Alpha and beta decays properties of the heaviest N = Z nuclei

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Abstract

We performed the spectroscopic studies of exotic nuclei in the vicinity of doubly-magic N=Z=50 ^{100}Sn by means of Recoil Mass Separator at the JAEA Tandem Laboratory. We obtained an experimental evidence for beta decay of new N=Z+1 isotope. This isotope is an alpha precursor of the super allowed alpha decay chain ^{109}Xe-^{105}Te-^{101}Sn observed earlier at JAEA Recoil Mass Separator. However, its decay is dominated by beta transitions and following proton emission. The identification of ^{113}Ba was enabled by a new detection technique for fast charge particle decays which has been developed at the University of Tennessee and commissioned at the JAEA Recoil Mass Separator. This technique is based on fast-response, radiation-hard and position sensitive YAP scintillator detector allowing to identify alpha-activities with half-lives down to 100 ns level. It was designed for the experiment aiming in a discovery of new N=Z nuclei ^{108}Xe and ^{104}Te located near the doubly magic ^{100}Sn and in the investigation of their super allowed alpha decays. Coupling the new detector to an array of LaBr3(Ce) scintillators will allow fast-timing measurements for the excited states populated by alpha transitions in odd-mass nuclei near ^{100}Sn. This research program got slowed down by the troubles with high energy ^{58}Ni beam of sufficient intensity at Tandem accelerator in December 2016, but it will continue after the Tandem operation will restart.

1. Research Objectives

The overarching goal of our studies is the investigation of nuclear structure of proton-rich nuclei around the doubly-magic nucleus ^{100}Sn having the same neutron (N) and proton numbers (Z). N=Z=50. ^{100}Sn is the heaviest N=Z nucleus discovered so far. The fact that protons and neutrons occupy the same orbitals may reveal a presence of a new type of pairing in nuclei – the proton-neutron (p-n) isoscalar pairing, which could be different from the well-known pairing between like nucleons (n-n and p-p), leading to a new type of superfluidity. An experimental program, which aims to identify heaviest N=Z nuclei is ongoing at the JAEA Tandem Laboratory. This project focuses on the discovery of the isotopes ^{112}Ba, ^{113}Ba, ^{108}Xe and ^{104}Te produced in the fusion-evaporation reactions. The main goal is to identify the so-called “superallowed” α-transition occurring in ^{104}Te→^{100}Sn decay. Specifically, a unique type of enhancement of the α-particle emission from nuclei in the vicinity of ^{100}Sn was predicted [1], made possible by the special properties of N=Z nuclei and the shell structure near ^{100}Sn. This project can achieve this goal by discovering two out of the three heaviest N=Z isotopes, present in the ^{108}Xe→^{104}Te→^{100}Sn superallowed α-decay chain. The alpha decay of ^{108}Xe generates also new isotope ^{104}Te (N=Z=52), the latter one decaying by the ultimate superallowed transition ^{104}Te→^{100}Sn. The production of ^{108}Xe is based on fusion-evaporation reaction; excited compound nucleus ^{112}Xe* is formed in the fusion reaction between ^{58}Ni and ^{54}Fe, and the ^{108}Xe is generated by evaporating 4 neutrons from ^{112}Xe*. This research is a continuation of the program initiated at the HRIBF (ORNL,USA) which resulted in numerous technical development [2,3], and enabled discovery experiments in the ^{100}Sn region.

Production of ^{108}Xe itself is already a big challenge in a nuclear physics community. Attempt at RIKEN-RIBF facility to produce N=Z nuclei beyond ^{100}Sn using fragmentation technique was done, but no clear decay data was reported so far. A future plan of Spiral2 at GANIL (France) also intends to produce these nuclei. Our objectives can be realized at the JAEA-Tandem using our new developed detection setup, combined to the JAEA Recoil Mass Separator [4]. The new N=Z isotopes of interest can be produced using high-energy (~250 MeV), intense (>30 pnA), stable Tandem beams or by a temporary re-operation of the Booster Linac.

Due to unfavourable conditions of the Tandem accelerator, neither scenario seemed realistic within FY2016. Hence we decided to reinvestigate the α-decay chain ^{109}Xe→^{105}Te→^{101}Sn, shown in Fig. 1, in which excited states in ^{105}Te and ^{101}Sn [5,6] are populated. The decay of these excited states, usually in the picosecond range, is expected to be slowed down to the hundreds of picosecond range by the change in two units of orbital angular momentum when the valence neutron moves from the $d_{5/2}$ to the $g_{7/2}$ orbit (L-forbidden M1 competing with E2 transition). For this transition to occur, the wavefunction of the valence neutron needs to mix with excitations of the ^{100}Sn core. These decays would constitute the first study of electromagnetic transition probability so close to this N=Z closed shell nucleus, and assess the magic nature of ^{100}Sn.

