EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of proton-neutron multiplets in ^{134}Sb populated in the ^{133}Sb(d,p) reaction in inverse kinematics with T-REX and MINIBALL

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K. Wimmer[1], A. Jungclaus[2], V. Vaquero[2], A. Gargano[3], K. Arnswald[4], A. Fernández[2], G. Fernández Martínez[5], A.-L. Hartig[5], C. Henrich[5], I. Homm[5], A. Illana[6], L. Kaya[4], T. Koiwai[1], Th. Kröll[5], E. Nácher[2], R. Orlandi[7], H.-B. Rhee[5], P. Reiter[4], D. Rosiak[4], Ph. Schrock[1], M. Seidlitz[4], M. Siciliano[6], Ch. Sürder[5], J.J. Valiente-Dobón[6], and N. Warr[4]

1 Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
2 Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
3 Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
4 IKP, Universität zu Köln, D-50937 Köln, Germany
5 TU Darmstadt, D-64289 Darmstadt, Germany
6 Laboratori Nazionali di Legnaro, I-46020 Legnaro, Italy
7 Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

Spokespersons: Kathrin Wimmer (wimmer@phys.s.u-tokyo.ac.jp)
Andrea Jungclaus (andrea.jungclaus@csic.es)
Local contact: Liam Gaffney (liam.gaffney@cern.ch)

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Abstract

We propose to study the proton-neutron multiplets in ^{134}Sb populated in the ^{133}Sb(d,p) reaction in inverse kinematics with the T-REX silicon-detector array and the MINIBALL γ-ray spectrometer. ^{134}Sb, with one neutron and one proton outside the doubly-magic nucleus ^{132}Sn, provides the most direct experimental access to the proton-neutron two-body matrix elements which are crucial for the shell-model description of nuclei in the Z=50-82, N=82-126 valence space (the quadrant north-east of ^{132}Sn). In particular, we are aiming for the identification of the members of the excited $\pi 0g_{7/2} \times \nu 2p_{3/2}$, $\pi 0g_{7/2} \times \nu 2p_{1/2}$ and $\pi 0g_{7/2} \times \nu 1f_{5/2}$ multiplets which are populated via ΔL=1,3 transfer. At the same time the proposed study would allow to path the way towards future studies of more exotic nuclei in this region using transfer reactions, for example the ones situated in the south-east of ^{132}Sn, which are very difficult to access by other means.

Requested shifts: 15 shifts
Beamline: MINIBALL + T-REX

The physics case

The properties of the nearest neighbours of doubly-magic nuclei are of fundamental importance for the understanding of nuclear structure. The one-valence particle nuclei, possessing or lacking only one nucleon in otherwise empty or filled shells, provide the energies of single-particle (SPE) and single-hole (SHE) states which are important empirical parameters in any microscopic description of nuclear properties of atomic nuclei. Nuclei with two particles outside a doubly-magic core give the most direct information on the correlations between pairs of nucleons occupying orbitals close to the Fermi surface. Even-even nuclei provide the effective interaction between like nucleons, while the odd-odd isotopes give access to the proton-neutron ($\pi\nu$) two-body matrix elements (TBME).
In the ^{208}Pb region extensive experimental information (including all SPEs in ^{209}Bi and ^{209}Pb, all SHEs in ^{207}Pb and ^{207}Tl and a large number of π-ν^{-1}/π-ν multiplets in Z=83 ^{208,210}Bi [1,2]) is available. Starting with the pioneering work of Kuo, Herling and Brown [3] these SPEs and SHEs enabled both the development of empirical shell model interactions as well as the test and refinement of effective interactions which are derived from modern nucleon-nucleon potentials such as CD-Bonn. As a consequence the shell model description of the nuclear structure in this region of the nuclear chart is under control to such an extent that for example the discrepancies between experimental and predicted electric transitions may be interpreted as clear indication that some correlations are missing, for instance, those due to the effective three-body force [4].

