ALTO

PROPOSAL FOR EXPERIMENT

PAC session:	EXP # (Do not fill in):

Title**: Investigation of high spin structures in ^{44}Ti and ^{42}Ca via discrete and continuum gamma spectroscopy using nuBall2, PARIS and OPSA setup** Is it a follow-up experiment? [Yes/No]: No If yes, experiment number:		
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and the nuBall2, PARIS and OPSA collaborations

Short abstract:

We propose to investigate a high spin states structure in ^{42}Ca and ^{44}Ti nuclei. To populate excited states in ^{42}Ca and ^{44}Ti at high angular momentum, up to 20 ħ, we propose fusion-evaporation reactions: ^{24}Mg (^{24}Mg, α2p) ^{42}Ca and ^{24}Mg (^{24}Mg, 2p2n) ^{44}Ti at a beam energy of 110 MeV. The proposed experiment aims to extend the knowledge of the particle-hole excitation structures in the ^{42}Ca and ^{44}Ti up to or beyond the terminating states. Extension of the SD bands, decaying via discrete E2 transitions, up to and beyond the band terminating state will be combined with spectroscopy of high-energy γ rays of a statistical nature, possibly feeding the SD band. In this way, new light can be shed on the expected link between collective modes such as rotation at high temperatures but also in a cold nucleus. The large-scale nuclear mean-field calculations will be used to provide a detailed interpretation.

Beam area (room number) **:**	

Instrumentation needed (check webpage)**:**	**nuBall2 + OPSA + PARIS**

Fill in completely:	**Ion(s)**	**Energy (MeV)**	**Intensity (nAe or pps)**	**UT/beam**	**Pulsed beam (yes/no If yes specify time structure)**
ALTO-HEB (Beam)	1. 24Mg 2. 3.	110 MeV	3 pnA	33 UT	
ALTO-LEB (Beam)	1. 2. 3.				

Fill in completely:	**Element / compound**	**Target manufacturer**	
		IJCLAB[1]	other[2]
ALTO-HEB (beam production) Targets	^{24}Mg, 1 mg/cm^2 target from IJCLab		

1 Please contact as soon as possible IJCLAB …. link

2 Please specify if empty target frames at Tandem standard are requested

Fill in completely:	Type of target	Type of source
ALTO-LEB (Beam production)	1. 2. 3.	

TOTAL number of beam UTs Requested: (1 UT=8 hours): **33 UTs**	Time (UTs) required for setting up the apparatus: Time (UTs) needed for off-beam calibration and dismounting:

Acquisition system:	

SAFETY:	list any hazardous equipment or substances to be used, such as. radioactive target, liquid nitrogen, explosive gas, etc.,:

New devices:	List any NEW devices needed for this experiment which still have to be bought or manufactured:

At what date do you expect these to be available?

Special devices:	List any special devices needed for this experiment which would require to be mounted prior to the experiment (special target chambers, detector arrays, etc.):
How long will it take to mount the particular device(s) once the area is available to you?	

Status of previous ALTO experiments:	Give the status of previous experiment(s) made by this group in the last 3 years at ALTO: e.g. results from or status of analysis of previous experiments at ALTO, list publications, conference presentations, PhDs awarded etc :

Laboratoire de Physique des 2 infinis Irène Joliot-Curie

Additional comments:	

Physics Motivation

Light nuclei lying close to the *N*=*Z* line in the vicinity of the doubly magic ^{40}Ca exhibit many features characteristic for well deformed heavier nuclei. In many nuclei from this region from ^{36}Ar to ^{44}Ti, there are reported discoveries of super-deformed bands, interpreted in terms of exotic many particle-hole configurations [1-5]. At the same time, these are the lightest nuclei in which the nuclear mean-field approximation [6] explains the very strong *E2*-transitions as caused by super-deformation (SD) – the elongated *prolate* shape with an axis ratio close to 2:1. Since the effective moments of inertia of super-deformed configurations are expected to be relatively large, the corresponding bands are expected to become *yrast* with increasing spin. Moreover, the nuclei of interest manifest the presence of negative parity bands, decaying via strong *E1* transitions, that may point to octupole shape, for example as in ^{44}Ti [12].

