EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Resubmission of Proposal P-277 to the ISOLDE and Neutron Time-of-Flight Committee

Coulomb excitation of ^{116}Te and ^{118}Te: a study of collectivity above the $Z = 50$ shell gap

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Abstract:

We propose to study the nature and collectivity of low-energy excitations in ^{116}Te and ^{118}Te. We aim to measure the transition probability of the $0^+ \rightarrow 2^+$ transition by means of Coulomb excitation, employing REX-ISOLDE and MINIBALL. The proposed study probes the systematics of $B(E2)$ values in light Te nuclei, which lie in a region of the nuclear chart where unusual phenomena and evolution of collectivity have been observed. The proposed study will shed light on the role of the residual proton-neutron interactions in the development of collectivity when approaching the $N = Z$ line. This is a resubmission of the P-277 proposal. The suggestions of INTC have been taken into account and the data from the Yale ^{120}Te study has been included.

Requested shifts: 18 shifts, (split into 2 or 3 runs over 2 years)

Introduction

Nuclei near closed proton or neutron shells exhibit a rich variety of phenomena. In such regions of the nuclear chart, a small change in the number of constituent nucleons can introduce dramatic changes in the structures of observed states. The region around the $Z = 50$ shell closure, particularly in neutron-deficient isotopes when the $N = Z$ line is approached, provides a fertile ground for studies of the proton-neutron interaction as the protons and neutrons occupy orbitals with high spatial overlap. In the $Z = 50$ Sn nuclei it is the valence neutrons that should determine low-energy spectra, but in the $Z = 52$ Te nuclei both valence protons and neutrons can contribute. Thus, the neutron-deficient Te nuclei provide us with a region where the details of the proton-neutron interaction are enhanced [1]. Moreover, spectroscopy studies may indicate a sudden onset of collectivity when approaching the $N = 50$ shell closure as a decrease in the first 2^+ and 4^+ level energies has been observed starting at ^{112}Te (see Fig. 1). Similar behaviour has also been observed in neutron-deficient Xe isotopes and has been attributed to the isoscalar proton-neutron interactions [2].

The development of collectivity and the role of the proton-neutron interaction can be studied through quantities such as level energies and reduced transitions probabilities, the latter rendering it possible to extract knowledge of nuclear wavefunctions. Indeed such studies have been carried out in the neutron-deficient Te nuclei. Figure 1 illustrates the systematics of observed level energies and $B(E2)$ values in Te nuclei. The energies of the first excited 2^+ and 4^+ states show vibrational patterns almost throughout the isotopic chain with a two-phonon triplet observed in ^{120}Te [3]. The 2^+ and 4^+ states minimise their energies near the neutron mid shell and consequently a large $B(E2)$ value from the 2^+ state has been observed in ^{120}Te. The measured $B(E2; 2^+ \to 0^+)$ value for ^{118}Te, albeit with rather large error bars, suggests a weakening of collectivity with decreasing N. However, as can be seen from the Fig. 1, the current knowledge of the $B(E2)$ values in Te nuclei with $A \leq 120$, particularly from the systematics point of view, is scarce.

Whilst the present knowledge of the $B(E2; 2^+ \to 0^+)$ values in the Te nuclei around the mid shell may suggest a dip in such values, the absence of systematic data prohibits a definitive assignment of the trend, thus making further measurements in the vicinity of $N = 66$ important. It is worth noting that deviations from the predicted parabolic behaviour have also been observed in neutron-deficient Sn isotopes, where it has been previously suggested that the $B(E2; 2^+ \to 0^+)$ values remain almost constant when moving towards the $N = Z = 50$ shell closure [4, 5]. However, a very recent experimental study of the $B(E2; 2^+ \to 0^+)$ values in the neutron mid-shell Sn isotopes have, in fact, revealed a shallow minimum at $N = 66$ [6] indicating the need for precision measurements.

