in the measurement to study ^{44}Ar a ^{109}Ag target was used (Z=47), while we propose to

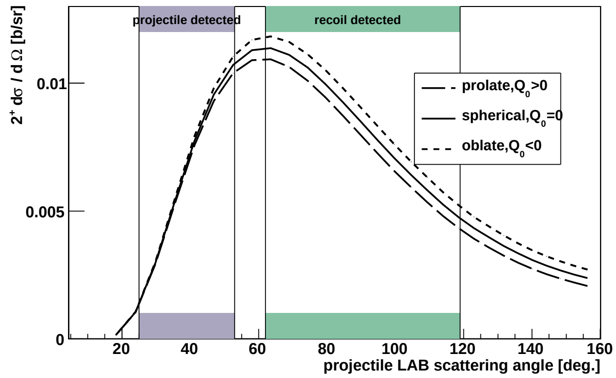

Figure 2: Dependence of the cross-section of the 2_1^+ state in ^{42}Ar on the projectile LAB scattering angle, calculated for scattering of a 2.85 MeV/A ^{42}Ar beam on a ^{194}Pt target. The three curves correspond to oblate, spherical and prolate deformation. The transitional matrix element $\langle 2_1^+ \| \mathrm{E2} \| 0_1^+ \rangle$ was assumed to be equal 0.20 eb [9], the magnitude of the diagonal matrix element $\langle 2_1^+ \| \mathrm{E2} \| 2_1^+ \rangle$ was chosen to be equal $\pm$0.1 eb.

replace it by a ^{194}Pt target (Z=78).
The lifetime of ^{42}Ar is as long as 33 years and it decays to ^{42}K, which has a 12h lifetime, and given the large difference in halflives the two are quickly in equilibrium. The total number of ^{42}Ar nuclei that should be delivered at MINIBALL for the proposed measurement is 8 $\cdot$ 10^{10}, which corresponds to the activity of ^{42}Ar and ^{42}K of the order of 100 Bq.
The beam energy of 2.85 MeV/A available at present at ISOLDE is sufficient to reach the goal of the proposed measurement.
Summary of requested shifts: We estimate that **12 shifts** of ^{42}Ar at $2 \cdot 10^5$pps at the target are necessary to determine the $B(E2; 0_1^+ \rightarrow 2_1^+)$ and the quadrupole moment of the 2_1^+ state in this nucleus.

References

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: MINIBALL + only CD

	Availability	Design and manufacturing
MINIBALL + only CD	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed MINIBALL + only CD installation.

Additional hazards: none

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		

• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			

Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): none