Studies of single-particle properties in Te nuclei above the $Z = 50$ shell gap through neutron-transfer reactions

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Abstract: We propose to study the single-particle properties of low-energy excitations in neutron-deficient Te nuclei. We aim to measure both the location of the main neutron single-particle strength and the occupancies of single-particle orbitals by means of neutron-transfer reactions at HIE-ISOLDE. The proposed investigation aims to study the structure of the light Te nuclei, which lie in the region of the nuclear chart where departures from the expected energy-level systematics have been observed. The experiment will enable us to investigate single-particle and collective properties and the role played by the residual proton-neutron interaction in the development of collectivity and single-particle behaviour when approaching the $N = Z = 50$

region. The proposed experiment will employ the solenoidal spectrometer to be constructed for HIE-ISOLDE.

Requested shifts: 42 shifts (in three separate runs)

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. Significant effort has been invested in the study of $N \approx Z$ nuclei residing just above the $Z = 50$ shell gap. For example, recent γ-ray spectroscopy studies of neutron-deficient Te [1], I [2] and Xe [3] nuclei, which have provided extensive energy level systematics, suggest evidence of enhanced collectivity when approaching the $N = 50$ shell gap. However, a recent lifetime measurement in ^{108}Te does not support such a conclusion [4]. Thus, in order to provide a detailed understanding of the behaviour of the level-energy systematics in the light Te nuclei it will be important to obtain information of the relative energies and occupancies of the single-particle states over a wide range of neutron number. At the present time knowledge of the single-particle (proton and neutron) occupancies is virtually non-existent for the proton-rich Te nuclei.

Physics background: The experimental level-energy systematics of the 2^+ and 4^+ states in neutron-deficient Te nuclei (shown in Fig. 1) suggest that there may be an enhancement in collectivity which begins around ^{112}Te and persists as the $N = 50$ shell closure is approached. The decreasing trend of the energy of the 2^+ and 4^+ states from ^{114}Te is observed down to ^{108}Te, before increasing again slightly at ^{106}Te. It is interesting to note that a similar phenomenon has also been observed in neutron-deficient I and Xe nuclei and the origins are probably related to those in the Te nuclei. This effect has previously been suggested to arise from increased octupole correlations [5] or from isoscalar proton-neutron interactions as N approaches Z [3].

A lifetime measurement of the 2^+ state in ^{108}Te has recently been performed [4] and in contrast to the level-energy systematics for these nuclei, and what has previously been measured in light Sn isotopes [6], the result does not provide evidence for any enhancement in the $B(E2 : 2 \rightarrow 0)$ transition probability in the light Te nuclei as the $N = 50$ shell gap is approached (see Fig. 1). This result clearly suggests that the decreasing trend of the level energies below $N = 62$ is therefore most likely not a deformation driven effect. Another possibility is that the observed trends may result from tensor-force effects and be related to the occupation probabilities of the $2d_{5/2}$ and $1g_{7/2}$ neutron and/or the equivalent proton orbitals. The importance of the $1h_{11/2}$ neutron orbital is also not entirely clear, especially as the proton-neutron monopole interaction between the $1g_{7/2}$ ($j_<$) and $1h_{11/2}$ ($j_>$) is expected to be strong. The monopole component of the tensor force has recently been shown to be responsible for changes in shell structure [7]. Due to the spatial overlap between the proton $1g_{7/2}$ and neutron $2d_{5/2}$ (or vice versa) orbitals, the tensor force should be strong (illustrated in Fig. 2) and, therefore, the departure from a well behaving shell-model system in the light Te isotopes could arise as a result of the configuration mixing effects between the $1g_{7/2}$ and $2d_{5/2}$ orbitals. Indeed in shell-model calculations the occupancy of the orbitals is found to be particularly sensitive to the proton-neutron monopole terms involving the $1g_{7/2}$ and $2d_{5/2}$ orbitals with isospin $T = 0$ and 1.

