EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STATUS REPORT to the ISOLDE and Neutron Time-of-Flight Committee

Spectroscopy of particle-phonon coupled states in ^{133}Sb by the cluster transfer reaction ^{132}Sn on ^{7}Li: an advanced test of nuclear interactions

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Aim of the experiment

In the experiment IS595, we have proposed to investigate, with MINIBALL coupled to T-REX, the structure of one-valence-proton ^{133}Sb nucleus, and use the obtained information to validate the newly developed "Hybrid Configuration Mixing" model (HCM), which should allow an unprecedently precise description of excitations in nuclei with one or few valence nucleons. Excited states in ^{133}Sb will be populated in the reaction of a ^{132}Sn beam on a ^{7}Li target by using transfer of a triton into ^{132}Sn, followed by the emission of an alpha particle (detected in T-REX) and 2 neutrons. The aim of the experiment is to locate states arising from the coupling of the valence proton of ^{133}Sb to the collective low-lying phonon excitations of ^{132}Sn (in particular the 2+, 3^- and 4+), as well as to simpler core excitations, involving few nucleons only. According to calculations performed with HCM model, these states lie in the 4 – 5 MeV excitation energy region and in the spin interval 1/2 - 19/2, i.e., in the region populated by the cluster transfer reaction. The results will be used to perform advanced tests of the HCM model, which takes into account couplings between core excitations (both collective and non-collective) of the doubly magic nucleus ^{132}Sn and the valence proton.
In the considered reaction, also the one-valence-proton and one-valence-neutron nucleus ^{134}Sb will be produced in a transfer of triton into ^{132}Sn, followed by the emission of an alpha particle and one neutron. In this case, a very detailed test of effective proton-neutron interactions above Z=50 and N=82 will be possible by locating multiplets of proton-neutron states and comparing them with the results of shell-model calculations employing realistic interactions.
Predictions for the reaction mechanism, the expected statistics and the observed γ transitions are based on the experience gained in a test experiment performed by this collaboration at REX-ISOLDE in November 2012, in preparation of the present research program.

The experiment was scheduled in November 2018. Few days before running, the experiment was cancelled, as a consequence of severe difficulties in providing the ^{132}Sn beam.

Requested shifts: 21 shifts (split into 1 run over 1 year)

Developments which occurred in the period after the approval of the experiment (i.e., in the years 2014-2019) and strengthened the proposed case

- *Proving potential of the cluster transfer reactions induced by radioactive beams on a ^{7}Li target in populating yrast and non-yrast states in neutron-rich nuclei*

  In 2015, the collaboration has published the results of a short, preparatory experiment performed with MINIBALL+T-REX at REX-ISOLDE in November 2012, in which triton-transfer reactions induced by ^{98}Rb and ^{98}Sr beams on a ^{7}LiF target were used to populate low-lying excitations in ^{99}Sr and ^{99}Y neutron-rich nuclei (S. Bottoni et al., Phys. Rev. C 92, 024322 (2015)). At the same time, alpha-transfer process lead to excited states in ^{100}Y and ^{100}Zr neutron-rich systems. As shown in Figure 1 and 2, measured cross sections were of the order of 10 and 2 mb/sr, for t and alpha transfer, respectively, and were found to be consistent with the population of medium-high spins, in the 10-25 $\hbar$ range. The work shows the validity of the transfer-cluster reactions for accessing excited structures at low and medium spins. In the current proposal, the nuclei of interest, ^{133}Sb and ^{134}Sb, will be similarly populated by the cluster-transfer reaction with a ^{7}LiF target, 1.5 mg/cm^{2}-thick, bombarded by the HIE-ISOLDE radioactive beam of ^{132}Sn at 510 MeV (about 3.9 MeV/A, corresponding to 3.5 MeV/A at mid-target).