In Ref. [12] $B(E2)$ values have been calculated for $10 \leq Z \leq 110$ nuclei with $N \leq 200$ using the Cogny D1S interaction in the Hartree-Fock-Bogoliubov theory extended by the generator coordinator method and mapped onto a five-dimensional collective quadrupole hamiltonian. That study predicts spectroscopic properties of ground and excited states of even-even nuclei. The results of the $B(E2)$ values relevant for the proposed study are shown in the top panel of Fig. 1 as solid squares. The measured $B(E2)$ values down to ^{124}Te have been reproduced remarkably well, while large deviations occur for the

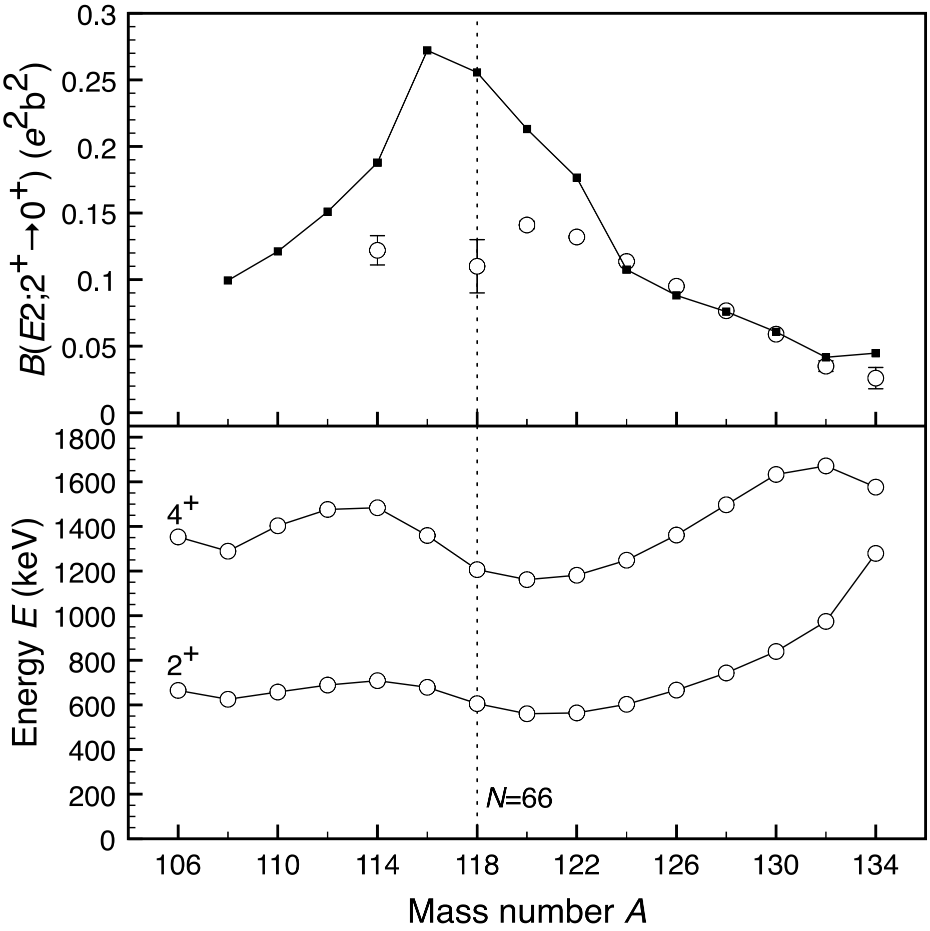

Figure 1: Reduced transition probability $B(E2;2^+\rightarrow 0^+)$ (top panel) and 2^+ and 4^+ level-energy (bottom panel) systematics for even-mass Te isotopes. The experimental data marked with open circles are taken from Refs. [7, 8, 9, 10, 11]. The neutron mid shell at $N=66$ is marked with the dotted vertical line. In the top panel calculated $B(E2)$ values [12] are shown as solid squares. The re-measurement of the $B(E2;2^+\rightarrow 0^+)$ value in ^{120}Te by the Yale group is also included [11].

