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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

MULTIPLE COULOMB EXCITATION OF A NEUTRON RICH ^{88}Kr BEAM TO STUDY SYMMETRIC AND MIXED SYMMETRIC STATES IN INVERSE KINEMATICS

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Abstract: We propose to use the MINIBALL setup at the HIE-ISOLDE facility to perform a Coulomb excitation experiment with a ^{88}Kr radioactive beam. The motivation is the study of transition strength between low-spin states in ^{88}Kr including the precise study of the decay of the 2^+_3 Mixed Symmetry state observed recently. The proposed experiment will provide additional data to the Coulomb excitation of a relativistic ^{88}Kr beam performed within the scope of the PreSPEC campaign at GSI. A total of 7 days of beam time will be sufficient for the experiment to extract precise B(E2) and B(M1) strengths that characterise the proposed mixed symmetric 2^+_3 state in ^{88}Kr and the low-spin symmetric states.

Requested shifts: 21 shifts, (can be split into 2 runs (3+18 shifts) over 1 year)
Installation: MINIBALL + CD-only

1 Scientific motivation

The atomic nucleus with its two different constituents, protons and neutrons, represents a unique finite quantum many-body system. The evolution of its properties can be investigated in detail by varying the finite number of protons and neutrons. One of the fundamental aspects of nuclear structure physics is the understanding of how collective quantum phenomena, such as deformation or phonon excitations, arise. From these studies one knows that proton-neutron correlations in the valence space play an important role in the formation of collective motion. However, possible combinations of protons and neutrons which could be studied in detail were up to now mostly limited to stable and proton rich nuclei. Important observables, needed for such studies, are lacking for nuclei on the neutron-rich side of the nuclear chart.

In principle, the nuclear shell model represents the ideal theoretical microscopic tool to attack the problem of understanding the evolution of collective nuclear structure. However, the description of collective excitations requires often a very large configuration space and, hence, model calculations must be truncated to appropriate valence spaces leading to necessary re-adjustments of the parameters of the effective residual interactions and single-particle energies. These effective model parameters must be obtained from experiment. The investigation of symmetries can help to gain a more detailed understanding of nuclear forces (see also [1]). The isospin symmetry represents for instance one of the fundamental symmetries of nucleonic systems.

Recent nuclear structure studies address the detailed investigation of nuclear shell structure, in particular, at extreme values of isospin. Besides the studies of yrast excitations in very neutron-rich nuclei another sensitive probe for the isospin dependence of nuclear forces in the valence shell is represented by the properties of collective isovector valence shell excitations.

The interacting boson model (IBM) [2] represents a very powerful kind of drastically truncated shell model appropriate for the description of quadrupole collectivity. Besides its schematic character the IBM offers very useful insights into the nuclear structure revealing different symmetries of the nuclear wave functions. Because the IBM is based on nucleon pairs formed by either two valence neutrons or two valence protons, it allows also the study of proton-neutron correlations, albeit of nucleon pairs. The framework of the IBM-2 extends the isospin formalism to the IBM boson systems. These bosons are considered to be "elementary" particles that form a doublet with projection +1/2 (proton boson) and -1/2 (neutron boson). In order to avoid confusion with the ordinary isospin for nucleons the "boson-isospin" is called F-spin. It should be also mentioned that the F-spin in the IBM does not match the total isospin of corresponding valence nucleon pairs. However, formally, isospin and F-spin are complementary analogous. The former applies to "elementary" nucleons, the latter to "elementary" bosons, formed by pairs of identical valence nucleons.

For the description of a given nucleus with fixed numbers of proton and neutron bosons, N_π and N_ν, respectively, the z-component of the F-spin is a good quantum number, namely it is $F_z = (N_\pi - N_\nu)/2$. For a given total boson number, $N = N_\pi + N_\nu$, the total F-spin quantum number can take values between F_z and $F_{max} = N/2$.

