EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Core breaking and octupole low-spin states in ^{207}Tl

25th of September 2013

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Abstract

We propose to study the low-spin level structure of the ^{207}Tl nucleus populated by the beta decay of ^{207}Hg. While ^{207}Tl is a single-proton hole nucleus, the majority of the observed states will have three-particle structure thus requiring the breaking of the neutron or proton core, or a collective octupole phonon coupled to the single proton hole. Thus information will be obtained on the single particle orbitals in the vicinity of the N=126 and Z=82 magic numbers, and on the size of the shell gap.

The results will be used to improve the predictive power of the shell model for more exotic nuclei as we move to lighter N=126 nuclei.The experiment will use the ISOLDE Decay station, and will take advantage of the ^{207}Hg beam from the molten lead target. A test on the feasibility to produce ^{208}Hg beam from the same target, with the aim to study the beta-decay into ^{208}Tl, could be performed at the same time.

Requested shifts: 17 consecutive shifts

Motivation

^{208}Pb with 82 protons and 126 neutrons is a classic shell model core. The present proposal aims at investigating the proton single particle states and their interactions below Z=82, and indirectly the robustness of the N=126 closed shell, by studying the single proton-hole nucleus ^{207}Tl. There are two main mechanisms predicted to drive shell evolution in nuclei: the monopole migration [Otsuka05] and shell quenching due to a softening of the potential shape by excessive neutrons [Dobaczewski94]. Observation of core-breaking states can be used to infer the size of the shell gap and identify the mechanism responsible for its change [Gorska09].

^{207}Tl has one proton less, therefore its low energy excited states correspond to the single-proton hole configurations $s_{1/2}$, $d_{3/2}$, $h_{11/2}$ and $d_{5/2}$.

The nuclei around ^{208}Pb are characterised by large octupole collectivity due to the coherent contribution of several $\Delta l = \Delta j = 3$ particle-hole excitations available in this nuclear region. The lowest energy excited state in ^{208}Pb is the collective 3^- octupole state at 2614 keV which decays by a strong E3 transition of $B(E3;3^- \to 0^+)$=33.8(6) W.u. [Martin07]. In ^{207}Tl a collective octupole 17/2+ state was also observed, based on the πh^{-1} 11/2x3^-, and decays via a 2645 keV transition to the $\pi h^{-1}_{11/2}$state [Rejmund00,Wilson13].

Therefore in ^{207}Tl excited states at higher energies can be obtained by coupling the single proton-hole orbitals below Z=82 to the collective octupole vibration (3- state). Alternatively, it can be done by breaking the magic core (mainly the neutron core [Wrzesinski01,Fornal01]). Some of these can be populated from the beta decay of the $(9/2^+)$ ground-state of ^{207}Hg. These are expected to be far from the yrast line. Several of these were identified more than 30 years ago, but without spin-parity values assigned [Jonson81]. The yrast states, which are generally based on the high angular momentum $h_{11/2}$ proton orbital, can be populated in deep-inelastic reactions. Such an experiment was performed at Gammasphere, employing the ^{208}Pb+^{208}Pb reaction, and is under analysis [Wilson13].

The simplest way to estimate the properties of the excited states of more complex nature (not single particle) is to couple the single hole states in ^{207}Tl to the lowest energy excited states of the ^{208}Pb core (see figure 1).

In order to have a better understanding of the low-spin structure of ^{207}Tl shell model calculations have been performed. The OXBASH code [Brown04] was employed.
The model space considered consisted of $\pi d_{5/2}$, $h_{11/2}$, $d_{3/2}$, $s_{1/2}$ below Z=82 and $\pi h_{9/2}$, $f_{7/2}$, $i_{13/2}$ above, and the neutron orbitals $\nu i_{13/2}$, $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ below N=126 and $\nu g_{9/2}$, $i_{11/2}$, $j_{15/2}$ above. The single particle/hole energies relative to ^{208}Pb are taken from experiments and are shown in [Grawe07]. The two-body interaction matrix elements (TBMEs) are based on the Kuo-Herling interaction [Kuo71] including core polarisation. Core excitations across the ^{208}Pb double-shell closure were allowed. At present the calculations can be done considering only one particle-hole excitation (t=1). These calculations work well for the core excited states in ^{208}Pb, with a typical accuracy of 200 keV. However these calculations for ^{207}Tl have some limitations:
-the energies of octupole states cannot be predicted by the present calculations. These states are collective, therefore their wave function contains a large number of core excitations.

