EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Proton-neutron balance in the properties of ^{136}Te

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Abstract:
It is proposed to perform a Coulomb excitation experiment on ^{136}Te. The ^{136}Te radioactive ion beam will be delivered by HIE-ISOLDE with an energy of 4.7 MeV/u impinging on a ^{196}Pt target. The γ-rays of deexcitation will be detected by the MINIBALL array and scattered particles will be detected by the Double Sided Silicon Strip Detector (DSSSD) in forward direction. The purpose of this experiment is threefold:

- Development of post-accelerated Te ion beams;
- Investigating the proton-neutron balance of the properties of the excited states in ^{136}Te by measurement of the $B(E2)$ of 2^+_1 state;
- Proving the mixed-symmetry character of the 2^+_2 state by measurement of the transition probability.

Requested shifts: 15 shifts, (split into 1 run over 1 year)
Installation: [MINIBALL + CD-only]

1 Introduction

Atomic nuclei are complex quantum systems. Their dynamics are reflected by collectivity, shell structure and isospin degrees of freedom. In many cases one of these properties has a dominating role, which enables us to study them separately. However, the balance and interplay between these key aspects of nuclear structure is an intriguing subject, which has not been entirely understood. A good ground for probing the transition from single-particle properties to collectivity is the evolution of nuclear properties going away from doubly-magic cores. With the addition of valence particles the proton-neutron component of the residual interaction increases, which drives collective behaviour.
The impact of local shell structure on the proton-neutron (pn) balance of low-energy 2^+ states at the onset of collectivity near neutron-rich shell closure is of particular interest for contemporary nuclear research. Two fundamental one-phonon quadrupole excitations are normally found in near-spherical nuclei, both mixtures of the underlying proton and neutron 2^+ configurations. They can be simplified into a two-state mixing scenario $\left|2_i^+\right\rangle = \alpha_i \left|2_\pi^+\right\rangle \pm \beta_i \left|2_\nu^+\right\rangle$. The 2^+ state, resulting from an in-phase combination of proton and neutron contributions, is the fully symmetric state (FSS). The other one is the pn-mixed-symmetry state [1] with the opposite phase - the lowest energy isovector valence shell quadrupole excitation. Mixed-symmetry states (MSS) can be experimentally identified by their strong isovector $M1$ decay to the low-lying fully-symmetric states [2].
The fundamental MSS in weakly collective vibrational nuclei is the one-quadrupole phonon $2^+_{1,ms}$ state [1]. MSS have been identified in stable and radioactive nuclei in the mass A≈90 region [3, 4, 5, 6, 7, 8, 9] and A≈130 region [10, 11, 12, 13]. Recent studies have investigated a new possible region - namely around the double-magic ^{208}Pb [14, 15, 16].
The main reason for the small number of studied cases comes from the fact that the even-even isotopes in those mass regions have relatively low abundance. This comprises an experimental problem because an unambiguous identification of MSSs can be done only on the basis of measured large absolute M1 strengths. To obtain this experimental information, one needs to perform several experiments [7], which in the case of low-abundant or unstable isotopes is not possible. A technique successfully used for such studies in recent years proves to be projectile Coulomb excitation [17].
A region of interest in the last decades has been neutron-rich nuclei with few valence particles outside the doubly-magic ^{132}Sn. The tellurium isotopes, having two protons outside the Z=50 shell closure, provide an excellent probing region for two-body matrix elements. For further insight, an investigation into the evolution of transition probabilities in the higher-lying states in neutron-rich Te isotopes is needed.

2 Physics case

Mixed symmetry states have been already discovered in the N=84 isotones [18]. In the stable ^{144}Nd [19] the one-quadrupole phonon MSS is fragmented and split mainly between the 2_3^+ and 2_4^+ states. Similar is the picture of the next stable neighbour ^{142}Ce. Going to the unstable N=84 isotones the available information becomes scarce. In the case of ^{140}Ba information of the multipole mixing ratios for the 2_2^+, 2_3^+ and 2_4^+ states is available