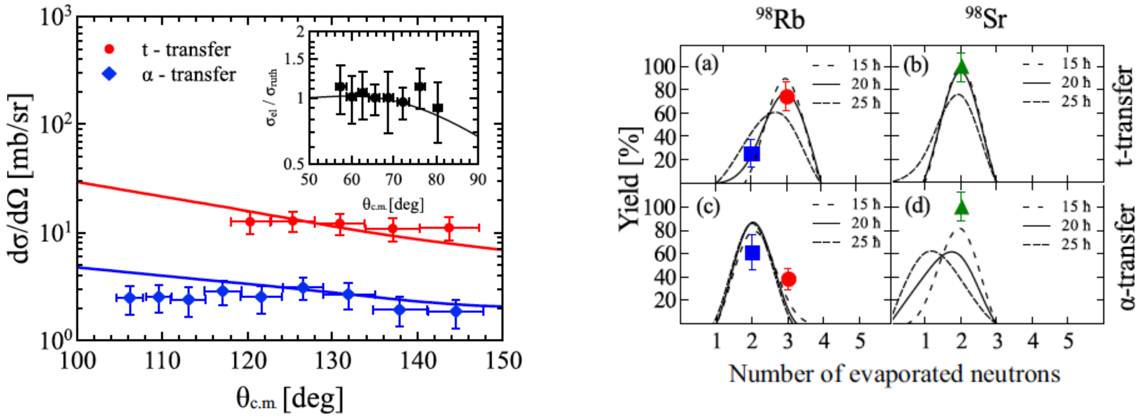

Figure 1. Results obtained from the short test experiment performed with MINIBALL+T-REX *(Bottoni et al.,* Phys. Rev. C 92, 024322 (2015)). ***Left:*** *Angular distribution for t (red symbol) and α (blue diamonds) transfers on ^{98}Rb compared with theoretical calculations performed with the code FRESCO (solid lines), following the reaction ^{98}Rb (2.85 MeV/nucleon)+ ^{7}Li, performed at REX-ISOLDE in 2012. Inset: ratio between the elastic and the Rutherford cross sections as a function of the ^{7}Li scattering angle.* ***Right:*** *Experimental yield of neutron evaporation for both t and α transfers on the ^{98}Rb and ^{98}Sr beam components compared with CASCADE predictions for different spin distributions. Panels (a) and (b) show the experimental data corresponding to t transfer, panels (c) and (d) correspond to α-transfer channels. Squares (blue) and triangle (green) symbols correspond to 2n evaporation, dots (red) refer to 3n channels.*

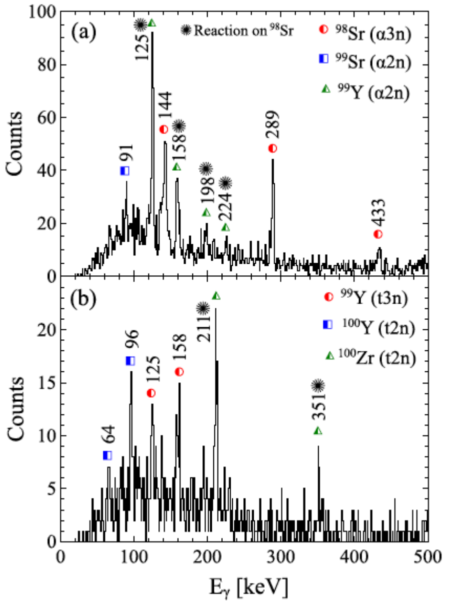

Figure 2. Results obtained from the short test experiment performed with MINIBALL+T-REX *(Bottoni et al.,* Phys. Rev. C 92, 024322 (2015)). *Particle-gated γ-ray spectra for cluster transfer channels followed by neutron evaporation for reactions on both ^{98}Rb and ^{98}Sr beam components. (a) α-γ coincidence data corresponding to the t-transfer channel. (b) t-γ coincidence spectra corresponding to the α-transfer channel.*

- *Identification of yrast states above the μs isomer in ^{133}Sb, crucial for the study presented here*

Our collaboration has studied high-spin yrast states in the nucleus ^{133}Sb, object of the present ISOLDE approved proposal, taking advantage of a large data set collected in 2013 for products of neutron-induced fission on ^{235}U and ^{241}Pu targets, during the EXILL campaign at ILL (Grenoble). The data analysis allowed to identify four new transitions feeding the 16.6 μs isomer as shown in Fig. 3 (G. Bocchi et al., Phys. Lett. B 760 (2016) 273–278). They can now serve as starting points to extend the ^{133}Sb level scheme further up in excitation energy, when the data from the cluster-transfer reaction ^{132}Sn + ^{7}Li, proposed at ISOLDE, will be available. The new information will be crucial to validate the predictions of the recently developed Hybrid Configuration Mixing model (see below), which allows to calculate excited states of one-valence particle/hole nuclei taking into account collective (phonon) and non-collective excitations of the doubly-magic core.