Despite the significant progress achieved in recent years much less abundant experimental information is available for nuclei around ^{132}Sn, e.g. still three of the SPE/SHE, namely the energies of $2s_{1/2}$ protons, $0i_{13/2}$ neutrons and $0f_{5/2}$ proton holes, are experimentally unknown (and the important $\pi 1p_{3/2}$ SHE has been determined only very recently [5]). With respect to the multiplets, only the lowest-lying $\pi 0g_{7/2}$ x $\nu 1d_{3/2}^{-1}$ and $\pi 0g_{7/2}$ x $\nu 1f_{7/2}$ multiplets are experimentally established in ^{132,134}Sb, while experimental information is even scarcer for ^{130,132}In. Note that the latter nucleus, ^{132}In, has been the first in the quadrant south-east of ^{132}Sn in which the gamma decay of excited states has been observed [6]. That experiment, in which ^{132}In was populated following β-delayed neutron emission from ^{133}Cd at RIKEN, clearly demonstrated the difficulty in accessing the region of Z<50, N>82 isotopes using β decay. The most promising alternative approach to obtain experimental information in the region south-east of ^{132}Sn, which is of crucial importance for the astrophysical *r* process, may in the future be the use of low-energy neutron-transfer reactions at ISOL facilities. Transfer reactions in inverse kinematics using radioactive ion beams have been successfully employed in the past both at ISOLDE and Oak Ridge. At HRIBF a lot of effort has been devoted to experiments in the region of ^{132}Sn in the last years before the shutdown, just to mention here the studies of single-neutron (single-hole) states in ^{133}Sn (^{131}Sn) via neutron-transfer (neutron-stripping) reactions [7,8]. Since the reaction mechanisms are well under control, the amount of information which can be obtained for the proton-neutron multiplets in the odd-odd nuclei ^{132,134}Sb and ^{130,132}In using radioactive ^{133}Sb and ^{131}In beams mainly depends on the available beam intensity.

We propose to perform as a first step a ^{133}Sb(d,p)^{134}Sb measurement. The results will provide valuable new information about $\pi\nu$ TBMEs and thus allow to test the different shell model approaches available for the quadrant north-east of ^{132}Sn. In addition, it will provide an experimental basis to judge the feasibility of accessing the quadrant south-east of ^{132}Sn using neutron-transfer reactions in the future.

In ^{134}Sb the members of the lowest-lying multiplet with $\pi 0g_{7/2}$ x $\nu 1f_{7/2}$ configuration are known from β decay [9]. They are compared to shell model (SM) calculations using effective realistic interactions derived from the CD-Bonn nucleon-nucleon potential by the Naples group [10] in Fig. 1. The same comparison is also shown for the analog multiplet (single-particle states with quantum numbers (n,l+1,j+1) instead of (n,l,j)) in ^{210}Bi, one harmonic oscillator shell higher [11]. Interestingly the agreement seems to be slightly worse in the case of ^{134}Sb. It is the goal of the present proposal to extend the experimental basis for a more systematic comparison between SM and experiment in the line of the one already available for ^{210}Bi [12] thus leading to a more detailed investigation of the similarity between the two regions.

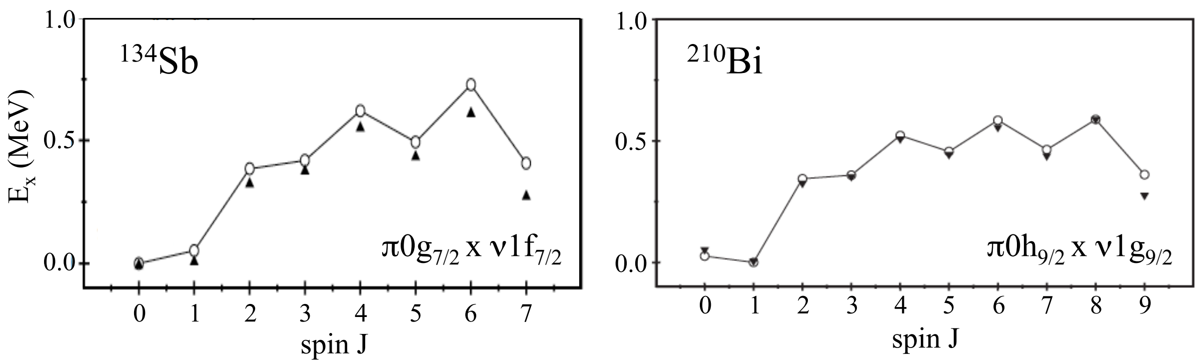

Figure 1: Experimental excitation energies (solid triangles) of the lowest-lying proton-neutron multiplets in ^{134}Sb (left) and ^{210}Bi (right) compared to SM calculations (open circles) [10,11].