[20]. The small values for the two higher-lying states are a first indication for an eventual fragment of the MSS, but no information is available of the B(M1) transition probabilities. Going down on the isotonic chain, investigations of ^{138}Xe [21] conclude that the 2_2^+ contains significant components of both 1-d mixed symmetry and 2-d boson configurations and thus cannot be identified as a mixed symmetry state.
The ^{136}Te isotope has two valence protons and two valence neutrons outside the doubly-magic core of ^{132}Sn. The structure of the first excited states of ^{136}Te can be described as a superposition of the excitations of its two even-even neighbours - ^{134}Te and ^{134}Sn, as presented in Fig. 1. Those neighbouring nuclei have both 2 same type particles outside doubly-magic core and they exhibit strong seniority-like regime. The question, which emerges, is whether seniority is still a good quantum number in ^{136}Te.

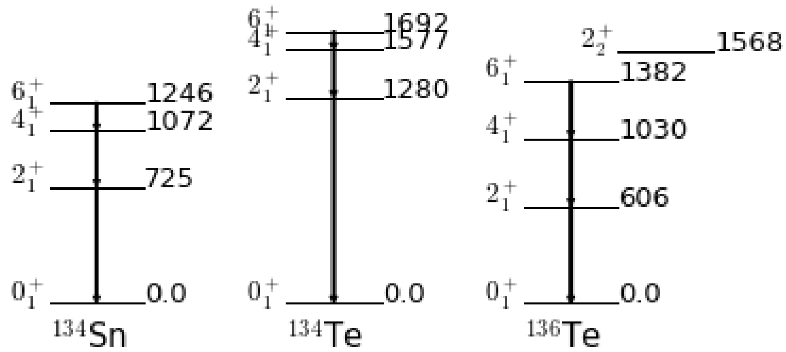

Figure 1: Partial level schemes of ^{134}Te,^{134}Sn and ^{136}Te. First excited states in ^{134}Te and ^{134}Sn - a result of the residual interaction in a two-particle configuration - $(\nu f_{7/2})^2$ and $(\pi g_{7/2})^2$, respectively. The structure of first levels of ^{136}Te is a superposition of the excitations in its neighbours.

In the neutron magic ^{134}Te the energy of the excited states and the measured reduced transition probabilities follow the seniority scheme. In ^{132}Te, two neutrons short of a closed shell, the one-quadrupole phonon MSS was identified as the 2_2^+ state [22]. However, the astonishingly large M1 transition strength of 5.4(3.5) μ_n^2 stands out in the nuclear chart. The large uncertainty is mostly due to the 50% uncertainty of the literature value of the branching ratio $2_2^+ \rightarrow 0_1^+/2_2^+ \rightarrow 2_1^+$ [23]. A re-measurement of the branching ratio $2_2^+ \rightarrow 0_1^+/2_2^+ \rightarrow 2_1^+$ [23] and the $B(M1)$ value is the goal of an experimental campaign at the Tandem accelerator of IFIN-HH, Bucharest, Romania [24], the first part of which was in March 2021 and will be continued at the end of May 2021.
A recent study performed on even-even neutron-rich Te isotopes [25] summarizes the available theoretical and experimental information and emphasizes the importance of further investigation. The first excited 2_1^+ state in ^{136}Te has a relatively low energy, which indicates neutron dominance in the wave function. Information on $B(E2)$ values, which would give insight into the proton-neutron balance of the state, is contradictory. A Coulomb excitation experiment from Oak Ridge [26, 22] and a fast-timing measurement from ISOLDE [27] indicate reduction of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ transition probability

Table 1: Comparison of the experimental values for transition probabilities $B(E2; I_i \to I_f), [e^2b^2]$ of ^{136}Te