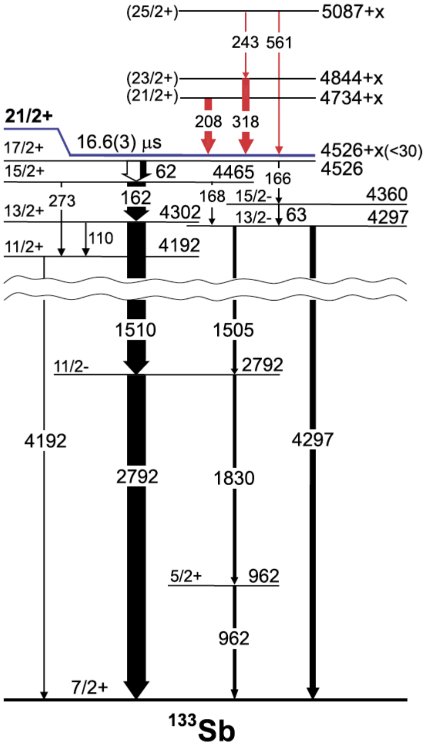

Figure 3. *Experimental level scheme of ^{133}Sb: in black, the decay below the long lived 21/2^{+} isomer. Transitions marked in red, feeding the isomer, were found by our collaboration in the EXILL campaign (G. Bocchi et al., Phys. Lett. B 760(2016)273–278.*

- *Progress in theory*

The theory members of the Milano group, participating in this project, have recently developed a new approach called "Hybrid Configuration Mixing" (HCM) model, which allows to describe complex excitations in one-valence particle/hole nuclei around doubly magic systems (G. Colò, P. F. Bortignon, and G. Bocchi, Phys. Rev. C95, 034303 (2017)). The model is a first step towards a complete self-consistent description of low-lying excitations of odd nuclei. It does not contain any free adjustable parameter and it is based on a Hartree-Fock (HF) description of the particle states in the core, together with self-consistent randomphase approximation (RPA) calculations for the core excitations. As a consequence of this approach, different types of states can be addressed: i) states arising from single nucleon excitations, ii) multiplets of states based on couplings between particle and collective phonons of the core, as well as iii) states of shell-model types, like 2 particles–1 hole. In heavy mass systems (e.g., around ^{132}Sn), such complex types of excitations cannot be fully treated within a standard shell model (SM) approach, as it would require full SM calculations in the configuration space that encompasses proton and neutron orbitals below and above ^{132}Sn (D. Lacroix, International Joliot-Curie School (EJC2009), arXiv:1001.5001 [nucl-th], 2009; SciDAC Rev. 6 (2007) 42).
Figure 4 shows predictions of the HCM model for ^{133}Sb, for states of single particle character (black) and for excitations arising from the coupling of the unpaired proton with either 2+,3-,4+ collective phonons of the ^{132}Sn core (blue), as well as non collective particle-hole excitations of ^{132}Sn (green). Red symbols refer to known experimental states. It is seen that the model predicts a number of states in the 4-5 MeV region, which we aim to probe by the cluster-transfer reaction ^{132}Sn+^{7}Li, here proposed at ISOLDE.