Light and medium mass nuclei are good candidates to study Jacobi shape transition, which is an abrupt change from an *oblate* to collective tri-axial or *prolate* shape at high angular momentum. The Jacobi shape transition was investigated in a few light mass nuclei via γ decay of the giant dipole resonance (GDR) [7-9]. Splitting of the GDR strength function into multiple components with a narrow peak around 10 MeV is interpreted as a sign of the Jacobi shape transition in the ^{46}Ti compound nucleus [21]. Moreover, the low-energy GDR component seems to feed preferentially the highly deformed band in the ^{42}Ca evaporation residuum. This result suggests that the very deformed shape of a hot compound nucleus persists in the entire evaporation process.
Also, super-deformed *oblate* geometry having axis ratio 1:2 (as opposed to 2:1 for *prolate*) occurs to be important in interpreting the deformation in light nuclei with Z=N=14 [10], the more recent study [11] indicates that this effect should be strongly present at Z, N=14, 16, 20, 26/28. More exotic shapes could be also considered. For example, following [11], the privileged super-deformed shape corresponds to the combination of quadrupole and hexadecapole deformations α_{20}=-0.7 and α_{40}=-0.3, in the literature, referred to as toroidal-super-*oblate*. An example of such a shape predicted for ^{44}Ti ground state is illustrated in Fig.1.

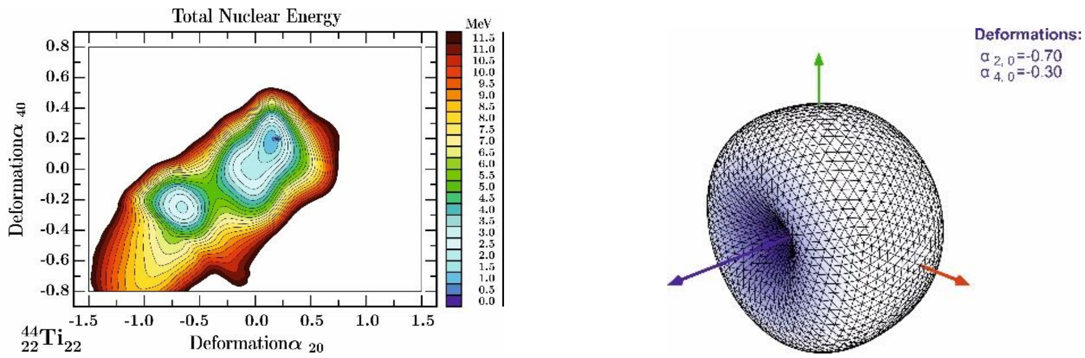

Fig.1: Left: Total energy surface for [44]Ti nucleus calculated using phenomenological mean-field theory (Ref. [11]). Besides the *prolate* shape minimum at (α_{20}~0.3, α_{40}~0.3) the *oblate* shape appears, referred to as super-*oblate*. The *oblate* minimum coexist at α_{20}~ -0.7 – however, very important – it combines with a strong negative hexadecapole component α_{40}=-0.3, resulting in a characteristic toroidal-like structure. Right: The shape of the nuclear surface corresponding to the secondary minimum.

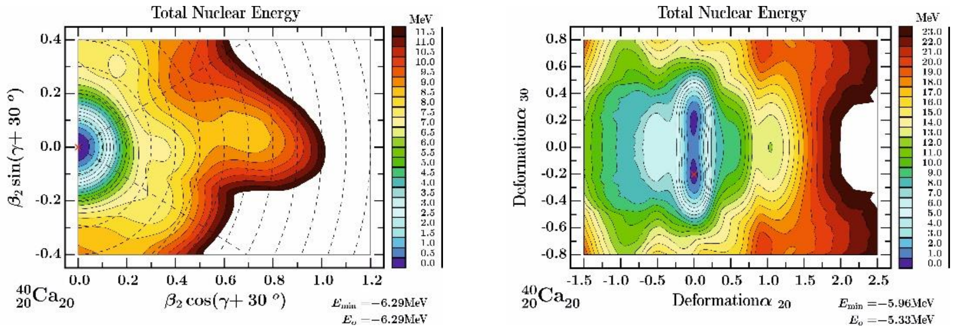

Fig.2. Left: Total energy calculation results for [40]Ca including the standard combination of the quadrupole deformations, here in the form of the so-called (β_2-γ) representation, where at each point the energy was minimized over the hexadecapole deformations β_4=α_{40}, showing a spherical minimum within this representation. However, allowing for an extra octupole shape minimization shows the static pear-shape minima separated by a potential barrier of about 1 MeV – Right. Such configurations are expected to lead to the parity doublets, associated parity double bands (from Ref. [11]).