$0_1^+ \to 2_1^+$	$2_2^+ \to 0_1^+$	$2_2^+ \to 2_1^+$	$4_1^+ \to 2_1^+$	$6_1^+ \to 4_1^+$	Reference
0.122(18)					Danchev et al. [22]
0.122(24)					Fraile et al. [27]
0.191(26)	< 0.0038		0.061(31)		Vaquero et el. [31]
0.181(15)	< 0.004	< 0.09	0.060(9)		Allmond et al. [30]
> 0.110			$0.042^{+0.03}_{-0.009}$	$0.046^{+0.02}_{-0.009}$	Lozeva et al. [25]

with respect to lighter isotopes. This smaller value clearly violates the empirical rules for properties of quadrupole collective states [28, 29]. A more recent Coulomb excitation experiment from Oak Ridge [30] and an experiment from RIKEN [31] show an enhanced reduced transition probability than previously measured. Those values are not consistent with previous measurements and imply prolate-deformed quadrupole collectivity and greater proton content than expected. In a most recent fission experiment at IJCLab [25], an upper limit for the lifetime of the 2_1^+ state is reported, which is in agreement with all the previously mentioned experiments. However, measured lifetimes of the higher-lying 4_1^+ and 6_1^+ states indicate a slowing down of collectivity with the addition of neutrons.
The availability of two proton orbitals - $1g_{7/2}$ and $2d_{5/2}$ would lead to proton dominated 2_2^+ state, which may lead to a significant $B(M1; 2_2^+ \to 2_1^+)$ transition strength. In the above mentioned recent studies, the transition strength $B(E2; 4_1^+ \to 2_1^+)$ and upper limits for the $B(E2; 2_2^+ \to 2_1^+)$ and $B(E2; 2_2^+ \to 0_1^+)$ transition strengths have been reported. A summary of all measured values is presented in Table 1.
In order to determine the character of the excited states and the balance between proton and neutron contributions in the wave functions of the 2_1^+ and 2_2^+ states, an additional measurement is of high importance. Thus, we propose an experiment using projectile Coulomb excitation of the nucleus ^{136}Te produced by ISOLDE using the MINIBALL spectrometer.

3 Feasibility of the proposed experiment

We propose an experiment using the well-established technique of sub-barrier projectile Coulomb excitation to extract the electromagnetic matrix elements of transitions between excited states in ^{136}Te.
The ^{136}Te ions will be produced with and extracted from a standard UCx /graphite target with intensities $> 4 \cdot 10^7$ ions/μC [32]. They will be charge-bred by REX-EBIS and accelerated by HIE-ISOLDE to energies of 640 MeV (4.7 MeV/u). A considerable contamination of the beam with isobaric ions, in particular ^{136}Ce, may persist after charge-breeding. Therefore we request to use a selective laser-ionization scheme by means of RILIS and intend to measure in the well-known laser on/off-mode. Laser schemes have been successfully tested with Ti:Sa lasers [33]. Additionally, in an effort to suppress surface-ionized isobaric contaminants the Laser Ion Source and Trap (LIST) will be used [34]. Application of LIST will affect the production of Te and reduce it by a factor of

20-50. A beam intensity of $\approx 10^4 - 10^5$ ions/s can be expected at the secondary target of 2 mg/cm^2 of ^{196}Pt at MINIBALL. Both projectile and target nuclei will be excited via Coulomb excitation in the scattering process. The scattered nuclei will be detected by the annular CD detector placed 20 mm behind the secondary target and covering scattering angles of 24-62 degrees in the laboratory system. The reaction kinematics is shown in Fig. 2. Scattered target-like and beam-like nuclei will be detected in the DSSSD. The energy of the projectile ions has been chosen such that safe Coulomb excitation is ensured for all scattering angles covered by the DSSSD. Deexcitation γ-rays will be detected by the MINIBALL array. Background will be suppressed by employing particle-gamma coincidences.