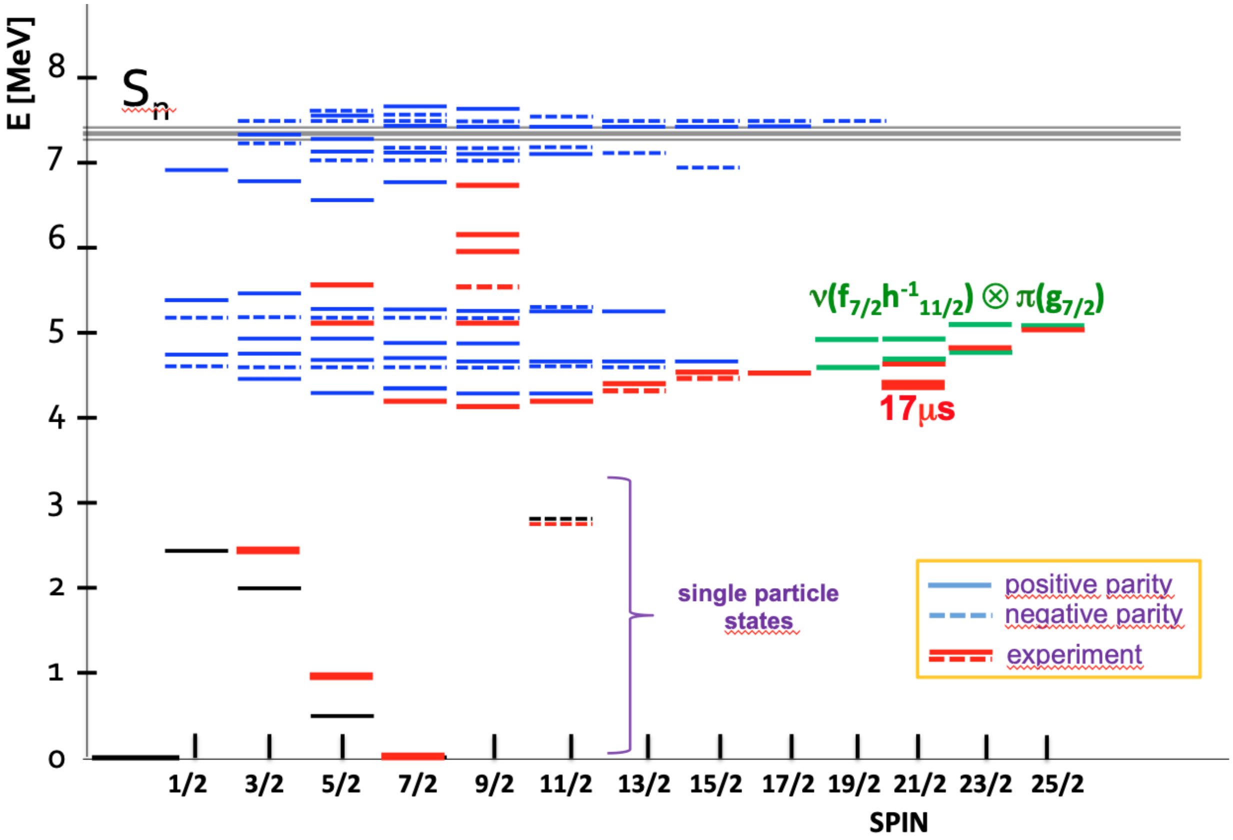

Figure 4. Predictions obtained from the Hybrid Configuration Mixing (HCM) model of G. Colò et al. for different types of excitations in ^{133}Sb, *namely i) states of single particle nature (black) and states based on couplings of the unpaired proton with ii) 2^+, 3- and 4^+ phonon excitations of the ^{132}Sn core (blue) and iii) non collective particle-hole excitations of ^{132}Sn (green). Known experimental states are marked in red. Solid and dashed lines refer to positive and negative parity states, respectively (G. Colò, P. F. Bortignon, and G. Bocchi, Phys. Rev. C95, 034303 (2017)).*

In recent years, calculations for proton-neutron valence particle excitations in ^{134}Sb became available to our collaboration, from the Napoli theory group (A. Gargano et al.). They are obtained with shell model using a realistic (V_{low-k}) interaction. As shown in Figure 5, the calculations predict multiplets of states extending up to 6 MeV excitation energy, which could provide a very specific test of effective proton-neutron interactions above Z=50 and N=82. Experimentally, only few states, at the lowest energies are known. A large fraction of these types of excitations, are expected to be located in the here proposed ^{132}Sn+^{7}Li experiment.