-the theoretical description of core breaking states is difficult, with the shell model calculations usually overestimating their energies. This is because of the complex configuration of such states and the need to consider more than one core breaking particle. In the ^{100}Sn region, it was shown that in order to get a good description of the excitation energies in ^{98}Cd several particle-hole excitations across the closed N=Z=50 shell had to be considered. However, due to computational problems, calculations with three (or five) particle-hole excitations cannot be performed for ^{207}Tl (t=2 does not help, as shown in figure 2). In ^{207}Tl the preformed shell model calculations can be compared with the preliminary unpublished level scheme (of yrast states) obtained from deep-inelastic reactions. The calculations systematically over predict the energies of the three-particle states by about 600 keV (see figure 2). This difference is probably due to overlooking the higher order core excitations, but it is also plausible that the interaction matrix elements involving the $\pi h_{11/2}$ are not correct.

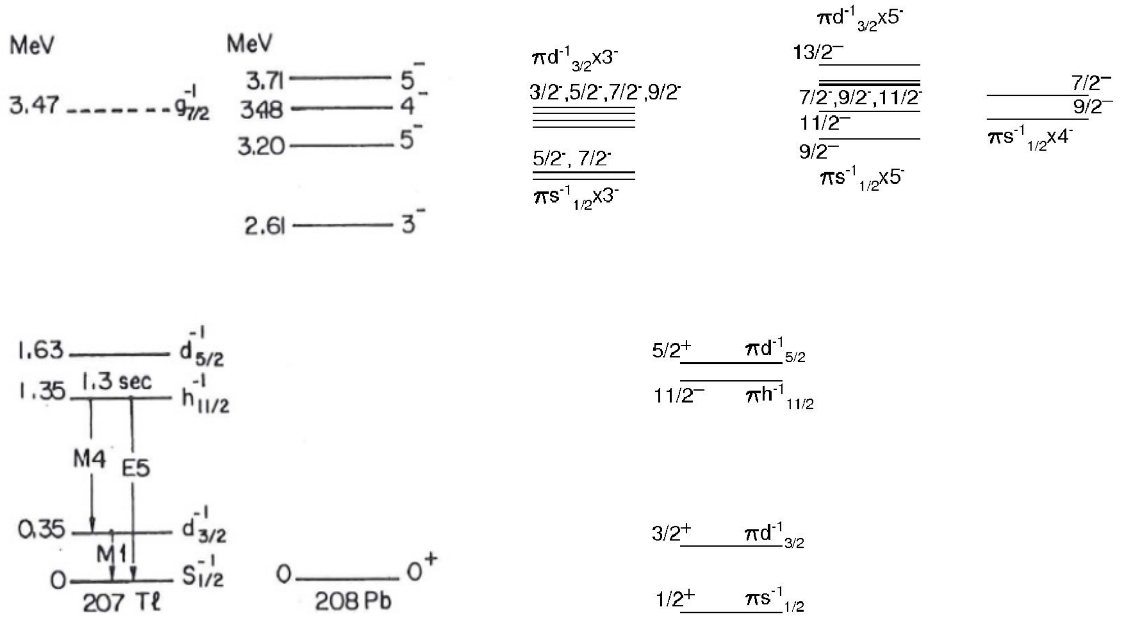

Fig.1.(Left): Single particle states in ^{207}Tl [Kondev11] as well as excited state in the core ^{208}Pb nucleus [ref]. *(Right):* Predicted level scheme of ^{207}Tl showing the lowest energy excited states expected to be populated in the beta decay (for details see the text).

Consequently, to show what states we expect to populate, we used the shell model calculations as a guide. We subtracted 600 keV from the predicted shell model values in the case of three particle states. The energy of the octupole state is estimated to be the sum of the 3- energy in the ^{208}Pb core (2614 keV) and the single proton-hole energy. This predicted level scheme is shown on the right-hand side of figure 1.

Information on the character of the excited states can be obtained considering the theory of β decay. The spin-parity of the ^{207}Hg ground-state is ($9/2^+$), therefore it will populate predominantly the 7/2, 9/2, 11/2 states in ^{207}Tl via allowed and first-forbidden β decays. As the lowest energy positive parity states are expected at ~4 MeV ($\pi h_{11/2}$x3^-), the first-forbidden decays will dominate. It was shown that the first-forbidden transition play an important role in lifetime calculations of nuclei in this region [Benzoni12]. As half-lives are basic ingredients of nucleosynthesis calculations, the understanding of the first-forbidden decays is important in order to understand the production of heavy nuclei via the r-process.