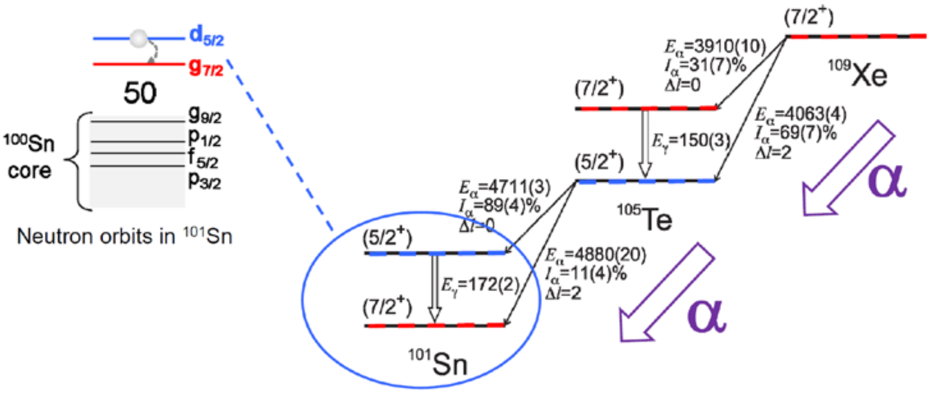

Fig 1 : Modified from [6]. Decay chain of ^{109}Xe, where the α decay of ^{105}Te(^{109}Xe) populates excited states in ^{101}Sn(^{105}Te). The neutron single-particle orbits involved in this M1 transition are shown in the inset on the left

2. Research Contents

Our experimental program to eventually measure the ^{104}Te α decay is still ongoing at the JAEA Tandem. The rare evaporation of 4 neutrons from excited ^{112}Xe create α-radioactive ^{108}Xe product. Since the cross section for ^{108}Xe corresponds roughly to only 1 part in a billion ($1/10^9$), the separation of reaction products is a critical issue. The JAEA Recoil Mass Separator (RMS) has been proven to be capable to isolate mass 108 isotopes from the other produced nuclei. The implantation of ^{108}Xe ions and subsequent α decay can be detected in a position sensitive detector at the focal plane of the separator. The selectivity required to identify the decays of these exotic isotopes can be achieved through the observation of the characteristic complete or partial α-decay chains. The ^{108}Xe activity will leave a unique double-alpha decay pattern allowing us to identify this rare nucleus and its decay products ^{104}Te and ^{100}Sn. This pile-up signal will result from two subsequent alpha decays within few tens of nanoseconds. The feasibility of the technique was proved in test experiments on the known ^{109}Xe α-decay chain and in the discovery experiment of ^{113}Ba [7]. Despite a much smaller than expected production cross-section, evidence of the first production of ^{113}Ba was deduced from the collected data and it constitutes the topic of the Ph.D. thesis of Y. Xiao at University of Tennessee, Knoxville. The worsening of the Tandem accelerator conditions delayed our main goal and, for FY2016, we developed an alternative program which could be achieved even with a lower Tandem terminal voltage (16 MV), i.e. the lifetime measurement of the 172-keV state in ^{101}Sn. If successful, this would be the first measurement of electro-magnetic transition probability neighboring ^{100}Sn.

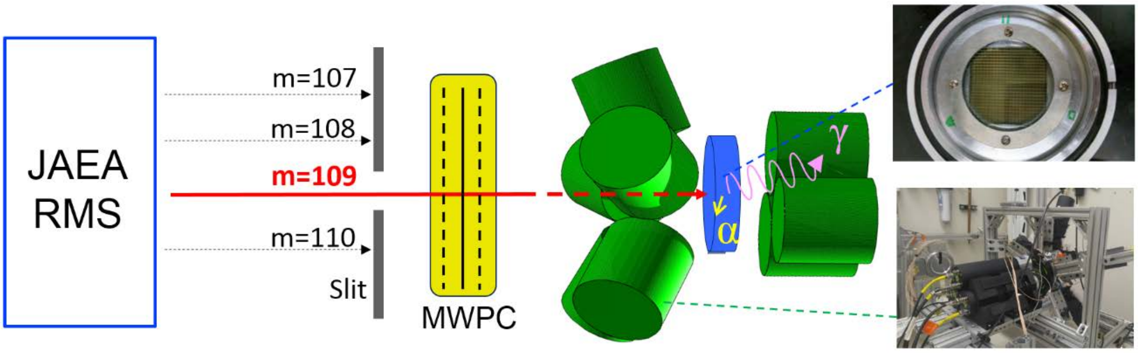

Fig 2 : Schematic diagram of new timing setup. Isotopes produced in the ^{58}Ni+^{54}Fe reaction at 220 MeV, separated according to the A/q by the RMS reach the focal plane. The new YAP scintillator detector, where mass 109 ions are implanted and decay, is surrounded by a compact array of $LaBr_3$(Ce) scintillators, for an absolute photo-peak efficiency of ~25% at 172 keV.

