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Breaking of the isospin symmetry in the A=71 mirror nuclei: Knock-out reactions in 71Kr-71Br nuclei (and neighbours) using Miniball at Riken.

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Isospin formalism, which describes the neutron and the proton as two states of the same particle, the nucleon, is amongst the essential descriptive tools of a broad range of nuclear phenomena. The success of the isospin symmetry concept belies its broken nature. Not only is the symmetry broken by the proton-neutron mass difference and the Coulomb interaction, but also by the nucleon-nucleon interaction itself. The investigation of isospin symmetry conservation and breaking effects has revealed a wealth of nuclear structure information. The so-called mirror energy differences (MED) are defined by the differences in the excitation energies of analogue states and are regarded as a measure of isospin symmetry breaking in an effective interaction that includes the Coulomb force. The MED have been extensively studied for pairs of mirror nuclei in the upper sd- and the lower fp-shell regions. In both cases a remarkable agreement between experimental data and shell model calculations has been achieved allowing a clear identification of the origin of the MED based on the Coulomb force and on an isospin non-conserving term of the nuclear interaction, which turns out to be essential for a quantitative description of the data [1, 2, 3]. These studies allow one to extract several nuclear structure properties, such as the nature of particle angular- momentum re-coupling along yrast structures (e.g.backbending), the evolution of the nuclear radius or deformation and the identification of pure single-particle configurations.

An important aspect that can strongly influence the MED in the upper fp shell concerns the possible breaking of the isospin symmetry due to shape coexistence, which refers to the ability of some atomic nuclei to assume competing mean-field shapes at low excitation energies. A variety of nuclear shapes is expected around $A \sim 70$ due to the complexity of the Nilsson diagram which shows pronounced subshell gaps at nucleon numbers 34 and 36 (oblate), 34 and 38 (prolate), and 40 (spherical). Several studies have shown that the even-even neutron-deficient Kr isotopes represent one of the unique regions where the ground-state deformation appears to change from prolate to oblate shapes as the self-conjugate nucleus ^{72}Kr is approached. The occurrence of the oblate ground state in ^{72}Kr is of particular interest in relation to the well-known open question about the pre-dominance of prolate deformation in well-deformed nuclei [4]. Recent results [5] on the structure of ^{72}Kr obtained at NSCL with the Gretina array seems to confirm this picture. Further studies of the ground state shape have also been made recently with the TAS technique [6]. ^{72}Kr appears therefore to be a transitional nucleus in which oblate shapes are predicted to dominate at low energy, though coexisting with prolate ones. This is supported by shell model calculations, presented recently by Zuker and co-workers [7].

The presence of deformed shell gaps at oblate and prolate deformation may give rise to opposite shapes even in mirror nuclei. An anomalous (negative) behavior of the Coulomb Energy Differences (CED) between 70Br and 70Se seems to indicate the presence of different deformation mixing for analogue states [8]. On the other hand shell model calculations predict both 70Br and 70Se to have the same shape and suggest that the origin of the unexpected trend of the CED is in the spin-orbit contribution [9]. To pin down such possible breaking of the isospin symmetry and to disentangle the different contributions we plan to investigate the Mirror Energy Differences (MED) in the mirror nuclei ^{71}Kr–^{71}Br populated from ^{72}Kr using knock-out reactions. Shape coexistence has been reported in ^{72}Kr. Experimentally the level scheme is well known and it is characterized by the presence of a Jπ = 9/2+ isomeric state at 759 keV with $T_{1/2} = 33$ ns. Related studies can be found in refs. [10, 11, 12, 13]. The latest results from Fischer et al. [13] suggest the presence of eight distinct Nilsson bandheads below ~ 1 MeV, corresponding to different deformation, from oblate to prolate. In this work the level scheme of ^{71}Br has been extended up to $J \sim 41/2$.

Regarding ^{71}Kr, the only information available comes from β decay studies. The spin assignment to the g.s. was made first by Arrison [10] and Oinonen [11] based on mirror symmetry. Urkedal and Hamamoto pointed out in [12] that this could be the first case of mirror nuclei where the isospin symmetry is broken in the g.s.. This was deduced from Nilsson model calculations and a change in the spins of the lowest states was proposed. Finally Fischer et al. [13] changed back the spin of the first excited state in ^{71}Br following observations of the angular distribution of the 397 keV transition and so the g.s. spin of ^{71}Kr was proposed to be $5/2^{-}$.