lighter isotopes. The $B(E2)$ values for the $2^+\rightarrow 0^+$ transitions are predicted to follow a nearly parabolic behaviour around the neutron mid shell, reaching their maximum at around ^{116}Te. Furthermore, the $B(E2;2^+\rightarrow 0^+)$ values calculated in the framework of the microscopic configuration mixing approach [13] with the Gogny D1S interaction are found to follow a similar trend and also show marked deviations from the experimental data for $A\leq 120$. Moreover, a recent IBA study of the Te nuclei [14] reproduces the experimental $B(E2;2^+\rightarrow 0^+)$ values down to ^{122}Te but fails to explain the deviation of calculated values from the experimental data for the $A\leq 120$ Te nuclei. Interestingly in Ref. [1], where calculations in the framework of the quasiparticle random phase approximation have been carried out for the neutron-deficient Te nuclei, different trends for the $B(E2)$ values have been predicted. In that study, the proton-neutron pairing gap parameter was varied as a function of N and the trend of the resulting $B(E2; 2^+ \to 0^+)$ values varies accordingly (see Fig. 8 of Ref. [1]). In contrast to the other theoretical studies, the study in Ref. [1] does reproduce the experimental trend of decreasing collectivity towards the mid shell, however, one must point out that the predicted absolute $B(E2; 2^+ \to 0^+)$ values are offset by an order of magnitude compared to the experiment.

The near degeneracy of the transition energies of the $4^+ \to 2^+$ and $2^+ \to 0^+$ transitions in ^{116,118}Te ($N = 64, 66$) sets severe constraints for studies of the $B(E2; 2^+ \to 0^+)$ values with lifetime measurements exploiting stable beams and fusion-evaporation reactions. In order to provide accurate data on the transition probabilities near the $N = 66$ mid shell and shed more light on above mentioned discrepancies, we propose to measure the $B(E2; 0^+ \to 2^+)$ values in ^{116}Te and ^{118}Te by exploiting Coulomb excitation at ISOLDE. It should be emphasised that ISOLDE remains the sole facility worldwide where post-accelerated neutron-deficient Te beams can be produced.

The objectives of the proposed study are:

1. To provide detailed information of the wavefunctions in ^{116}Te and ^{118}Te, for which different predictions of the $B(E2; 2^+ \to 0^+)$ values and their trend exist.
2. To initiate required target and beam developments for the future (Coulomb excitation and transfer) studies of the light Te nuclei at HIE-ISOLDE.

Proposed experiment

A radioactive beam of ^{116}Te could be produced using the fibrous ZrO_2 primary target and the hot plasma ion source [15]. Spallation of the ≈ 1.5 mass% hafnium impurities in the ZrO_2 target will produce ^{116}Te as noted in Ref. [15]. It was also recommended that HfO_2 or CeO_2 would be suitable target materials for the production of neutron-deficient Te beams. Indeed target development would enhance the scope of the present proposal and allow Coulomb excitation and particle transfer studies of Te nuclei to be extended towards the $N = 50$ shell closure at HIE-ISOLDE [16]. Therefore, beam time for a test measurement is requested as a part of this proposal. Nevertheless, the following conservative estimate will demonstrate that the objectives of the present proposal can be achieved with the ^{116}Te and ^{118}Te beams produced as described in Ref. [15].

The required charge state to accelerate ^{116,118}Te beams up to 2.7 MeV/u with the REX-ISOLDE linear accelerator will be obtained with the REX-EBIS charge breeder. Post-accelerated ^{116,118}Te beams will be delivered to the MINIBALL target position where they will be Coulomb excited using a secondary 2 mg/cm^2 thick ^{64}Zn target ($E_{2^+} = 992$ keV). The MINIBALL Ge-detector array, with a photopeak efficiency of $\approx 7\%$ for 1.3 MeV γ rays, will detect γ rays de-exciting the first 2^+ states in ^{116}Te ($E_{2^+} = 678.9$ keV) and in ^{118}Te ($E_{2^+} = 605.7$ keV). Both scattered projectiles and target recoils will be detected using an annular double sided silicon strip detector (CD) positioned on the beam axis downstream of the secondary target. The CD detector covers the angular range from 16° to 53° with respect to the beam direction.