The IBM predicts new entire classes of collective states with F-spin quantum numbers

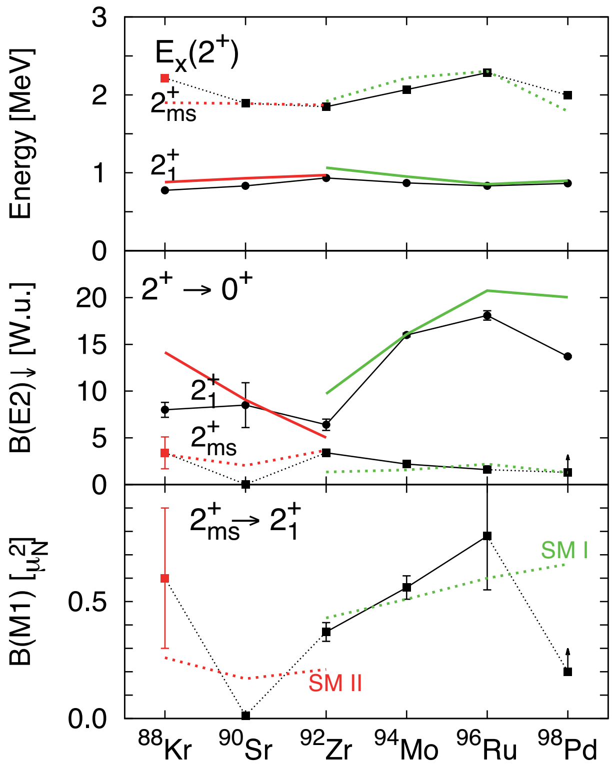

Figure 1: Excitation energies (a), $E2$ (b), and $M1$ transition strengths (c) from the 2^+_1 and 2^+_{ms} states in $N = 52$ isotones [7–14] together with the newly determined values for ^{88}Kr in red. Additionally shown are the results from shell model calculations using the SDI [15] (green lines) and from new calculations based on the work of Ref. [16] (red lines). Figure from Ref. [14].

F < F$_{max}$. Wave functions of such states contain at least one pair of proton and neutron bosons that is antisymmetric under the exchange of the proton and neutron labels. These states are called mixed-symmetry (MS) states. They are different from the low-lying collective states, which are symmetric with respect to the pairwise exchange of boson isospin labels.

According to the IBM approach the whole class of MS states is formed by quadrupole-collectivity. The building block of all MS excitations is, therefore, predicted to be the MS 2^+_{ms} state, which should occur in spherical nuclei as the lowest, one-phonon MS state on which collective multiphonon structures can be built. The existence of such a multiphonon structure with MS character was discovered in the nuclide ^{94}Mo [3–5] and can be explained by the F-spin symmetric O(6) limit of the IBM-2 [6]. Measurements on ^{94}Mo and other N = 52 isotones confirm [7–12, 14] the initial findings as a general phenomenon

The N = 52 isotones close to the Z = 38, 40 sub-shell closures correspond to sufficiently small valence spaces for a practical description in terms of the nuclear shell model. This fact offers the unique possibility to compare IBM to shell model calculations and thus to achieve a microscopic understanding of the building blocks of nuclear collectivity [15, 16]. Moreover, the evolution of MS states in N = 52 isotones can be tracked over different proton shells enabling us to investigate the variation of the proton-neutron interaction as a function of the nuclear valence space. It is of great interest to study the cases with the smallest possible number of valence particles which are already able to induce the collective features. There we can apply the shell model to understand the generating mechanism of collectivity, the role of the proton-neutron interaction, to explore the microscopic origin of the symmetries in the IBM and to test the limits of application of the IBM.

Unfortunately, the light N = 52 isotones below Z = 40 are unstable neutron-rich nuclei and, therefore, limited data on absolute transition rates exist. Absolute electromagnetic transition rates and magnetic moments for low-lying states are, however, necessary information in order to uniquely identify MS states and are, therefore, the prerequisites for the systematic understanding of the proton-neutron non-symmetric building blocks of nuclear collectivity. It is the aim of our proposal to study the quadrupole collectivity and to identify MS states in neutron rich N = 52 isotones by using multiple Coulomb excitation. It was demonstrated that the process of Coulomb excitation in inverse kinematics is very well suited also for the population of one-phonon MS states [7]. The multistep Coulomb excitation reaction in ^{88}Kr will populate in a very clean way the excited low-spin states and the B(E2; $0_1^+ \rightarrow 2_i^+$) and B(E2; $2_1^+ \rightarrow L_i^+$) transition strengths and large B(M1; $2_i^+ \rightarrow 2_1^+$) values can be deduced from the measured cross sections, angular distributions and branching ratios. These absolute transition strengths will then be used for comparison with shell model calculations based on a ^{78}Ni core and an extended model space $(1f_{5/2}, 2p_{1/2}, 2p_{3/2}, 1g_{9/2})$ for protons and $(2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2}, 1h_{11/2})$ for neutrons [16], the F-spin symmetric O(6) limit of the IBM-2 and semi-microscopic IBM-2 calculations based on self-consistent mean-field calculations using a microscopic Gogny energy-density functional [17]. As an example we compare the shell model predictions of reference [15] for nuclei above Z=40 and of reference [16] for nuclei below Z=40 in Fig. 1 with the available data.