Excited levels in ^{71}Kr have been investigated over many years using different techniques and setups. Three attempts used the ^{40}Ca + ^{40}Ca reaction at 160 or 180 MeV. There were experiments at LNL with GASP + ISIS and EUROBALL + ISIS and at ORNL using the recoil separator plus HYBALL (CP array) and the CLARION gamma-ray array. It was possible to observe the ^{71}Br lines from the 2α1p channel but there was no convincing

evidence for the observation of excited states in ^{71}Kr. Those experiments performed with coupled gamma-particle spectrometers (GASP + ISIS and EUROBALL + ISIS) suffered heavily from the poor channel selectivity as a consequence of the lack of tagging of the neutrons evaporated in the reaction. The experiment at ORNL reported a limited resolution in Z in the ion chamber of the recoil separator as a consequence of the low velocity of the residual nuclei. This poor channel resolution in Z translated into contaminated spectra where background subtraction had to be used extensively in order to highlight the transitions of interest. This challenging procedure compromises the identification of the most exotic nuclei.
Similar limitations also affected an experiment performed using Gammasphere coupled to the FMA recoil detector, that has a limited channel selection for recoils of such large mass. In this measurement the ^{36}Ar + ^{40}Ca reaction at 103 or 105 MeV was used.

Recently the ^{71}Kr isomeric decay has been studied at RIKEN. Assuming, based on the mirror symmetry, the existence of a longer living isomer, the ^{71}Kr ions produced by fragmentation after mass selection were implanted at the focal plane of the zero degree spectrometer. No gamma rays could be clearly identified as belonging to the ^{71}Kr decay indicating that the expected isomer, if it exists, has to be significantly shorter than the flight-time in the spectrometer.The RIKEN RIB facility, combining the largest production of unstable isotopes with the highest selectivity of the reaction products, should allow us to clarify this longstanding issue. We propose to study excited states in ^{71}Kr exploiting the unique channel selectivity provided by the BigRIPS magnetic spectrometer allowing full identification of the incoming and outcoming particles. A ^{72}Kr secondary beam will be used to populate, through neutron and proton knock-out, the ^{71}Kr-^{71}Br mirror nuclei identified event-by-event in the zero degree spectrometer. Prompt gamma rays de-exciting excited states will be detected in the Miniball array. The high resolution of the Ge detectors will be essential to disentangle the complex level scheme. Due to the mixing of the oblate and prolate components in the ground state of ^{72}Kr, we expect to have access to the different shape structures in the final products. Mirror fragmentation (populating at the same time ^{71}Kr and ^{71}Br) will be used to control the populated excited states allowing a direct indication of the possible breaking of the mirror symmetry. For delayed gamma radiation at the focal plane we propose to mount the Total Absorption Spectrometer DTAS [14] of the Gamma Spectroscopy group from IFIC (Valencia) at the focal plane after the zero degree spectrometer recording delayed coincidences. We know that the sensitivity to a possible short living isomer will be better here than in the previous experiment where the ^{71}Kr beam had to travel along the full BigRIPS spectrometer in order to reach the focal plane at F11. The DTAS will be available at Riken during the Miniball campaign.

We propose to use a primary ^{78}Kr beam (^{124}Xe is an alternative) at 345 MeV/u with an intensity of 300 pnA. In order to help the spin-parity assignment we plan to use longitudinal momentum analysis of ^{71}Kr. To this purpose the acceptance of BigRIPS can be reduced to 0.5% to obtain the needed resolution in the momentum transfer. Even with such small acceptance we expect to have a secondary beam with an intensity of 3.5 104 pps at F8. The expected beam purity for ^{72}Kr is 90%.

Assuming an efficiency of 3% for the Miniball array we expect a gamma/particle counting rate of 1 and 2 Hz, respectively, for the lowest lying transitions of the mirror nuclei. Therefore we expect to be able to identify the main prompt gamma transitions in one day of beam time and to have sufficient statistics for a gamma-gamma correlation analysis.

The large statistics, high precision, measurement of knockout reaction towards ^{71}Kr and ^{71}Br will allow the verification of the symmetry rules that are expected to hold for mirror knockout reactions. Differences in the cross section for the population of isospin analogue states will be exploited to highlight differences in the structure of such states.

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Primary authors: MONTANER-PIZÁ, Ana (Università Degli Studi di Padova- INFN Sezione di Padova); DEANGELIS, giacomo (INFN LNL); RECCHIA, Francesco (INFN LNL); RUBIO, Berta (CSIC Valencia)

Co-authors: LENZI, Silvia M. (University of Padova and INFN); VALIENTE DOBON, Jose Javier (LNL-INFN); CORTES, Martha Liliana (RIKEN Nishina Center); Dr TAIN, José Luis (IFIC, Valencia, Spain); GOTTARDO, Andrea (LNL - INFN); Dr ILLANA, Andrés (INFN LNL); ALGORA, Alejandro (IFIC (CSIC-Univ. Valencia)); Dr GALTAROSSA, Franco (INFN LNL); Prof. GELLETLY, William (University of Surrey, Surrey, UK); Prof. MENGONI, Daniele (Padova University); Dr GOASDUFF, Alain (Università di Padova- INFN Sezione Padova)

Presenter: RECCHIA, Francesco (INFN LNL)

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