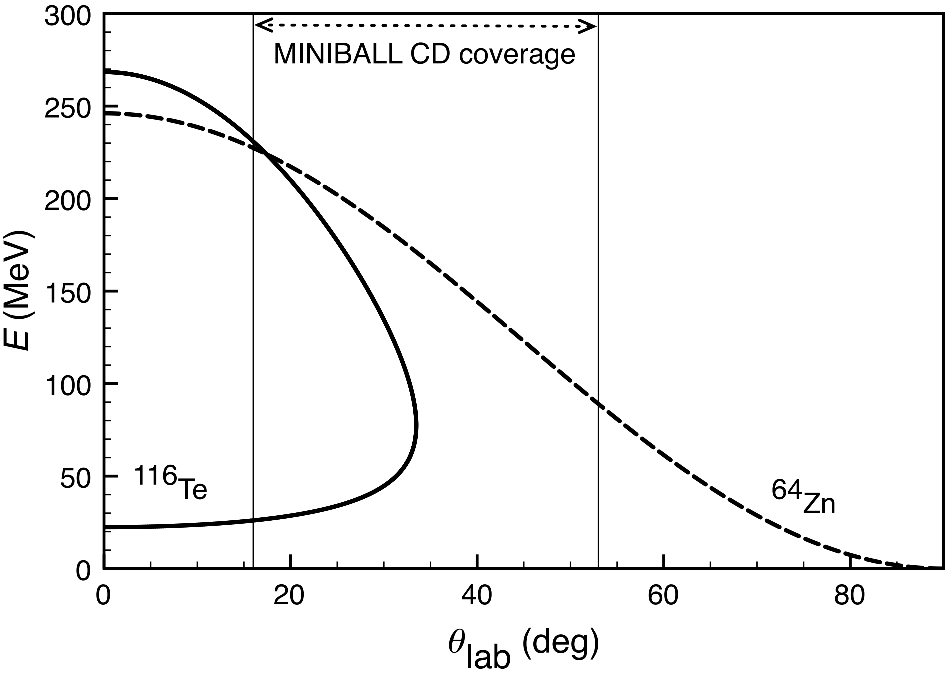

Figure 2: Kinematic plot of the 2.7 MeV/u ^{116}Te beam impinging on the 2 mg/cm^2 ^{64}Zn target. The vertical lines denote the angular coverage of the MINIBALL CD detector.

In Fig. 2, the scattering of a ^{116}Te projectile impinging on the 2 mg/cm^2 thick ^{64}Zn target is shown. It is evident that the target nuclei can be clearly distinguished from the projectile nuclei within the angular coverage of the CD detector. The reaction kinematics are very similar for the ^{118}Te beam. One should note that the reaction kinematics for the proposed study are similar to that used in previous Coulomb excitation studies in this mass region [17], in which the $B(E2; 2^+ \to 0^+)$ values have been extracted for ^{100,102,104}Cd. The final beam energy of 2.7 MeV/u is well below the the safe bombarding energy of ≈ 3.4 MeV/u [18]. Therefore, a 'safe' Coulomb excitation measurement can be performed and the $B(E2)$ value for the $0^+_{\text{g.s.}} \to 2^+_1$ transition can be extracted from the measured γ-ray yield. It is important to note that with the proposed beam energy the cross section of the second-order excitation of the 4^+ state will be negligible. Therefore, the influence of the γ-ray doublet resulting from the $4^+ \to 2^+$ and $2^+ \to 0^+$ transitions (most notably in ^{116}Te) will not interfere with the Coulomb excitation γ-ray yield measurement of the $2^+ \to 0^+$ transition. The target Coulomb excitation γ-ray yield information is required in order to carry out a relative measurement to extract the $B(E2)$ value from the ^{116,118}Te γ-ray yield.

The mass separated radioactive beam may contain isobaric impurities introducing additional target excitations. One should note that the half-lives of other $A = 116$ and $A = 118$ isobars in the vicinity of ^{116,118}Te are much shorter than those of ^{116}Te ($t_{1/2}$=2.5 h) and ^{118}Te ($t_{1/2}$=6.0 d). This fact favours the extraction of ^{116}Te and ^{118}Te from the ion source. One of the objectives of the requested test measurement is to ascertain the level of isobaric impurities in the ^{116,118}Te beams. Should issues from the isobaric contaminants arise, we would wish to request use of the selective laser ion source, RILIS, in order to exploit the laser on/off method, which will allow us to ascertain the level of beam impurities. This is a standard procedure that has been successfully applied *e.g.* in the Pb experiment (IS494). In either event, beam impurities should not pose a problem for the proposed experiment.

