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Spectroscopy of exotic nuclei with MINIBALL and FATIMA

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Abstract. The investigation of the structure of exotic nuclei is the aim of many experimental and theoretical efforts in nuclear physics. Of particular interest is the evolution of nuclear structure near to shell closures. An important experimental tool for such investigations is prompt γ-ray spectroscopy. Some examples employing state-of-the-art intrumentation will be presented.

1. Introduction

Many efforts in experimental and theoretical nuclear physics investigate the structure of nuclei in regions around shell closures and magic numbers. Their reproduction is a benchmark for any nuclear theory. Going away from the valley of β-stability, traditional magic numbers may disappear or new ones may appear in exotic nuclei. These fingerprints indicate changes of the nuclear interaction relevant for their existence. However, the investigation of unstable nuclei is a challenge for experiments. In this contribution, some examples illustrating different techniques for both the population of exotic nuclei and their investigation by γ-ray spectroscopy are presented.

The mechanisms to populate excited states in the exotic nuclei discussed cover a broad range from gentle Coulomb excitation via nucleon-transfer reactions to more violent nucleon-knockout reactions and neutron-induced fission. The experiments have been performed at REX-ISOLDE (CERN), ILL (Grenoble, France), and GSI (Darmstadt, Germany). Although the experimental method applied is always prompt γ-ray spectroscopy for all presented physics cases, the actual set-ups are quite different and use both large arrays of segmented high-resolution HPGe detectors, e.g. MINIBALL [1], and fast scintillators, e.g FATIMA consisting of $LaBr_3(Ce)$ crystals [2]. The accessible observables to characterise nuclear states are excitation energies, spin-parity assignments and electromagnetic transition probabilities as well as spectroscopic factors.

2. Physics examples

2.1. Island of inversion

The "island of inversion" is a region of the nuclear chart where the traditional magic number $N = 20$ disappears. The structure of neutron-rich Mg isotopes is characterised by a competition of nearly spherical sd configurations and deformed fp intruder configurations. In ^{30}Mg, a nearly spherical ground state and a deformed excited 0^+ state have been found, for results from ISOLDE see Refs. [3, 4, 5], locating this isotope just outside of the island. Going to ^{32}Mg, the inversion occurred and the deformed 0^+ state is now the ground state. Mg isotopes at the border of the "island of inversion" have been populated in one- and two-neutron transfer reactions in inverse kinematics [6, 7] at REX-ISOLDE. The spectroscopy has been done by a combination of the MINIBALL γ-ray spectrometer and the T-REX Si detector array for particle spectroscopy [8].

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The most prominent result was the identification of the long-sought excited 0^+ state in ^{32}Mg [6], the analogue of the ground state in ^{30}Mg, which is expected to have a nearly spherical shape too. This state was populated in a (t,p) reaction in inverse kinematics employing a radioactive tritium target. The 0^+ spin-parity assigment is based on the characteristic angular distribution of the outgoing protons. From the observed γ-ray yield a lower limit for its lifetime of > 10 ns could be estimated, similar to the excited 0^+ state in ^{30}Mg [3].

Indeed, the cross section for the population of the excited 0^+ state in ^{32}Mg can be explained assuming a *sd* configuration with a small $p_{3/2}$ admixture in its wave function which is consistent with what is observed in the one-neutron knockout from the ground state of ^{30}Mg. However, it remains a challenge to nuclear theory to reproduce consistently both the low excitation energy of 1058 keV and the large cross section in the two-neutron transfer reaction.