On the other hand, the typical octupole bands known from the heavy nuclei e.g., in the Actinide region correspond to the nuclear shapes as superposition between the quadrupole-elongated, $\alpha_{20} > 0$ and octupole pear-shape components, $\alpha_{30} \neq 0$. Also, in the vicinity of [40]Ca the newest realistic mean-field calculations [11], predict the presence of a new form of the nuclear octupolarity, which does not involve the quadrupole degrees of freedom, $\alpha_{20} = 0$ with $\alpha_{30} \neq 0$. Such deformed ground state configuration could be a foundation for the excited negative parity structures known in some even-even nuclei, among others [44]Ti [12].

The N~Z~20 nuclear region turned out to be a privileged one as Large-Scale Shell Model (LSSM) calculations for natural parity states in the full f-p configuration space get in general very good agreement

with experimental data [14-16]. Super-deformed states resulted from the multiple particle-hole excitations across the magic N=Z=20 shells were discovered in ^{36,38,40}Ar, ^{40,42}Ca, and ^{44}Ti [1-5].
The level scheme of the ^{44}Ti nucleus is shown in Fig 3. In this nucleus, beside the GS band of positive parity, known up to $J_{max} = 12^+$, negative parity states form two rotational bands with a band-head at spin $J^\pi = 3^-$. Also, terminating structure partner bands, typical for the nuclei in the lower half of the $f_{7/2}$ shell (like in ^{45}Sc or ^{45}Ti [22]) are expected. In the ^{44}Ti, they were interpreted as 5p-1h [5] excitation and should arrive at the maximum aligned spin of $J_{max} = 15^-$, however, such a terminating state has not yet been observed in this nucleus. The positive parity excited band is interpreted as a super-deformed band [17]. In the shell model picture, it corresponds to a mixture of 8p-4h (beta~0.4) and 6p-2h (beta~0.3) excitations, dominant at low and high spins respectively [5], with $J_{max} = 16^+$, but this state was not observed experimentally so far.

