LoI for AGATA prePAC

Multiple-shape coexistence in ^{120}Sn

Tandem - AGATA + SPIDER (+ DANTE)

Spokesperson(s): Frank Wu, Marco Siciliano

F. Wu[1], C. Andreoiu[1], M. Siciliano[2], V. Karayonchev[2], N. Sensharma[2], M. Balogh[3], G. de Angelis[3], A. Gottardo[3], P.E. Garrett[4], D. Kalaydjieva[4], K. Stoychev[4], M. Zielinska[5], K. Hadyńska-Klęk[6], A. Krzysiek[6], M. Komorowska[6], P.J. Napiorkowski[6], I. Piętka[6] P. Sekrecka[6], K. Wrzosek-Lipska[6], N. Marchini[7], A. Nannini[7], M. Rocchini[7], I. Zanon[8], K. Mastakov[4], F.H. Garcia[1], M. Madhu[1], H. Asch[1], C.M. Petrache[9], P. Jodadir[9,10], B.F. Lv[10], S. Guo[10], K.K. Zheng[10], J. Williams[11], Y. Zhu[11], G. Colombi[4], m W.L. Pu[12], S. Lenzi[13], Y. Chen[12], K. Wei[12], ...

[1] *Simon Fraser University, Burnaby (BC), Canada.* [2] *Argonne National Laboratory, Argonne (IL), United States.* [3] *INFN, Legnaro National Laboratories, Legnaro, Italy.* [4] *University of Guelph, Guelph (ON), Canada.* [5] *Irfu/DPhN/CEA Saclay, Gif-sur-Yvette, France.* [6] *HIL, University of Warsaw, Warsaw, Poland.* [7] *INFN, Sezione di Firenze, Florence, Italy.* [8] *KTH, Stockholm, Sweden.* [9] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France.* [10]*IMP, Lanzhou, China.* [11]*TRIUMF, Vancouver, Canada.* [12]*Peking University, Beijing, China.* [13] *INFN, Sezione di Padova, Padova, Italy. ...*

Abstract

We propose to investigate the phenomenon of multiple-shape coexistence in the $Z \approx 50$ region by performing a multi-step Coulomb-excitation measurement of ^{120}Sn using the AGATA+SPIDER setup. The aim of the experiment is the measurement of the electromagnetic properties of the low-lying states in ^{120}Sn, in particular the spectroscopic quadrupole moments of the $2^+_{1,2,3}$ excited states. Such results will allow us to determine the quadrupole-deformation parameters (β_2, γ) of the $0^+_{1,2}$ states, as well as the deformation strength of 0^+_3 headband. The outcome of the measurement will allow us to shed light on the phenomenon of shape coexistence in the neutron-rich $Z \approx 50$ region, providing demanding test for state-of-the-art theoretical models which propose contradicting interpretation of the shape evolution for the Sn isotopic chain.

I. SCIENTIFIC MOTIVATION

Shape coexistence is a phenomenon where states or bands take different shapes in the same nucleus. Once considered a rare and exotic occurrence on isolated islands in the nuclear chart, shape coexistence is now a wide-spread feature that is believed to appear in almost all but the lightest nuclei [1, 2]. Microscopically, shape coexistence is often described as deformation driven by the promotion of nucleon pairs across shell gaps, where the energy cost in the cross-shell excitation is comparable to the energy gained from the increased proton-neutron interactions. As a result, the effect appear in the mid-shell members of semimagic nuclei, where a *deformed* excited state/band of cross-shell excitation intrudes into "normal" states that are traditionally viewed as *spherical*.

More recently, a novel form of shape coexistence, *multiple shape coexistence*, was observed that in a few nuclei, such as ^{110,112}Cd [3] and ^{186,190}Pb [4, 5], where more than two shapes can exist in the same nucleus. While multiple shape-coexistence is still considered to be rare, it was recently observed in ^{116}Sn [6] following a successful experiment using GALILEO in LNL.