Theoretical calculations have been performed in order to explain the observed trends in systematics. Most recently, in Ref. [4] large-scale shell-model calculations with different single-particle energies have been carried out. These calculations reproduce the $B(E2; 2^+ \rightarrow 0^+)$ values locally in the most neutron-deficient isotopes, but underestimate them near the mid shell. In general, shell-model studies using different parameterizations have been carried out in order to explain different observations such as ordering of the single-particle levels [12] or the trend of the $B(E2)$ values in the neutron-deficient Sn region, but a more comprehensive picture of the nuclear structure is missing. Fig. 3 shows the energies of the lowest $5/2^+$, $7/2^+$ and $11/2^-$ neutron and proton states in the trans-Sn region. It is evident that for nuclei above ^{100}Sn the situation becomes very complex due to the two nearly-degenerate $g1_{7/2}$ and $2d_{5/2}$ orbitals. At around the neutron mid shell the neutron $1h_{11/2}$ orbital appears to introduce additional com-
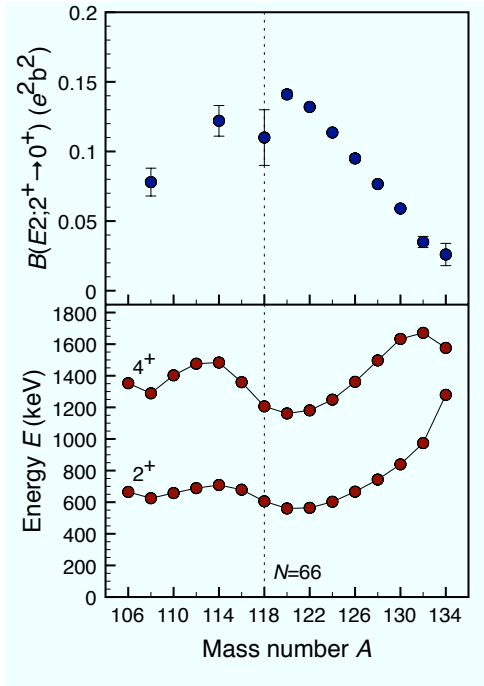
Figure 1: Reduced transition probability $B(E2; 2^+ \to 0^+)$ (top panel) and 2^+ and 4^+ level-energy (bottom panel) systematics for even-mass Te isotopes. The experimental data marked with open circles are taken from Refs. [1, 4, 8, 9, 10, 11]. The neutron mid shell at $N = 66$ is marked with the dotted vertical line.
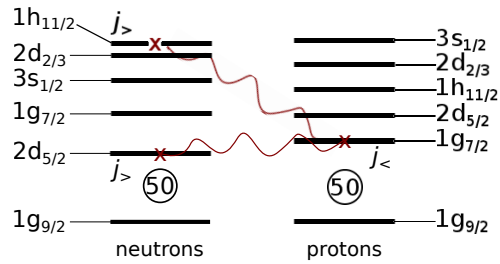
Figure 2: Single-particle levels above the $N = Z = 50$ shell gaps. The attractive tensor forces between the proton $1g_{7/2}(j_<)$, neutron $2d_{5/2}(j_>)$ and $1h_{11/2}(j_>)$ orbitals are illustrated.

plexity. A transition from the seniority scheme, as in Sn isotopes, to the collective scheme is expected in Te isotopes since the attractive proton-neutron monopole interaction brings down the $1h_{11/2}$ orbital which makes the neutrons more evenly distributed over the active orbitals. The structure effects are therefore expected to be very sensitive to the nucleon distributions.

The experimental data of single-particle occupancies and location is crucial to determine the importance of several monopole terms and improve our understanding of the nature and origin of the nuclear structure around the doubly magic ^{100}Sn. Single-particle properties are vital especially as the evolution of the quadrupole degrees of freedom are going to be driven by the underlying single-particle structure.

The goal of the Letter of Intent (I-112) submitted in 2010 was to address these issues by measuring the proton and neutron single-particle levels and their occupancies over a wide range of proton-rich Te nuclei. In the present proposal we wish to focus on the neutron single-particle properties through an investigation of (d,p) reactions in inverse kinematics. For the ^{120,122,124}Te nuclei there exist earlier (d,p) reaction data, which can be used to provide information of the neutron orbitals of interest. However, what is required is similar data on even-mass Te nuclei with $N \leq 67$. Given the nature of the experiments we initially plan to make measurements
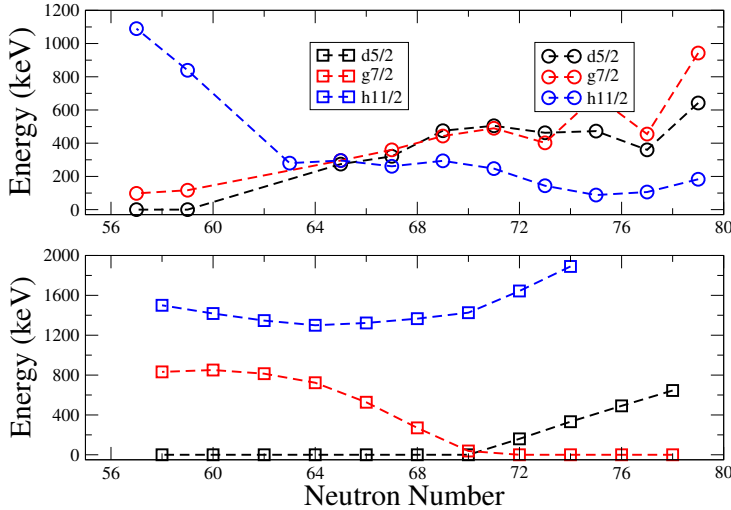
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Figure 3: The energies of the lowest $5/2^+$, $7/2^+$ and $11/2^-$ assumed neutron (top panel) and proton (bottom panel) states in the odd-mass Te isotopes and Sb isotopes, respectively. The data are taken from Ref. [8].