The signature of the production of ^{101}Sn is given by the unique pile-up signal corresponding to the double α decay $^{109}Xe \rightarrow {}^{105}Te \rightarrow {}^{101}Sn$. ^{109}Xe can be produced via the ^{58}Ni+^{54}Fe fusion-evaporation reaction at 220 MeV. The RMS separate the evaporation residues (ERs) according to their mass-to-charge ratio, and focus them onto a compact decay station, drawn schematically in Fig. 2. The setup comprises mechanical slits to select only the mass of interest, a Multi Wire

Proportional Counter (MWPC) to monitor the trajectories of ERs and scattered beam background, and a **newly developed YAP scintillator detector** where ^{109}Xe implant and decay. The YAP detector, constructed at UTK/ORNL, is a 100-μm-thin YAP scintillator crystal, mounted on a segmented light guide (24x24 pixels) and a position-sensitive photomultiplier tube to obtain high pixilation to compensate for the high implantation rate. Time-correlations between MWPC and YAP permit to discriminate charged-particle decays from implants of residues and from scattered beam. Eight $LaBr_3(Ce)$ scintillators, with a timing response of 200 ps resolution, provided by the UTK collaborators, surrounding the target chamber, enable particle-γ coincidences. The delayed coincidence between decay α particles detected in YAP and γ–rays detected in the $LaBr_3$ permit to determine lifetime of the first excited states in ^{101}Sn and ^{105}Te. According to systematics for the L-forbidden transition, these lifetimes are expected to be in the 500-1000 ps range. A two-week experiment was scheduled to run in January 2017, but it had to be canceled due to a temporary closure of the accelerator due to a vacuum issue occurred in late 2016. The experiment will be carried out after the Tandem restart.

3. Research results

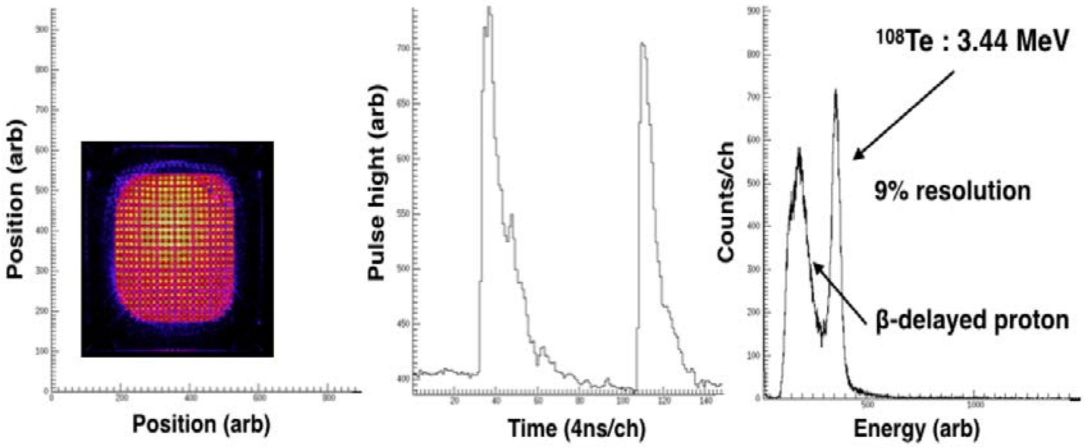

Fig 3: (from left to right) 2-D map of implant positions, time response and in-beam decay energy spectra obtained with the new YAP detector developed at UTK-ORNL. Its radiation hardness permits to expose this detector to intense particle bombardment for extended period of time without any appreciable loss in time resolution (~200 ps) or energy resolution, measured to be ~9% for an α energy of 3.44 MeV.

The temporary unavailability of intense ^{58}Ni beam at the JAEA Tandem resulted in a setback of our anticipated completion time and of our publications. Nonetheless, the JAEA Tandem is the only facility, in addition to ORNL, where the ^{109}Xe-^{105}Te-^{101}Sn double alpha chain was observed, and probably the only facility worldwide to have gathered evidence for the production of ^{113}Ba. This work resulted in the doctorate thesis work of Y. Xiao at the University of Tennessee, and a publication summarizing the results is in preparation [8]. Furthermore, the development and commissioning of the YAP scintillator, of which representative spectra are shown in Fig. 3 and its employment to detect fast consecutive α decays, is the topic of a technical publication to be submitted to the journal Nuclear Instruments and Methods in Physics Research [9].

4. Conclusion

The achievements of this research programme, driven by the desire of measuring the superallowed α decays in ^{104}Te, brought us very close to carry out a measurment which large-scale facilities like RIKEN or GANIL are still uncapable of carrying out. Our newly-developed detection setup makes this ambitious project more likely to succeed at the JAEA-Tandem. In our experiments at the JAEA-Tandem RMS, performed with detection system combing UTK, ORNL and JAEA detectors and state-of-art digital data acquisition from UTK/ORNL, the decay chain ^{109}Xe-^{105}Te-^{101}Sn was observed and the evidence for a decay of new isotope ^{113}Ba was obtained. On our side, all is ready to carry out our proposed measurements, and we sincerely hope that all these efforts will be repaid by some successful experimental runs when the Tandem accelerator facility will become again capable of providing the intense, high-energy beams required by this project. When the production capabilities at JAEA Tandem will be recovered, preferably with a the Booster Linac being a part of the acceleration scheme, the discovery of the new isotopes ^{108}Xe and ^{104}Te may be achieved at JAEA laboratory.

5. References

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