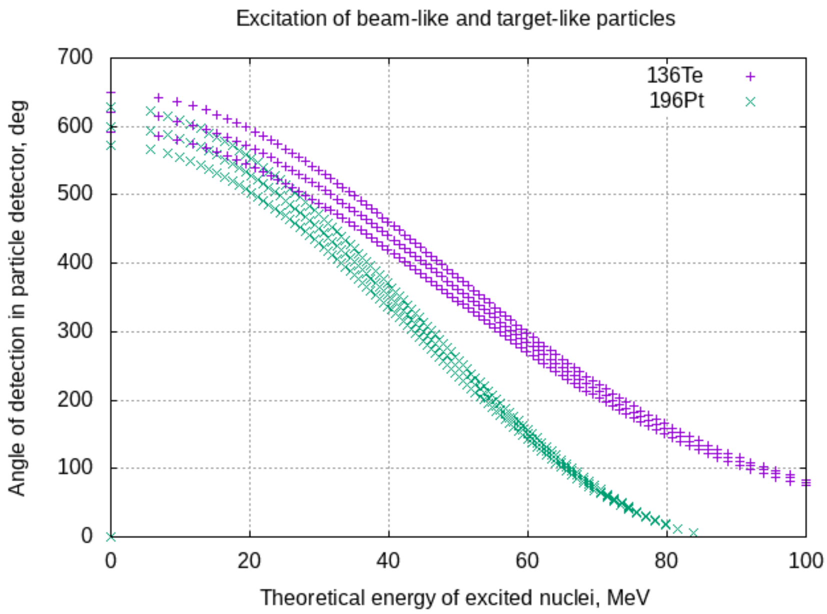

Figure 2: Kinematics of the scattering of ^{136}Te on 2 mg/cm^2 ^{196}Pt.

The electromagnetic matrix elements for the transitions of the projectile nucleus ^{136}Te will be extracted from a fit of the matrix elements to the experimentally observed γ-ray yields. A normalization can be performed using the known value for $B(E2; 2_1^+ \rightarrow 0_1^+)$ of the target of ^{196}Pt.
Estimates for the expected count rates have been calculated using the standard Coulomb excitation code CLX and are presented in Table 2. Recent results for reduced transition strengths [30] have been used for the calculations. Energy loss in the target has been taken into consideration when calculating the cross-sections. The interaction is assumed to happen in the middle of the target. The total efficiency for γ-ray detection of MINIBALL is estimated to be 5%.
Moreover, angular correlations of the emitted gamma-rays will be analyzed in order to extract the multipole mixing ratio $\delta_{E2/M1}$ of the transition $2_2^+ \rightarrow 2_1^+$.

Table 2: Estimated cross sections and count rates for projectile Coulomb excitation of ^{136}Te on a 2 mg/cm^2 platinum target. γ-ray detection efficiency is assumed to be 5%. Beam intensity is 10^5 pps.

Level	Energy, (keV)	Cross section, (b)	Yield (cts/day)
2_1^+	606.6	1.8761	4980
4_1^+	1030.0	0.06519	172.8
2_2^+	1568.4	0.03264	86.64

Summary of requested shifts: 15

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: MINIBALL + CD only

Part of the experiment	Availability	Design and manufacturing
(ISOLDE installation: MINIBALL + only CD)	☒ Existing	☒ To be used without any modification
[insert lines if needed]		

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

Additional hazards:

Hazards	MINIBALL + CD only
Thermodynamic and fluidic	
Pressure	
Vacuum	
Temperature	
Heat transfer	
Thermal properties of materials	
Cryogenic fluid	
Electrical and electromagnetic	
Electricity	
Static electricity	
Magnetic field	
Batteries	☐
Capacitors	☐
Ionizing radiation	
Target material	^{196}Pt, stable
Beam particle type	ions(^{136}Te)
Beam intensity	maximum available
Beam energy	640 MeV
Cooling liquids	[liquid]
Gases	[gas]
Calibration sources:	☒
• Open source	☒^{241}Am/Triple alpha
• Sealed source	☒^{60}Co,^{152} Eu
• Isotope	

• Activity	
Use of activated material:	
• Description	☐
• Dose rate on contact and in 10 cm distance	
• Isotope	
• Activity	
Non-ionizing radiation	
Laser	
UV light	
Microwaves (300MHz-30 GHz)	
Radiofrequency (1-300 MHz)	
Chemical	
Toxic	
Harmful	
CMR (carcinogens, mutagens and substances toxic to reproduction)	
Corrosive	
Irritant	
Flammable	
Oxidizing	
Explosiveness	
Asphyxiant	
Dangerous for the environment	
Mechanical	
Physical impact or mechanical energy	
Mechanical properties	
Vibration	
Vehicles and Means of Transport	
Noise	
Frequency	
Intensity	
Physical	
Confined spaces	
High workplaces	
Access to high workplaces	

Obstructions in passageways	
Manual handling	
Poor ergonomics	

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 0 kW