The decay calculations are complicated due to the octupole states. The beta-decay into these can be estimated by treating the ^{207}Hg ground-state as a mixture of $\nu g_{9/2}$ and $\nu j_{15/2} x 3^-$. For example such octupole coupling approach was used in order to understand the structure of excited states in ^{209}Pb [Rejmund00]. For β decay, conversion of the neutron $p_{3/2}$ and $f_{5/2}$ are important, which activate the $\nu p^{-1}_{3/2}\, g_{9/2}$ and $\nu f^{1}_{5/2}\, i_{11/2}$ components of the 3^- phonon.

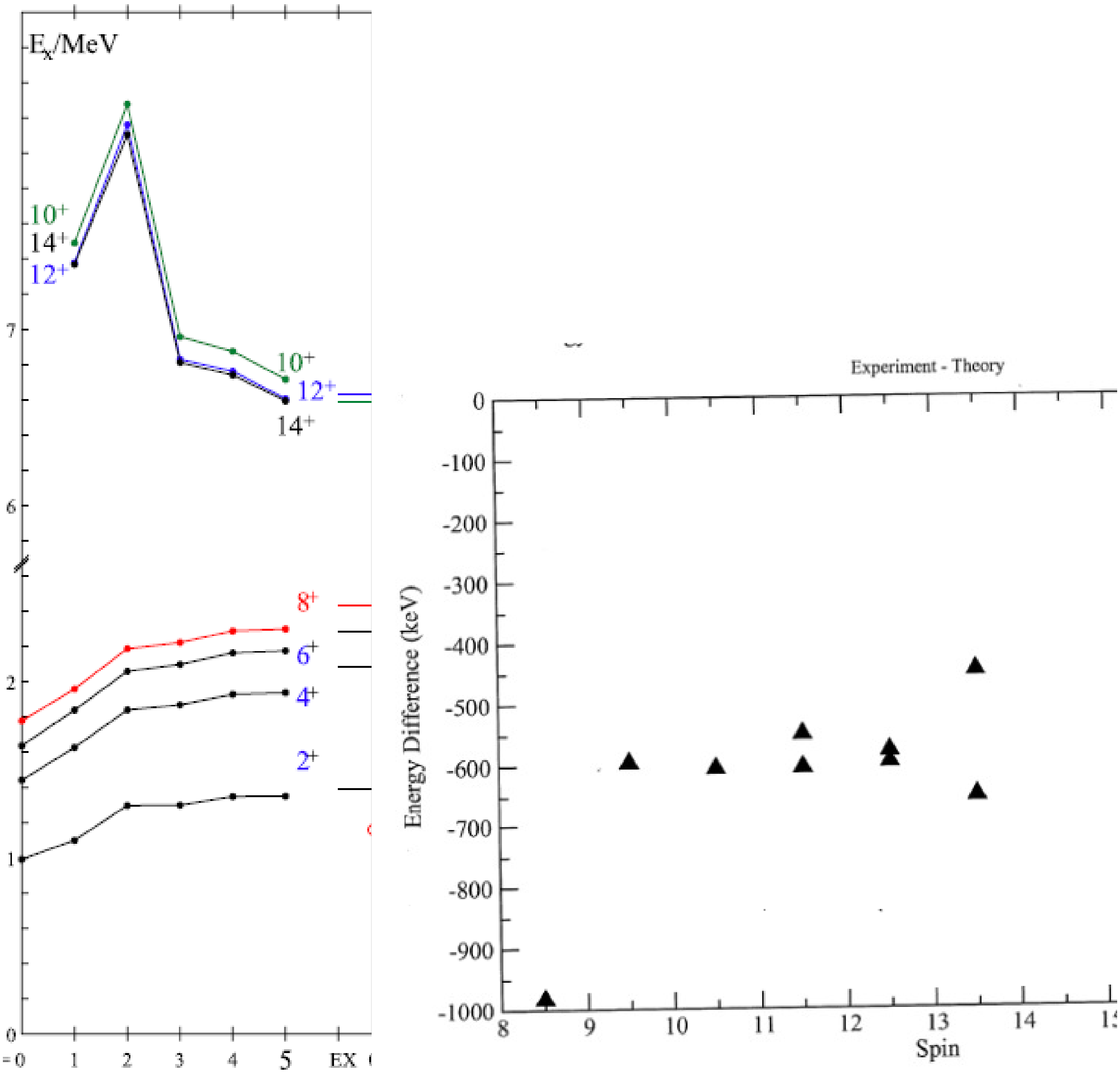

Fig. 2. (left) Convergence of large scale shell model calculations for ^{98}Cd. Excitation energies calculated for different particle-hole excitations (t) are compared with the experimental values (last column) [Faestermann13]. *(right)* Difference between (preliminary) experimental and calculated excitation energies as a function of spin in ^{207}Tl. The energies of the core excited state are over-

predicted by about 600 keV. The outlier $17/2^+$ state is an octupole state, therefore its energy cannot be predicted by this model.