In general, the semimagic $Z = 50$ Sn isotopes that span from before the $N = 50$ to beyond the $N = 82$ shell closures have retained continued interest for the investigation of shape coexistence. In the mid-shell Sn isotopes, excited 0^+ states intrude into the neutron-pair configurations, as shown in Fig. 1. In the best-studied case of ^{116}Sn, a strong $E0$ transition was observed between

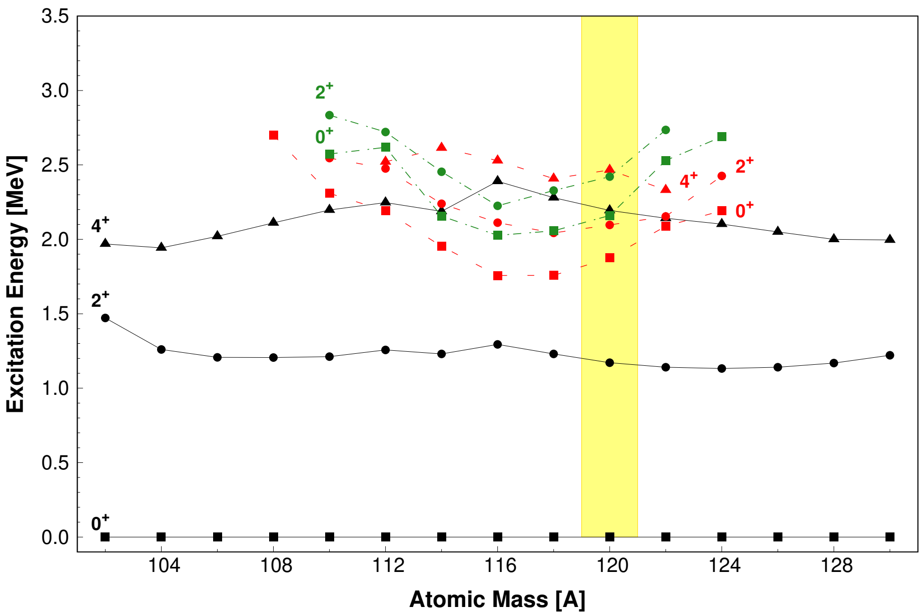

FIG. 1: Excitation-energy systematics in even-mass Sn isotopes: the low-lying 0^+, 2^+, and 4^+ states are reported with solid squares, circles, and triangles, respectively. The ground-state band is marked in black, while the intruder bands are shown in red and green – showing the typical "V-shape" expected in nuclei exhibiting shape coexistence.

the excited 0_2^+ and 0_3^+ states, which indicated strong mixing and a large shape difference of $\Delta\beta_2 > 0.22$ between these 0^+ states [7]. Furthermore, recent results from LNL observed for the first time that the low-lying states in ^{116}Sn also exhibit the very-rare multiple-shape coexistence [6]. Also recently, an enhanced $E0$ transition was observed for the first time in ^{120}Sn, suggesting that similar to ^{116}Sn, the excited 0_2^+ and 0_3^+ states are strongly mixed and have different shapes with $\Delta\beta_2 > 0.23$ [8]. Given the similar potential energy surfaces between ^{116}Sn and ^{120}Sn, as shown in Fig. 2, the observed shape difference in ^{120}Sn suggests that it may also exhibit multiple-shape coexistence, similar to ^{116}Sn. If true, it may suggest that multiple-shape coexistence is less rare than we currently think. A Coulomb-excitation measurement on ^{120}Sn is required to confirm this.

Another outcome from our proposed Coulomb-excitation experiment is to measure the deformation of the ground state of ^{120}Sn in a model-independent way. While the ground states of the semimagic Sn isotopes are traditionally considered to be nearly spherical, experimental observations by Allmond *et al.* [9] and Monte-Carlo shell model (MCSM) calculations by Togashi *et al.* [10] both indicate that the ground states of $^{110-124}$Sn are slightly deformed. However, contradicting deformations were reported by the two studies. While the MCSM predicts that all $0^+_{g.s.}$