2.2. New shell closure at $N = 32, 34$

The shell model reproduced until recently the traditional magic number at $N = 28$ in Ca only if empirical interactions are used. Newer developments with realistic interactions derived from NN potentials applying chiral EFT achieved with the inclusion of NNN forces this goal too [9]. Extrapolated to more neutron-rich isotopes both the shell model with empirical and realistic interactions, but also beyond-mean-field calculations [10], predict new shell closures at $N = 32$ and/or $N = 34$. The changes in the level ordering and the single-particle configurations contributing to the wave functions of the states have been investigated by one-neutron knockout reactions on isotopes north-east of ^{48}Ca at relativistic beam energies. The experiment was performed at the fragment separator FRS of GSI. The MINIBALL array, positioned at the intermediate focal point S2, allowed to obtain exclusive momentum distributions of the outgoing reaction products. These were measured using the second half of the FRS as high-resolution spectrometer.

In ^{55}Ti, for the ground state as well as for a newly found excited state at 955 keV a p configuration was found. This is in agreement with predictions obtained with the shell model [11]. For the Sc isotopes, it was observed that the cross sections observed cannot be reproduced using occupation numbers obtained by the shell model even if empirical interactions are applied. The observed $\Delta L = 1$ contribution indicating the knockout of a p neutron is larger whereas the $\Delta L = 3$ indicating the knockout of a f neutron is smaller than theory currently predicts [12].

2.3. Nuclei around ^{132}Sn

Many experiments at REX-ISOLDE with MINIBALL employ γ-ray spectroscopy following "safe" Coulomb excitation as a tool to study collective properties of exotic nuclei (see also [13]). Here, the beam energy is chosen such that projectile and target interact only via the well-known electromagnetic interaction. The radioactive isotope of interest impinges as beam on a target and either of them (or both) can be excited. From the double-differential cross sections, extracted from the measured γ-ray–particle yields, the electromagnetic matrix elements are determined. As the cross section depends on both transitional but also diagonal matrix elements (reorientation), reduced transition probabilities $B(E\lambda)$ as well as spectroscopic electric moments Q_λ can be extracted. In the analysis, the experimental data are compared with results of calculations and the matrix elements are obtained applying the maximum likelihood method, see e.g. [14]. Additional information, like lifetimes from independent experiments (DSAM, RDS or fast timing) can be considered too and helps in the analysis, in particular in cases where more than one state has been excited and many matrix elements have to be considered.

The region around the isotope ^{132}Sn is in the focus of many experimental and theoretical studies as it is one out of only two heavy doubly-magic nuclei on the neutron-rich side of the nuclear chart, ^{78}Ni is the other, which can be reached experimentally. Although near two shell closures, several isotopes exhibit a suprisingly irregular behaviour. One of the most prominent

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examples is ^{136}Te whose $B(E2; 0^+_{\rm gs} \rightarrow 2^+_1)$ value is considerably smaller than expected by theory [15]. However, a new analysis of the data [16] as well as a direct lifetime measurement using fast timing [17] corrected the value to about 20% larger values. At REX-ISOLDE, neutron-rich Cd and Xe isotopes have been studied in “safe” Coulomb excitation.

The excitation energy of the first 2^+ state of ^{128}Cd exibits a strange irregularity not observed anywhere else. Approaching the shell closure at $N = 82$ the energy does not increase from ^{126}Cd to ^{128}Cd, it even slightly decreases! This trend is not reproduced by the shell model, but only by beyond-mean field calculations resulting in the prediction of a considerable deformation of this nucleus. However, our results find only for the lighter isotopes ^{122,124}Cd $B(E2)$ values above the shell model predictions whereas for the heavier isotopes ^{126,128}Cd the values roughly agree [18, 19]. For the 2^+ state in ^{126}Cd the additional result of a DSAM measurement has been included in the analysis. Indeed, also the Q_2 values, although having large errors, are more consistent with spherical shapes. Hence, the excitation energy of ^{128}Cd remains an open challenge for theory.