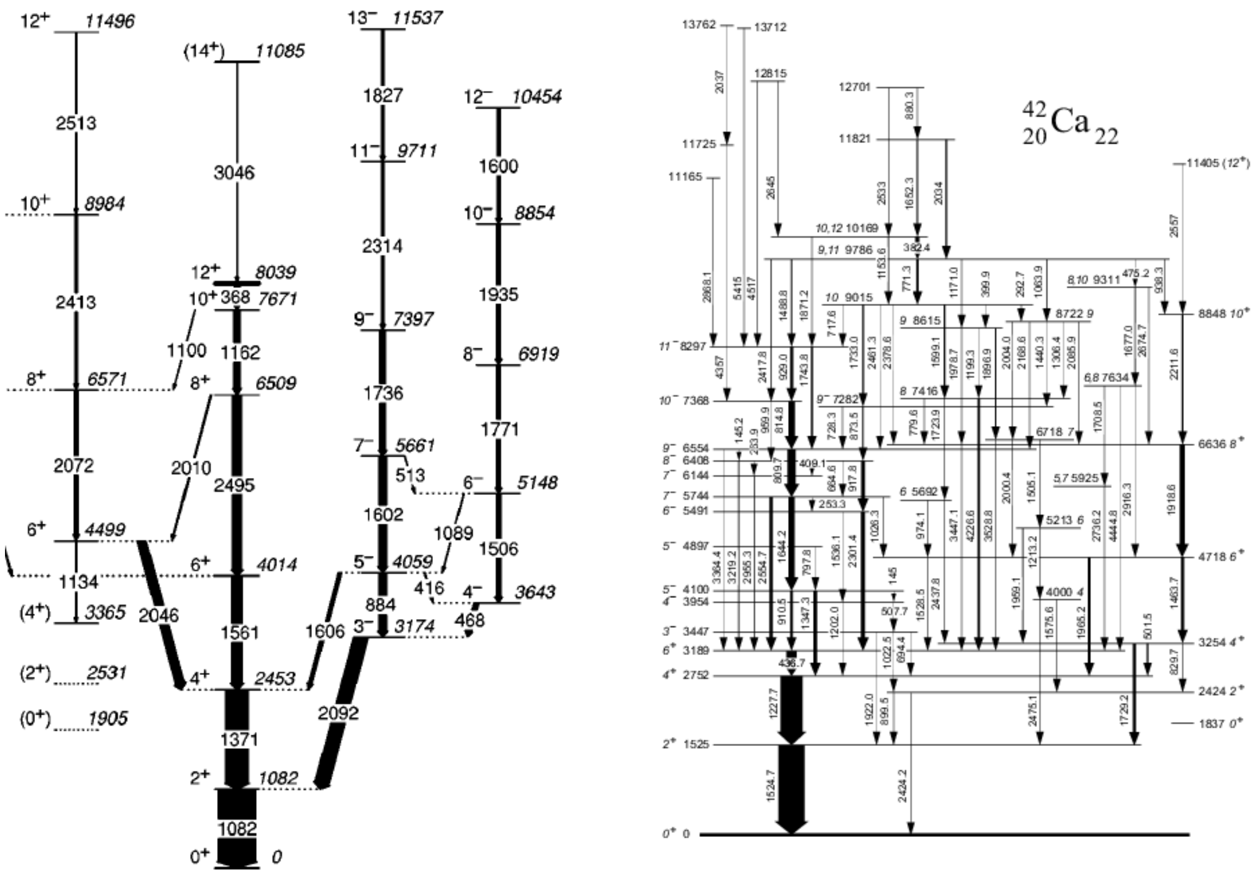

Fig.3. Left - Level scheme of ^{44}Ti [5]. The excited positive parity band in ^{44}Ti is interpreted as superdeformation and should terminate at the maximum aligned spin $J^\pi = 16^+$. Right - Level scheme of ^{42}Ca [4].

A similar structure can be observed in the N=22 isotone ^{42}Ca. Here, the positive parity excited band is known up to spin 12^+, and our previous measurements [4] indicated high deformation associated with this excitation (conditions of this experiment were not optimized for high spin spectroscopy of ^{42}Ca). Recently, shape parameters of the positive parity low-lying states belonging to the band of interest in ^{42}Ca were also determined from the Coulomb-excitation experiment [6]. As a result, the triaxial shape of this nucleus at the band head was determined: $\beta_2 = 0.43(2)$ and $\gamma = 13(+5, -6)$. However, according to the recent beyond mend field calculations [17] shown in Fig.4. excited triaxial shapes could result not only from excitation of at least 6 particles over the ^{40}Ca core giving rise to superdeformation (structure indicated in red in Fig.4) but also involving a smaller number of particles for example 2p-2h excitation (triaxial normal deformed shapes indicated in orange color in Fig.4). However, such a structure should terminate at moderate spin 14^+. Our experimental goal is to possibly extend the presumably SD band beyond this limit.

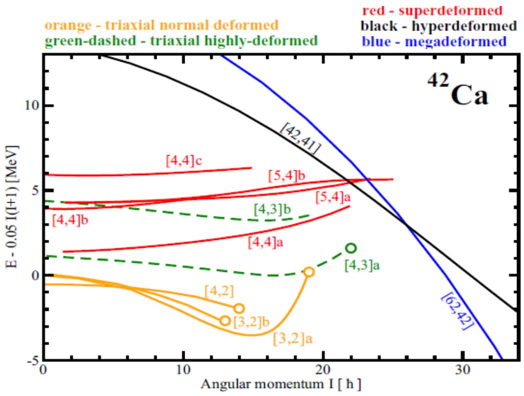

Fig.4. Calculated energies of the excited configurations in ^{42}Ca in the function of angular momentum. Note the overlap of the normal triaxial (orange) and superdeformed (red) configurations at low spins. The picture was taken from Ref. [17].

In this proposal, an extension of the knowledge of the excitation structures in the ^{42}Ca and ^{44}Ti nuclei, especially at high spins is proposed. Of special interest will be also the investigation of expected competition between many particle-hole excitations that induce quadrupole correlations giving rise to *prolate* super-deformed bands and the super-*oblate*-toroidal shape foreseen in these nuclei based on the mean-field theory (cf. Fig.1), [10]. At high temperatures, very elongated *prolate* shapes are expected as a natural manifestation of the Jacobi transitions and have been identified via GDR and charged particle studies in the neighboring ^{46}Ti nucleus at high temperatures. Extension of the SD band in ^{44}Ti, decaying via discrete E2 transitions, up to and beyond the band terminating state will be combined with spectroscopy of high-energy γ rays of a statistical nature, possibly feeding the SD band. In this way, new light can be shed on the expected link between collective modes such as rotation at high temperatures but also in a cold nucleus.