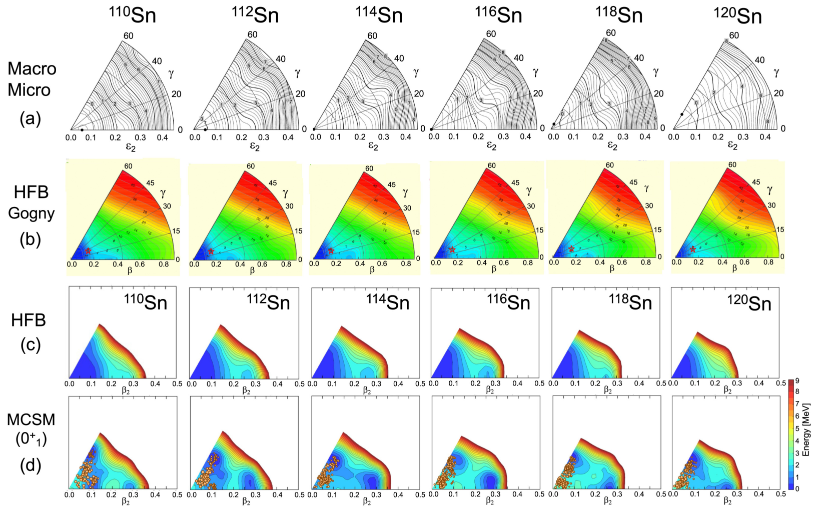

FIG. 2: Potential energy surface for the even Sn isotopes [2] calculated using various models.

states for $^{110-120}$Sn are oblate deformed [10], as shown in Fig. 2, Allmond *et al.* experimentally observed that the same states undergo a prolate-oblate transformation from ^{112}Sn to ^{124}Sn where the electric quadrupole moment $Q(2_1^+)$ is positive and decreasing for $^{112-118}$Sn and then become negative for ^{122}Sn and ^{124}Sn [9]. Although the systematics of the $Q(2_1^+)$ values seem to suggest that ^{120}Sn is the critical point where the quadrupole moment changes signs, $Q(2_1^+)$ was not measured for ^{120}Sn. The $Q(2_1^+)$ of ^{120}Sn will be measured in our proposed Coulomb-excitation experiment and, combined with the rich spectroscopic information from our (n,γ) experiment [8], the (β_2,γ) deformation parameters for the $0^+_{g.s.}$ state will be model-independently extracted.

II. PROPOSED EXPERIMENT

We propose to study ^{120}Sn via low-energy multi-step Coulomb excitation. This method is ideally suited to investigate collective properties, such as the shape, in a model-independent way. In fact, as a result of the unique information on relative signs of matrix elements (MEs) achievable solely with this technique, it is possible to extract the quadrupole shape invariants from transitional and diagonal E2 matrix elements, identifying any quadrupole shape (β_2,γ). Specifically, we aim to obtain:

- the diagonal MEs $\langle 2^+_{1,2}|\hat{E}2|2^+_{1,2}\rangle$, and consequently measure the spectroscopic quadrupole moments Q_s for $2^+_{1,2}$ excited states
- the quadrupole deformation parameters (β_2,γ) of the $0^+_{1,2}$ states, as well as $\delta\beta_2$ variance for the ground state
- the quadrupole deformation strength (β_2) of the 0^+_3 intruder state
- the transitional MEs connecting the low-lying states of ^{120}Sn, and consequent (indirect) determination of the lifetime of the excited levels
- the amplitude of the mixing acting between the coexisting configurations

The electromagnetic properties of the low-lying states in ^{120}Sn will be investigated via two multi-step Coulomb-excitation measurements. A ^{58}Ni beam will impinge at the energy of 190 MeV and 170 MeV onto a 1-mg/cm^2 ^{120}Sn target. The maximum beam energy has been fulfilling the Cline's safe distance criterion [11]; the second beam energy, instead, has been chosen to increase our sensitivity to quadrupole moments and matrix-element signs –since $|Q_s(2_1^+)|$ is expected to be very small, additional care is needed to properly determine the value of the corresponding matrix element. The beam current will be limited by the low melting point of the target materials so, building on the experience gained in previous experiments, the beam intensity will be 1 pnA at maximum.