Proton-neutron multiplets in ^{134}Sb and the ^{133}Sb(d,p) reaction

The odd proton, which populates the $\pi 0g_{7/2}$ orbital in the ground state of ^{133}Sb, can couple to a neutron occupying any of the six neutron orbitals of the N=82-126 major shell, $\nu 1f_{7/2}$ (0 keV), $\nu 2p_{3/2}$ (854 keV), $\nu 2p_{1/2}$ (1367 keV), $\nu 0h_{9/2}$ (1561 keV), $\nu 1f_{5/2}$ (2002 keV), and $\nu 0i_{13/2}$, to form proton-neutron multiplets in ^{134}Sb (in brackets we quote the experimental excitation energy of the respective single-particle state in ^{133}Sn [7]). The shape of these multiplets as obtained in SM calculations using interactions derived from the CD-Bonn nucleon-nucleon potential [10] is shown in Fig. 2a) together with the calculated spectroscopic factors C^2S (Fig. 2b) which vary between 0.5 and 1. The population of four of the six multiplets requires a neutron transfer with low ΔL (ΔL=1 for the 2p and ΔL=3 for the 1f orbitals) while the other two need ΔL=5,6 ($\nu 0h_{9/2}$, ν $0i_{13/2}$). In order to limit the number of excited states which will be populated in the (d,p) reaction we propose to use a relatively low beam energy around 5 MeV/u to supress the high-ΔL transfer and at the same time maximize the cross section for ΔL=1 transfer. To estimate the cross sections for the population of the different states of interest DWBA calculations have been performed using global optical model parameters from Lohr/Haeberli [13] for the deuteron-projectile potential and from Becchetti/Greenless [14] for the proton-ejectile and core-core optical potential. The resulting total single-particle cross sections are shown in Fig. 2c). Note that within each multiplet the single-particle cross sections increase with spin and that all states of interest are directly populated with significant total cross sections of up to 30 mb. The differential cross section in the laboratory system for the highest-spin member of each multiplet is shown in Fig. 3a). Clearly the forward hemisphere comprises the largest

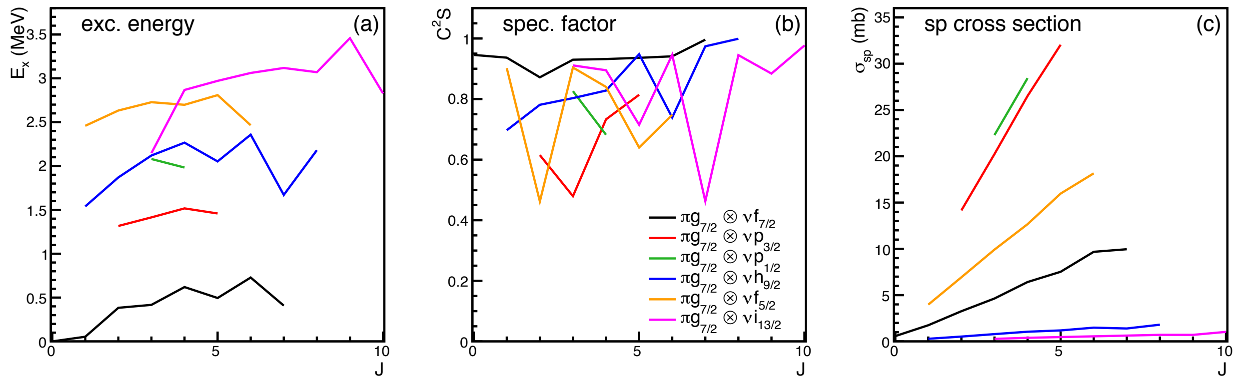

Figure 2: a) Excitation energies E_x and b) spectroscopic factors C^2S as a function of the spin for all six proton-neutron multiplets with the neutron in the N=82-126 shell coupled to a $0g_{7/2}$ proton as predicted by the shell model using effective realistic interactions [10]. c) Calculated single-particle cross sections for a beam energy of 5 MeV/u (see text for details).

fraction of the total cross section. In this region the energy of the recoiling protons is large (see kinematics plot in Fig. 3b) and the detection therefore independent on threshold effects. With the information provided in Figs. 1-3 all ingredients are now available which are needed for a reliable beam time estimate, which will be presented in the next section.

Experimental details and beam time estimate

The ^{133}Sb beam will be produced using a UC_x target and molecular beams as SbS+ from low-energy ISOLDE which break-up in REX-EBIS. Based on the experience gathered during the ^{132}Sn experiment IS551 [15] in 2016 a final yield of 10^5 pps ^{133}Sb on the MINIBALL target seems realistic [16]. This target will consist of 1 mg/cm^2 deuterated polyethylene (CD_2) as has already been employed in several successful experiments in the past. With this thickness the expected energy resolution for proton detection is rather poor, namely around 1 MeV. However, since even for a thinner target the resolution would not be good enough to resolve the states within the different multiplets and thus gamma selection is required in any case, a thick target seems to be the best choice.