on three nuclei, ^{112}Te ^{114}Te and ^{118}Te, which we believe can be completed within two weeks of beam time. The nuclei have also been chosen because they cover the region around the peak in the 2^+, 4^+ excitation energies and also the region where there is a lack of knowledge on the location of the lowest $5/2^+$, $7/2^+$ and $11/2^-$ states, which is in the region N=61-63 (see Fig. 3). In addition, the ^{118}Te experiment ensures that there is no large gap in the data going from ^{121}Te to ^{115}Te. Thus in order to track the single-particle orbitals as a function of neutron number we propose to study the d(^{118}Te,p)^{119}Te, d(^{114}Te,p)^{115}Te and d(^{112}Te,p)^{113}Te reactions at HIE-ISOLDE at the beam energy of 5.5 MeV/u. The present proposal follows the physics themes and experimental scenarios laid out by HIE-ISOLDE Letter of Intent I-112 and aims to establish both the location of the main strength related to the neutron orbitals of interest and the degree of occupancy as a function of neutron number.

Proposed experiments: We propose to exploit the high energy of the HIE-ISOLDE in the neutron-transfer reactions with neutron-deficient, radioactive Te beams (which are unique to ISOLDE). The odd-mass isotopes of ^{113}Te, ^{115}Te and ^{119}Te will be populated with the one-neutron transfer reactions with a deuterated polyethene (CD$_2$) target in inverse kinematics. The rare isotope beams of ^{112}Te, ^{114}Te and ^{118}Te will be produced with the spallation reactions of 1.4 GeV protons on to the HfO$_2$ or CeO$_2$ primary ISOLDE target [14] and ionised using RILIS laser ionisation. The present proposal will exploit the unique capability of the first stage of HIE-ISOLDE to accelerate rare isotope beams up to 5.5 MeV/u. The Q value of the reactions are positive, $Q = 6.89$, 6.02 and 5.31 MeV for the ^{112}Te, ^{114}Te and ^{118}Te beams, respectively. This will allow the population of the states of interest with reasonable cross sections. The angular distributions for the ^{112}Te case are shown in Fig. 4 for the $\Delta\ell = 2$, 4 and 5 transfer. The Q value for the (d,^{3}He) is positive (1.79 MeV) and for (d,t) largely negative and therefore suppressed. Although the (d,^{3}He) reaction has a positive Q value, the ^{3}He particles will be forward focused and therefore will not interfere with the proposed measurements. Beyond the present proposal, it is our long-term goal both to utilise proton-transfer reactions and to push the neutron-transfer measurements toward $N = 50$.
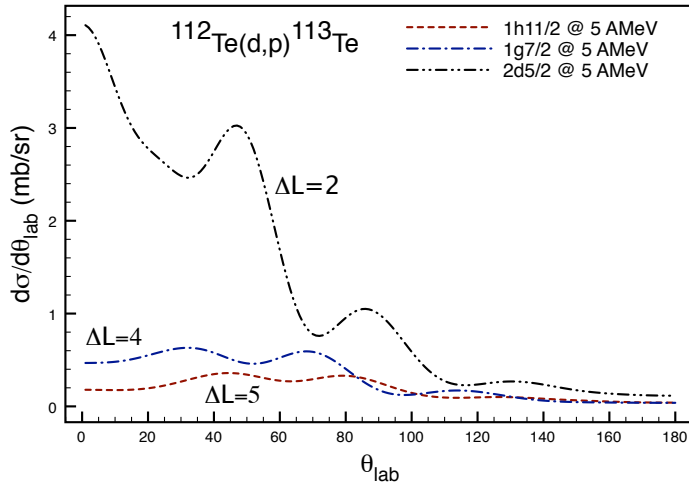
Figure 4: Calculated angular distributions of the protons in the laboratory system following the ^{112}Te(d,p)^{113}Te reaction.