- *Competitiveness of the proposed experiment at ISOLDE*

The neutron-rich ^{133,134}Sb nuclei will be populated by the cluster-transfer reaction with a ^{7}LiF target, 1.5 mg/cm^2-thick, bombarded by the HIE-ISOLDE radioactive beam of ^{132}Sn at 510 MeV (about 3.9 MeV/A, corresponding to 3.5 MeV/A at mid-target). The reaction channels of interest are uniquely associated with emission of an α particle. By detecting this α particle, we will be able to produce a very clean trigger of the ^{7}Li(^{132}Sn,αxnγ) processes. Moreover, the very inverse kinematics guarantees that the product nuclei all travel downstream in a very small recoil cone, thus Doppler reconstruction of the γ-ray data does not require, to first approximation, recoil detection. These two distinct features will greatly facilitate the detection of the discrete γ rays and their identification, as demonstrated by the REX-ISOLDE test case with the ^{98}Rb beam, discussed above (*(Bottoni et al.,* Phys. Rev. C 92, 024322 (2015)).

The here proposed experiment will provide the first example of extended spectroscopic studies of neutron-rich nuclei using heavy-ion (cluster)-transfer reactions induced by a low-energy radioactive beam. Therefore, in addition to the main goal of the proposal (i.e., elucidation of the structure of ^{133,134}Sb nuclei), the experiment is expected to provide a benchmark for future investigations relying on this type of reaction mechanisms, which has been proposed in several Letters of Intent at ISOL facilities.
The experiment can only be done at an ISOL facility able to provide an accelerated ion beam of ^{132}Sn, with intensity of the order of ~ 10^5 -10^6 pps. In recent years, such a beam could only be produced at ISOLDE, and it will take few more years before this beam will be available in other facilities, such as SPES at the Legnaro National Laboratory of INFN (Italy).

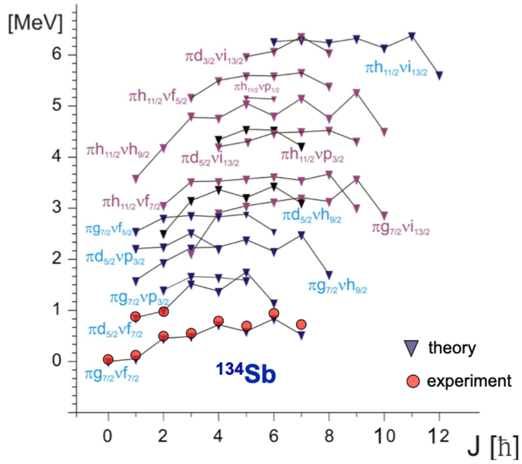

***Figure 5. Predictions obtained from the shell model with realistic (Vlow-k) interaction, for valence proton-neutron excitations in ^{134}Sb** (A. Gargano et al., private communications). Calculated states are given by triangles, presently available experimental data are indicated by red circles.*

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
HIE-ISOLDE	☒ Existing	☒ To be used without any modification
MINIBALL + T-REX	☒ 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

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + T-REX] installation.

Additional hazards:

Hazards	*HIE-ISOLDE*	*MINIBALL + T-REX*	*[Part 3 of the 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]	Secondary target: LiF_4 foil 1.5 mg/cm^2	
Beam particle type (e, p, ions, etc)	Heavy ions: tuning and calibrations : stable Sn, ^{22}Ne Measurement : ^{132}Sn	Heavy ions: tuning and calibrations : stable Sn, ^{22}Ne Measurement : ^{132}Sn	
Beam intensity	max 1 nA (injection plate REXTRAP)	max 10 pA (after EBIS)	
Beam energy		3.9 MeV/nucleon	
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐	☒ Standard alpha- and gamma-calibration sources	

		from ISOLDE	
- Open source	☐		
- Sealed source	☐ [ISO standard]		
- 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 (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
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]		

0.1 Hazard identification

3.2 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*