The lack of information on nuclei `below' ^{208}Pb is due to the difficulties in populating these neutron-rich nuclei. However, spallation has proved to be an efficient tool to produce exotic nuclear species. Here we capitalise on the availability of the ^{207}Hg beam from the molten lead target.

We note that a very similar experiment on the β decay of ^{207}Hg has been performed more than 30 years ago at ISOLDE [Jonson81]. At that time a ^{207}Hg yield of $2x10^5$ pps was obtained, and was attributed to the (n,2p) reaction. Gamma-rays in coincidence with β particles were recorded. For gamma-ray detection two small, 63 cm^3 and 40 cm^3, Ge(Li) detectors were used. In the present experiment we expect a large increase in the gamma-ray detection efficiency. This is essential, as the observation of week transitions will help assign spin-parities to the excited states. These transitions will often be at low energies around 100 keV or high energies of 2-2.5 keV (see figure 1). In addition, high statistics are needed to perform gamma-gamma angular-correlation analysis to aid spin-parity assignment.

Both nuclear structure and beta decay calculations will be used to aid the characterisation of the observed states.

Experimental details

The ^{207}Hg beam will be delivered from the molten led target. After mass separation, the nuclei will be implanted into a tape. Its beta-decay will be studied at the ISOLDE Decay Station, consisting of the Leuven tape system and a range of Ge detectors (four clover and one Miniball detectors) and a plastic detector for gamma-ray and beta particle detection respectively. The expected efficiencies for gamma-ray and β-particle detections are estimated to be around 10% (at 1 MeV) and 60% respectively.

During tests with the molten lead target performed in 2011, $8x10^7/\mu C$ of ^{206}Hg was obtained from the Pb463-VD5 unit. Based on measured cross-sections (of ^{208}Pb at E/A=1 GeV on ^{9}Be target, therefore not the same reaction as at ISOLDE!) of $\sigma(^{207}Hg)=0.011(5)$ mb [Morales11] and $\sigma(^{206}Hg)=0.53$ mb [Kurtukian10], the yield of ^{207}Hg can be estimated to be around $1.6x10^6/\mu C$.

On these units, one can take about 0.5 μA proton intensity on average, so that this translates into $\sim10^6$ pps ^{207}Hg. Assuming a 50% overall transmission through the mass separator to the ISOLDE Decay Station we get a ^{207}Hg beam intensity of $4x10^5$ pps. This is in line with the measured yield of 10^5 pps measured more than 30 years ago [Jonson81].

A beam purity of 2% is expected. The main part of the beam will be ^{207}Pb from the natural lead target. Since this is stable and it is implanted at very low velocity, this should not affect our measurement.

The half-life of ^{207}Hg is 2.9(2) min [Kondev11,Jonson81]. Its daughter, ^{207}Tl, decays by β decay with $T_{1/2}$=4.77(3) min [Kondev11]. It populates mainly the ground-state of the stable ^{207}Pb and in addition two excited states. Therefore the present experiment will be clean.

Considering a duty cycle of 25%, there will be on average $\sim10^5$ decays per second. The rate of beta-gamma-gamma coincidences for a branch populated with an intensity of 10^{-4}, considering average gamma-ray detection efficiency of 5%, beta detection efficiency of 60% is 10^5*0.6*0.05*0.05*0.0001= 50 hour^{-1}. The value will be much lower for low energy transitions.

The study of ^{208}Tl, following the beta-decay of ^{208}Hg would be also of high interest. Such a measurement would give information on proton-hole neutron-particle interactions in the Z<82, N>126 region. Such information is almost non-nexistent due to the very limited amount of information on nuclei in this region. We propose to run a short test, and implant ^{208}Hg in the tape for a shift, thus trying to evaluate the yield of ^{208}Hg. It is not clear whether ^{208}Hg will be populated, maybe through double pion emission (working on it). With a naive expectation of ^{207}Hg to ^{208}Hg ratio of 1000, we would still have an implantation rate of 400 per second.

Summary of requested shifts: 15 shifts (5 days) of beam-time are requested. This does not include the time needed to set up the beam, which we estimate to be around 2 shifts.

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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
ISOLDE Decay Station (it will be a fixed installation starting from 2014)	☒ 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 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

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

The ISOLDE Decay Station will be a fixed installation from 2014. Hazards include: vacuum, liquid nitrogen, high voltage, standard radiation sources.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[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]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• 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)*