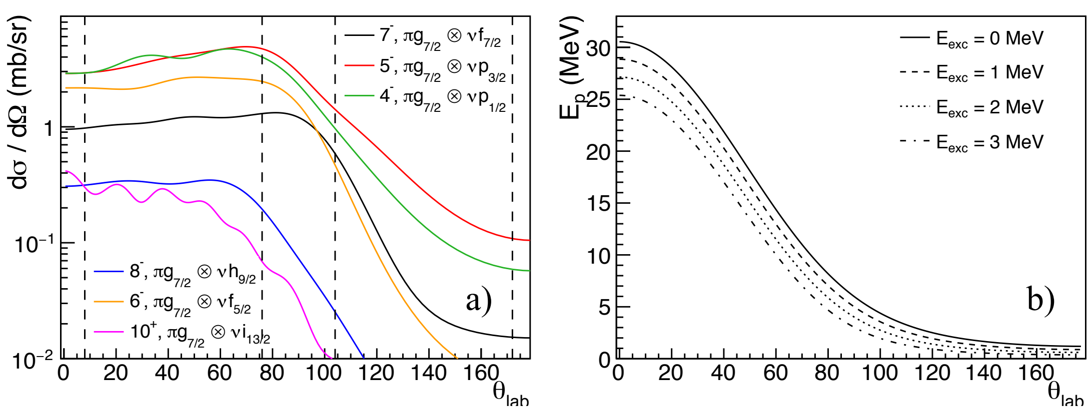

Figure 3: a) Differential cross sections in the laboratory system for the population of the state with highest spin of each multiplet for a beam energy of 5 MeV/u. b) Energy of the recoiling proton to be detected following the (d,p) reaction as a function of the laboratory scattering angle for excitation energies of E_x=0, 1, 2, and 3 MeV.

The experimental setup will comprise the T-REX silicon-detector array [17] coupled to the MINIBALL γ-ray spectrometer [18]. As demonstrated in the past at REX-ISOLDE, the coupling of these two arrays permits the efficient coincident detection of protons and γ rays [19,20]. The coverage of T-REX under the present conditions is roughly 60% of 4π while the MINIBALL photopeak efficiency varies from 13% at 250 keV to 6% at 1000 keV. The only missing piece of information to estimate the number of proton-gamma coincidences we can expect is now the decay pattern of the states of interest for which (except for the lowest-lying multiplet) we rely on the SM predictions using the Naples interaction [10] shown in Fig. 4.

Assuming an 1 mg/cm^2 deuterated polyethylene (CD_2) target, an average cross section of σ=15 mb for the states of interest (compare Fig. 2), a T-REX solid angle coverage of 60% and a ^{133}Sb beam intensity of 10^5 pps on the MINIBALL target, the number of detected protons amounts to 5800 per day. Most of the states of interest decay mainly via the emission of a γ ray in the energy range 900-1100 keV (see Fig. 4) for which 350 proton-gamma coincidences per day can be expected (6% photopeak efficiency and ignoring branching ratios <100%). During 5 days with beam on target thus on average 1750 gamma-gated protons will be available for excitation energy and angular distribution measurements for each member of the multiplets of interest. In order to fix the excitation energy of each individual state proton-gamma-gamma coincidences are required, a technique, which has already successfully been applied in Ref. [20]. On average 230 such pγγ events in 5 days of beamtime are estimated for the decay of each state of interest assuming $\varepsilon_\gamma \approx 13\%$ for the second γ ray with an energy in the range 160-300 keV (see Fig. 4). Finally, Fig. 5 shows simulated gamma-gated proton angular distributions and differential cross sections for two different states of interest, one populated with ΔL=1 transfer, the other with ΔL=3, as expected after 5 days of beamtime with the experiment parameters listed above. This