For the Xe isotopes beyond $N = 82$, previously only lifetimes of the first 2^+ and 4^+ states in ^{140}Xe were known, however for the 2^+ state two contradicting values can be found in literature. The longer lifetime corresponding to a smaller $B(E2)$ value would indicate a continuation of small $B(E2)$ values above $N = 82$ observed in ^{136}Te. Assuming vanishing quadrupole moments, $Q_2 = 0$, the $B(E2)$ values for the even isotopes $^{138-144}$Xe obtained from the Coulomb excitation data follow a smooth trend given by a simple Grodzins-type systematics along the Xe isotopic chain and no irregular behaviour is observed.

A different approach to direct lifetime measurements is the fast-timing technique involving fast scintillator crystals like $LaBr_3$. The set-up comprised the EXILL (EXOGAM@ILL) HPGe array and FATIMA, consisting of 16 $LaBr_3$ crystals. A detailled description of the method and the set-up is presented in a further contribution to this school [2]. Lifetimes in neutron-rich Xe isotopes populated in neutron-induced fission of ^{235}U and ^{241}Pu have been measured at ILL (Grenoble) in March 2013.

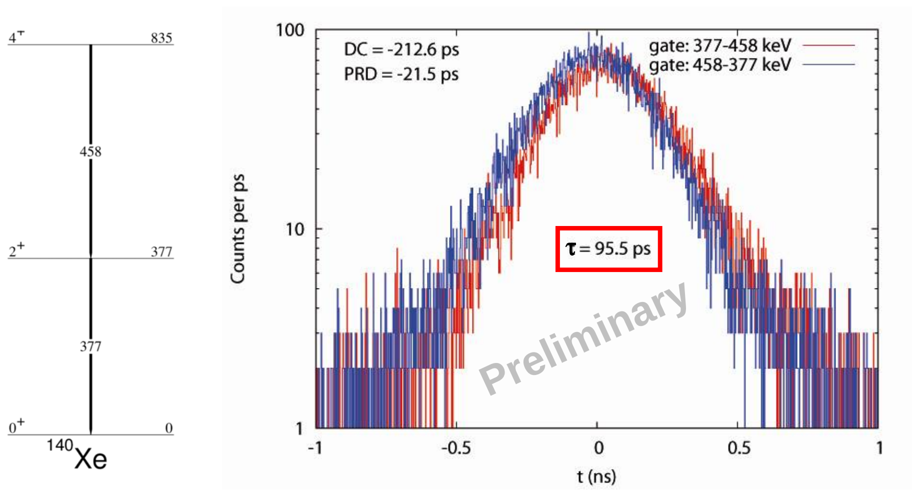

Figure 1. Partial level scheme of ^{140}Xe (left) and preliminary time difference spectrum analysing $LaBr_3$ doubles only (right). Plot by courtesy of S. Ilieva (TU Darmstadt).

In Fig. 1, one preliminary result of the analysis of $LaBr_3$ only coincidence data for a small part of the data set is shown. The obtained lifetime of $\tau = 95.5$ ps for the 2^+_1 state in ^{140}Xe is already near to the previously measured value of $\tau = 101.7(32)$ ps [20]. In conclusion, in Xe no irregular behaviour can be evidenced.

However, since the energy resolution of $LaBr_3$ is inferior compared to HPGe detectors, in many cases, in particular for weakly populated channels or the odd Xe isotopes, a further coincidence with Ge detectors may be required in the ongoing analysis to clean the spectra.

3. Future prospects

The Coulomb excitation programme at ISOLDE with MINIBALL will be continued at the upgraded facility HIE-ISOLDE which will offer a higher beam energy, an increased beam intensity and an improved beam quality. In particular, the higher beam energy will allow for multiple Coulomb excitation and the extension of the transfer programme towards heavier nuclei. The study of nucleon knockout reactions and quasi-free scattering is an important programme of R^3B at FAIR employing the spectrometer and calorimeter CALIFA. Large set-ups of $LaBr_3$ detectors like FATIMA will be used in future at several places like ILL, RIKEN, ISOLDE, JYFL or DESPEC at FAIR for prompt and delayed γ-ray spectroscopy.

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