It would be of considerable interest to compare these model predictions with more precise experimental data in ^{88}Kr that we will obtain using multiple Coulomb excitation at HIE-ISOLDE. They will allow us to obtain a microscopic understanding of the mixed symmetry states and their evolution with proton number.

Table 1: Deduced experimental transition strengths from the PreSPEC experiment [14] in comparison to model calculations in the O(6) limit of the IBM-2, semi-microscopic IBM-2 calculations based on self-consistent mean-field calculations [17] and shell model calculations based on a 78Ni core [16].

Transition	σL	$B(\sigma L)_{exp}$	$B(\sigma L)_{O(6)}$	$B(\sigma L)_{[17]}$	$B(\sigma L)_{[16]}$
$2_2^+ \rightarrow 0_{g.s.}^+$	$E2$	$\leq$ 1.3 W.u.	0 W.u.	0.2 W.u.	0.01 W.u.
$2_3^+ \rightarrow 0_{g.s.}^+$	$E2$	3.4(17) W.u.	0.8 W.u.	0.5 W.u.	3.23 W.u.
$2_3^+ \rightarrow 2_1^+$	$M1$	0.6(3) μ_N^2	0.30 μ_N^2	0.19 μ_N^2	0.26 μ_N^2

Using MINIBALL we were able to measure the B(E2; $2_1^+ \rightarrow 0_{g.s.}^+$) in ^{88}Kr at REX-ISOLDE [11]. But using low energy Coulomb excitation at a beam energy of 2.2 MeV/u the cross-section for the excitation of the MS state was a factor of 1700 smaller making that it was not possible to measure the B(E2) of the first 2_{ms}^+ state at REX-ISOLDE. More recently, we performed an experiment at GSI using the fast beam PreSPEC set-up with relativistic Coulomb excitation in which we excited the 2^+_3 state and were able to determine the absolute transition rates given in Table 1, albeit with large error bars and under the plausible assumption that the $2^+_3 \rightarrow 2^+_1$ transition is a pure M1 transition [14]. In the proposed experiment we want to confirm the M1 character and strongly reduce the error bars. At the same time we will be able to determine the collectivity of the symmetric low-spin states.

2 Experimental details and yield calculations

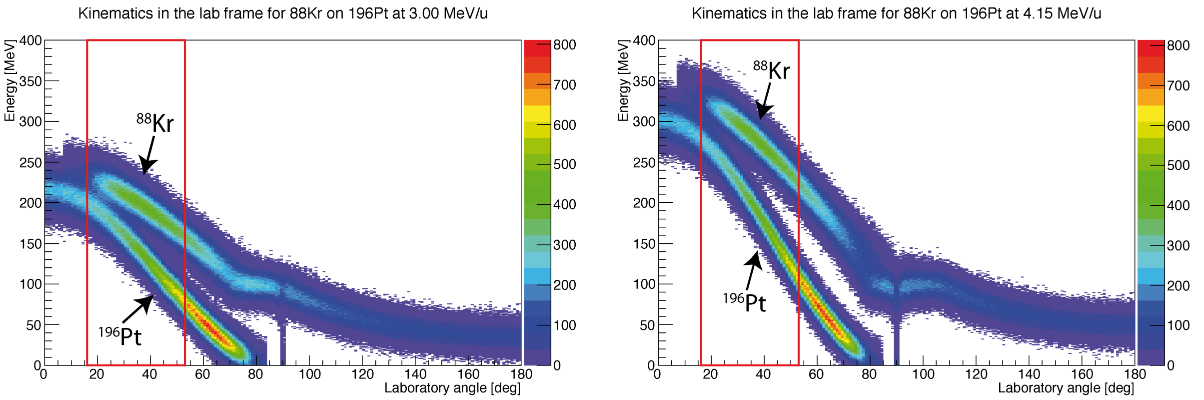

Figure 2: Reaction kinematics for the Coulomb excitation of ^{88}Kr on a 1mg/cm ^{2} ^{196}Pt target at 3.0 MeV/u and 4.15 MeV/u. The angular range covered by the CD detector is marked by the red frame.