Envisaged instrumentation: The experiment will use a solenoidal spectrometer for momentum analysis of the outgoing protons from the reaction, similar to that in use at Argonne National Laboratory (ANL) [15]. This design of spectrometer has three significant advantages over conventional charged-particle spectroscopy using silicon detectors, beyond the solenoid representing a much simpler and less complex detector system. Firstly, better proton energy resolution where it is not limited by target energy loss effects. This arises due to the linear function between centre of mass energy and the measured position and lab energy measured at the axis of the solenoid. Essentially, the lab ion energy resolution is identical to the centre of mass energy resolution. Secondly, the linear nature of this relationship also means that the dispersion between different excited states in the ion-energy and Q-value spectra are the same. In the conventional approach using Si at fixed angles, the non-linear relationship between proton energy and angle can mean that when moving from an ion energy spectrum to excitation energy, peaks become compressed by factors of up to three, degrading the effective Q-value resolution. Even for experiments where target energy-loss effects are important in the ion-energy resolution, the resulting Q-value spectrum with a solenoid still benefits from this lack of compression. As an example, a recent d(^{86}Kr,p) measurement achieved an excitation energy resolution of $\sim$ 70 keV [17]. Some conventional approaches use γ-ray measurements to recover the excitation energy resolution. This necessarily introduces an additional efficiency factor of up to 10% due to the coincidence requirement. A solenoidal system allows good resolution, sufficient for many purposes, from the measurement of outgoing ions alone and thus avoids the efficiency hit in yield for many experiments.

Based on the HIE-ISOLDE parameters the estimated energy resolution of the solenoidal spectrometer, limited largely by the energy spread < 0.9%, will be on the order of < 70 keV. The low-lying level density in ^{113}Te, e.g. 587, 1311 and 1994 keV will allow the cross sections and angular distributions to be extracted, even with $\sim$ 100 keV separations thus allowing the use of thicker target. A good example of transfer studies with heavy-ion beams in inverse kinematics and the HELIOS spectrometer at ANL can be found in Ref. [18]. In ^{119}Te the 5/2$^+$, 7/2$^+$ and 11/2$^-$ levels are located rather close in energy, in the worst case separated only by

~ 40 KeV. However, as the ^{118}Te beam intensity should be considerably higher, an improved energy resolution can be obtained by using a thinner target whilst maintaining sufficient level of statistics.

Count rate estimate and beam time request: The calculated total cross sections for the $\Delta\ell = 2$ transfer are on the order of 13 mb with 5.5 MeV/u beams. If assuming 10^5 pps beam intensity for ^{112}Te and 150 μg/cm^2 CD$_2$ target thickness, the count rates in the corresponding proton peak can be calculated. It is envisaged that the proton detection efficiency of solenoidal spectrometer, limited mainly by the solid angle coverage of the Si detectors, is on the order of 70%. This would yield to ~ 500 counts in a proton peak corresponding to $\Delta\ell = 2$ transfer in *ten shifts* of beam time integrated over the angular range. For the $\Delta\ell = 4, 5$ transfers this figure is around 250 counts (c.f. Fig. 4). The beam intensities are expected to be a factor of 10-20 higher for ^{114,118}Te. Therefore, we request **21 shifts** of beam time to complete the part of the experiment with the d(^{112}Te,p)^{113}Te reaction. For the d(^{114}Te,p)^{115}Te reaction we request **15 shifts** of beam time and for the d(^{118}Te,p)^{119}Te reaction **6 shifts** of beam time.

Summary of requested shifts: 42 shifts

Installation: Solenoidal spectrometer on the second beam line

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *Solenoidal spectrometer on second beamline*

Part of the	Availability	Design and manufacturing
	☐ Existing	☐ To be used without any modification
Solenoidal spectrometer	☐ 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

Additional hazards:

Hazards	Solenoidal spectrometer	[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	liquid He, 1 Bar, 1000 l		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	3 T		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			

Target material [material]	HfO$_2$ or CeO$_2$ primary target, CD$_2$ secondary target		
Beam particle type (e, p, ions, etc)	^{112,114,118}Te		
Beam intensity	10^5-10^7 pps		
Beam energy	5 AMeV		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	⊠		
• Open source	☐		
• Sealed source	⊠		
• 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): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]: ... kW