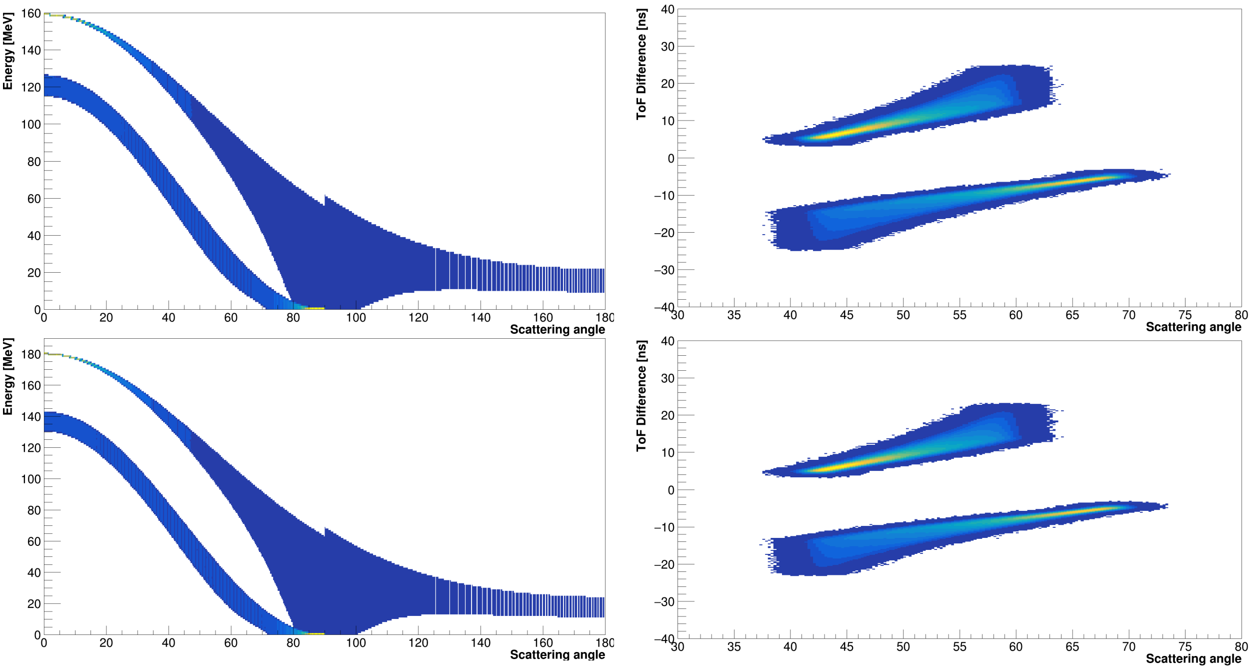

FIG. 3: Simulations showing (left) the kinematics of the ^{58}Ni+^{120}Sn reaction, and (right) the time-of-Flight (ToF) difference measured by DANTE. The results are shown for the (top) 170-MeV and (bottom) 190-MeV beam energy.

The emitted γ rays will be detected by the AGATA array ($\varepsilon_\gamma = 3.1\%$ at 1.332 MeV), while the scattered Ni ions will be detected with the particle detector SPIDER [12] at backward angles, where the probability of multi-step excitation and sensitivity to Q_s and signs of MEs are maximized. The employment of both AGATA and SPIDER are crucial for the goals of this experiment: the unique position sensitivity and detection efficiency of these arrays will allow us to reach unprecedented Doppler-correction capabilities and to exploit $\gamma-\gamma-$particle coincidence analysis to search for weak transitions. Furthermore, the large angular coverage of SPIDER at backward angles (123° - 161°) will enable determination of many transitional MEs, particularly for those excited states whose spectroscopic information is partial or scarce. If available, we would like to employ also the DANTE counters at forward angles: even though the goals of the current proposal can be achieved with the sole SPIDER, a larger angular coverage also at forward angles would provide additional constraints to the magnitude of the MEs.

It is worth noting that similar experiment was performed in 2020 at INFN-LNL with the GALILEO+SPIDER setup, aiming to investigate the phenomenon of shape coexistence in ^{116}Sn [6]. Despite the technical difficulties faced during that experiment, the high-quality data allowed for the measurement of $Q_s(2^+_{1,2,3})$ quadrupole moments, as well as the determination of the (β_2, γ) deformation parameters for $0^+_{1,2,3}$.

III. RATE ESTIMATES AND BEAM-TIME REQUEST

Taking into account the features of the experimental setup and the level scheme of ^{120}Sn (Fig. 4), the expected γ-ray yields were simulated using the GOSIA code [13]. The results of this calculation are listed in Table I. Considering the ambitious goals of the experiment and the estimated yields provided by GOSIA, we ask for:

- **Beam:** ^{58}Ni, 1 pnA, 190/170 MeV (Tandem)