Proposed experiment

To populate excited states in ^{42}Ca and ^{44}Ti at high angular momentum, up to 20 ħ, we propose fusion-evaporation reactions: ^{24}Mg (^{24}Mg, α2p) ^{42}Ca and ^{24}Mg (^{24}Mg, 2p2n) ^{44}Ti at the beam energy of 110 MeV. The experiment will be focused on simultaneous detection of discrete gamma-rays in the nuBall2 spectrometer together with high-energy gamma radiation ($E\gamma \geq 5$ MeV) in the PARIS array. Protons and alpha particles will be registered in the Orsay Particle Scintillator Array (OPSA). Particle-gamma coincidences will be then used to select the reaction channel of interest. The reaction will result in fast recoiling residual nuclei with v/c~ 4.5 %, which is why the use of the OPSA particle detector will help in the kinematical reconstruction of the recoil velocity. This will be useful in the reduction of a Doppler broadening of gamma-ray lines at high energy. In addition, some information on the entry line population in different channels will be possible by measuring gamma-multiplicity and sum-energy, using PARIS, gated by the charged particle spectra from OPSA. From the high-energy gamma-ray spectra measured in PARIS, gated either by the low-spin structures (normal- and super-deformed) in nuBall2, or by specific evaporation channel in OPSA, one can extract the GDR strength function, which parameters (centroid, width, and details of the line shape) could shed a light on the nuclear deformation in the high spin and high-temperature region.

The measurement aims mainly at:

- an extension of the knowledge of the excitation structures in the ^{42}Ca and ^{44}Ti up to, or beyond the rotational band terminating states interpreted so far as particle-hole excitations,
- search for possible feeding of the high states (close to the band termination) with high-energy discrete transitions and determination of the electromagnetic character of this radiation,
- establishing a link between the structures at high and low temperatures by coincident measurement of continuum and discrete gamma-rays.

The large-scale nuclear mean-field calculations will be used to provide a detailed interpretation (example results are shown in Figs. 1 and 2). Results of this experiments will be helpful in the evaluation of nuclear theories, as well as testing the hypotheses of the new types of octupolarities.

Beamtime estimation

In the studied cases, according to the PACE IV and GEMINI++ calculations, in the 110 MeV ^{24}Mg + 1mg/cm^2 ^{24}Mg fusion-evaporation reaction, the ^{42}Ca, and ^{44}Ti residua are expected to be produced with a cross-sections of order of $\sigma = 35$ mb (3% of σ_{fus}) and $\sigma = 60$ mb (5% of σ_{fus}), respectively. The angular momentum available for these evaporation residua should reach 20 ħ (i.e. exceeding the value of J_{max}=16).

The nu-Ball2 spectrometer consists of 24 clovers placed in two rings at 75.5 deg. and 104.5 deg, the approximate efficiency at 1 MeV is 4.5 %. The 72 phoswiches of the PARIS array will measure high-energy gamma rays with the efficiency of 4.5-3 % at 10-20 MeV, respectively. The OPSA is a charged particle detector using 24 LYSO scintillators positioned in two rings - the first ring (8 scintillators) is at 15 mm (center of the crystal) and the outer ring (16 scintillators) is at about 23 mm from the beam axis.

As concerns OPSA, for the reaction channel of interest, we may assume the efficiency of 10 % for alpha and 15% for protons.

Taking into account the reaction cross-section, a beam intensity of 3 pnA is considered a safe limit to use in combination with the OPSA detector. Together with the 1.0 mg/cm^2 target and the setup efficiency, a rate of ~200 events per second for ^{42}Ca, and ~370 events per second for ^{44}Ti is estimated under the discrete gamma-gamma-particle coincidence condition. Therefore, we would need 10 days of data taking. This will allow to collect statistics relevant for the identification of high-spin transitions in the SD band in the nuclei of interest and to link it with the structures in the hot nucleus. In total, we ask for 11 days of beam time including one day for set-up and calibrations.

We ask for:

- beam: ^{24}Mg, 3 pnA, 110 MeV
- target: ^{24}Mg, 1 mg/cm^2, self-supporting
- experimental setup: nuBall2, PARIS and OPSA
- beam time: 11 days

4. Literature

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