Yield estimate and beam time request

In Ref. [15] a primary ISOLDE yield of 10^6 ions/μC for ^{116}Te is reported. Assuming 1% transmission efficiency of REX and 1.5 μA proton current, $1.5 \cdot 10^4$ pps will be delivered to the MINIBALL target position. Furthermore, if assuming the reduced matrix element for the $2^+ \to 0^+$ transition in ^{116}Te to be equal to that in ^{118}Te, *i.e.* $\langle 0^+_{\mathrm{g.s.}} || O(\hat{E}2) || 2^+_1 \rangle$ = 0.75 eb [10], the Coulomb excitation γ-ray yield can be estimated with the Coulomb excitation code GOSIA [19]. Based on these assumptions, 260 particle-γ-ray coincidence events *per 8 hour shift* would be recorded with MINIBALL for the 678.4 keV $2^+ \to 0^+$ transition in ^{116}Te. A corresponding yield for the ^{64}Zn target excitations is 90 counts and is therefore the limiting factor for the accuracy of the proposed study. Therefore, in order to record spectra with sufficient statistics we request **6 shifts** of beam time for the Coulomb excitation study of ^{116}Te. The above yield estimate can be regarded as a conservative estimate for ^{118}Te thus the same beam time request holds for the study of the ^{118}Te nucleus. An additional **3 shifts** are requested for the set up of REX.

While the above estimate is carried out for ^{116}Te produced as in Ref. [15], it is anticipated that HfO_2 or CeO_2 primary targets would be more favourable for the production of ^{116}Te. In order to verify the primary yields with these targets, a further **3 shifts** of beam time is requested for the yield and contamination test prior to the actual Coulomb excitation measurements of ^{116,118}Te. The beam time request is summarised in Table 1.

The proposed experiment forms a part of the experimental programme to study the evolution of collectivity above the $Z = 50$ shell gap near the $N = 50$ shell closure at HIE-ISOLDE. The proposed measurements will contribute to the HIE-ISOLDE programme through the beam development and necessary systematic study of the Te isotopes at the neutron mid shell.

Table 1: Summary of the beam time request. Gamma-ray yield estimates for the $0^+ \to 2^+$ transitions in ^{116}Te and ^{118}Te and in the ^{64}Zn target nuclei are also given.

Beam	Target	Ion source	Shifts	$2^+ \to 0^+$ γ-ray yield	$2^+ \to 0^+$ γ-ray yield, ^{64}Zn
^{116}Te (test)	$ZrO_2/HfO_2/CeO_2$	Hot plasma/RILIS	3		
REX set-up	$ZrO_2/HfO_2/CeO_2$	Hot plasma	3		
^{116}Te	$ZrO_2/HfO_2/CeO_2$	Hot plasma	6	1500	540
^{118}Te	$ZrO_2/HfO_2/CeO_2$	Hot plasma	6	1500	540
Total			**18**		

Summary of requested shifts: The shifts are requested to be split over at least two separate runs, the beam yield/purity test (3 shifts) being the first one. In total 18 shifts are requested.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: MINIBALL + only CD

Part of the	Availability	Design and manufacturing
MINIBALL + only CD	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT Hazards named in the document relevant for the fixed MINIBALL + only CD installation.

Additional hazards:

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]	$ZrO_2/HfO_2/CeO_2$, ^{64}Zn secondary	$ZrO_2/HfO_2/CeO_2$, ^{64}Zn secondary	
Beam particle type (e, p, ions, etc)	^{116}Te	^{118}Te	
Beam intensity	10^6 pps	10^6 pps	
Beam energy	313 MeV	319 MeV	
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒	☒	
• Open source	☐		
• Sealed source	☒	☒	
• Isotope	^{152}Eu, ^{133}Ba	^{152}Eu, ^{133}Ba	
• Activity	$\approx$ 17 kBq each	$\approx$ 17 kBq each	
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): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]