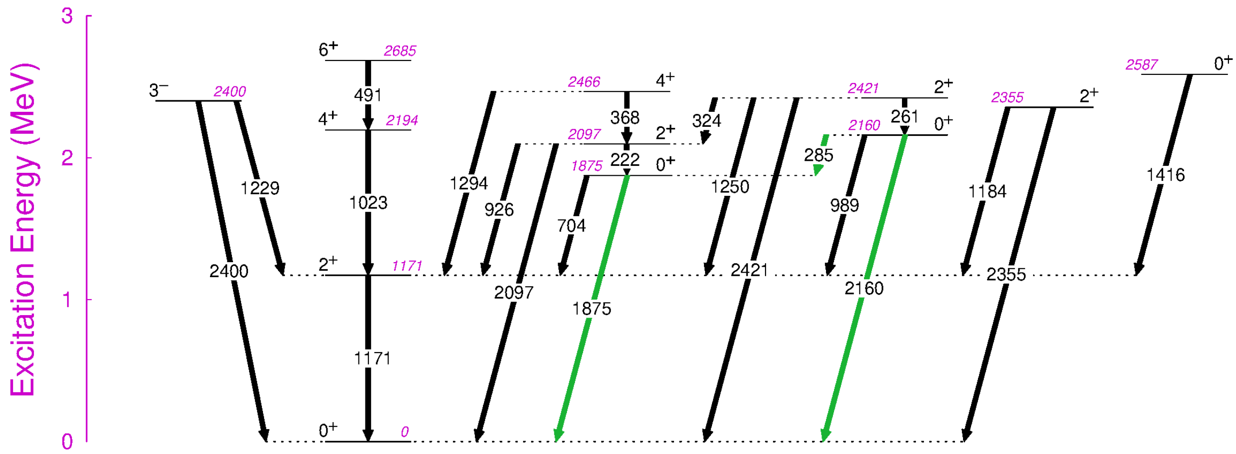

FIG. 4: Partial level scheme of ^{120}Sn, showing transitions included in the GOSIA calculations performed for this proposal. For the sake of the proposal, the known $E0$ transitions (also included in the estimations) are marked in green.

- **Target:** ^{120}Sn, 1.0 mg/cm^2, self supporting
- **Experimental setup:** AGATA + SPIDER (+ DANTE)
- **Beam time:** 5 days

TABLE I: Summary of counts estimated for the γ-ray transitions of ^{120}Sn. The reduced level scheme of Fig. 4 and a conservative choice of the non-diagonal ME signs are considered. Only the transitions with sufficient statistics to be observed during the experiment are reported.

$J_i^\pi \rightarrow J_f^\pi$	E_γ [keV]	SPIDER (190 MeV) Counts [1/day]	DANTE (190 MeV) Counts [1/day]	SPIDER (170 MeV) Counts [1/day]	DANTE (170 MeV) Counts [1/day]
$2_1^+ \rightarrow 0_1^+$	1171	$1.27 \cdot 10^6$	$3.67 \cdot 10^6$	$7.46 \cdot 10^5$	$2.17 \cdot 10^6$
$4_1^+ \rightarrow 2_1^+$	1023	$1.80 \cdot 10^4$	$3.25 \cdot 10^4$	$4.98 \cdot 10^3$	$9.78 \cdot 10^3$
$0_2^+ \rightarrow 2_1^+$	704	$1.08 \cdot 10^4$	$3.09 \cdot 10^3$	$3.36 \cdot 10^3$	
$2_2^+ \rightarrow 0_1^+$	2097	$1.65 \cdot 10^4$	$1.80 \cdot 10^4$	$5.19 \cdot 10^3$	$5.38 \cdot 10^3$
$2_2^+ \rightarrow 2_1^+$	926	$4.67 \cdot 10^3$	$6.29 \cdot 10^3$	$1.47 \cdot 10^3$	$1.88 \cdot 10^3$
$4_2^+ \rightarrow 2_1^+$	1295	$6.69 \cdot 10^3$	$1.72 \cdot 10^4$	$1.75 \cdot 10^3$	$4.61 \cdot 10^3$
$2_3^+ \rightarrow 0_1^+$	2355	$1.17 \cdot 10^3$	$1.43 \cdot 10^3$		
$2_3^+ \rightarrow 2_1^+$	1184	$4.16 \cdot 10^3$	$5.31 \cdot 10^3$	$1.07 \cdot 10^3$	$1.39 \cdot 10^3$
$2_4^+ \rightarrow 0_1^+$	2421	$2.59 \cdot 10^3$	$2.18 \cdot 10^3$		
$2_4^+ \rightarrow 2_1^+$	1250	$3.59 \cdot 10^3$	$3.80 \cdot 10^3$		
$3^- \rightarrow 2_1^+$	1229	$7.90 \cdot 10^3$	$3.07 \cdot 10^4$	$2.14 \cdot 10^3$	$8.42 \cdot 10^3$

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