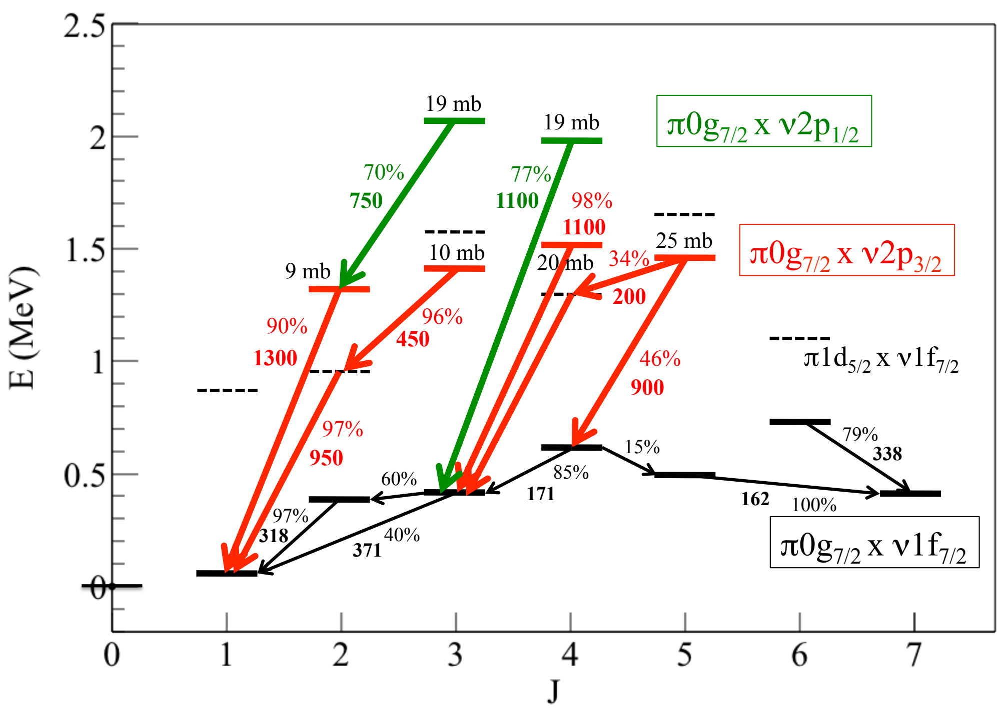

Figure 4: Decay pattern of the proton-neutron multiplets in ^{134}Sb as predicted by shell-model calculations using the effective interaction of Ref. [10]. For the lowest-lying multiplet the experimental information from Ref. [9] is used. The most strongly populated states at the proposed beam energy are labeled with their cross section.

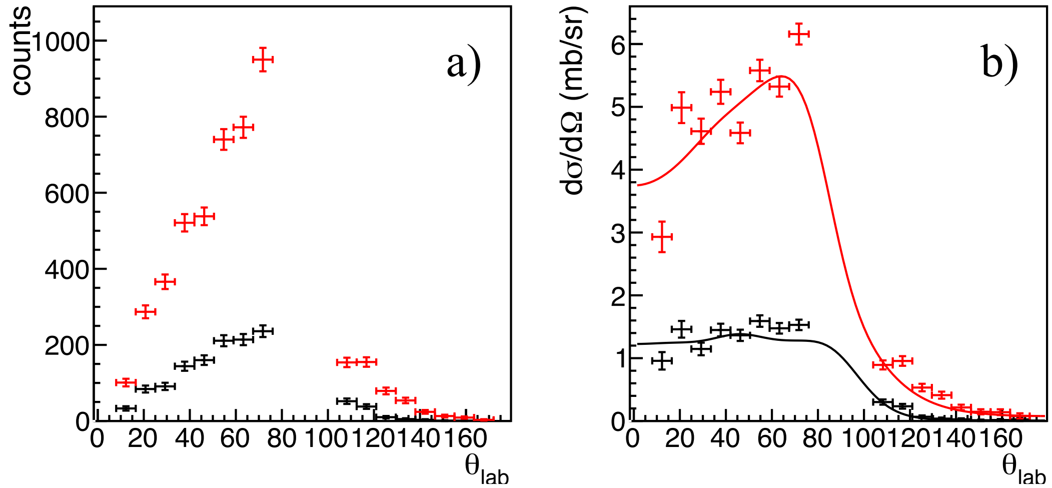

Figure 5: a) Simulated gamma-gated proton angular distributions and b) differential cross sections for the 7^- member of the $\pi 0g_{7/2}$ x $\nu 1f_{7/2}$ (black) and the 5^- member of the $\pi 0g_{7/2}$ x $\nu 2p_{3/2}$ (red) multiplet. A MINIBALL efficiency of 6% is assumed while the T-REX efficiency is implicitly included via the detector geometry. The simulated data correspond to 5 days of beam on target with E_B=5 MeV/u.

simulation shows that in many cases it will be possible to distinguish between the population of p and f orbitals on the basis of the measured proton angular distribution.

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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
MINIBALL + T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL + T-REX installation.