The ISOLDE yield database states a production cross section of 1.0x10^9 ions per 1 μC proton beam from the PS Booster that is irradiating a 174.39 g/cm^2 PbBi target [18]. Assuming a primary beam current of 1 μA and a transmission efficiency to the secondary target of 1%, we expect a secondary beam intensity of 1.0x10^7 pps for ^{88}Kr.
For the detection of the scattered projectiles after the secondary reaction, we propose to use an annular (CD) double sided strip detector (DSSD) placed at forward angles covering an angular range from 16° to 53° in the laboratory frame. This converts to a range of about 20° to 74° in the center of mass frame for our chosen targets (see below). Selecting these angles, ensures that the ^{88}Kr nuclei will undergo safe Coulomb excitation at the chosen beam energies as well as good separation of scattered projectiles and target recoils in the DSSD (see figure 2).
De-exciting γ-radiation will be observed with the MINIBALL germanium detector array, which consists of 8 triple clusters of 6-fold segmented Ge detectors [19]. We assume a γ-ray detection efficiency of 6-8% for the transitions of interest in ^{88}Kr. We want to optimise the position of the detectors to be able to measure the multipolarity of the $2^+_3 \rightarrow 2^+_1$ transition. Based on the findings of Ref. [20], we propose a configuration of the MINIBALL array similar to that shown in Fig. 3 which improves the sensitivity to different angular distributions of the emitted γ-rays.

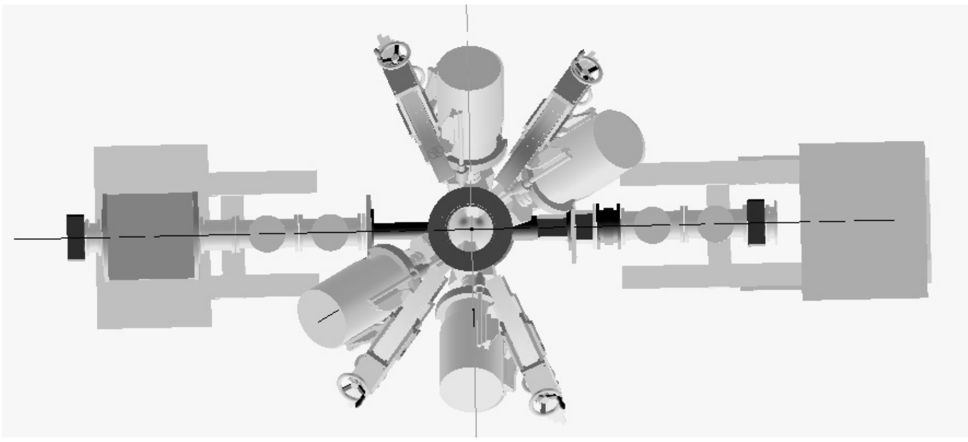

Figure 3: MINIBALL configuration optimised for the measurement of particle-γ angular correlations.

We used the code CLX [21] to calculate the Coulomb excitation cross sections for three energies on the high Z target ^{196}Pt (see table 2) assuming realistic transition matrix elements which we obtained from available experimental data in case of the $2_1^+ \rightarrow 0_1^+$ transition [12] and from shell model calculations based on a ^{78}Ni core and an extended model space $(1f_{5/2}, 2p_{1/2}, 2p_{3/2}, 1g_{9/2})$ for protons and $(2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2}, 1h_{11/2})$ for neutrons [16], where available. For the remaining transitions we calculated matrix elements using IBM-2 parameters based on self-consistent mean-field calculations using a microscopic Gogny energy-density functional [17].
An advantage of the ^{196}Pt target is the fact, that its well known lifetime of the first excited state would enable us to test the previously measured $2_1^+ \rightarrow 0_1^+$ transition strength in ^{88}Kr. This will be done using the lower energy of 3.0 MeV/u to minimise the multiple Coulomb excitation (see table 2) and help to disentangle the one and multi-step excitation process. The matrix elements of transitions to higher lying states could be determined relative to the latter in a clean way from the measurement with the ^{196}Pt target at 4.15 MeV/u.
Additionally, we calculated Coulomb excitation cross sections for the case that a beam energy of only 4.0 MeV/u is achievable at the time of our run. By changing the angular range of the CD detector to laboratory angles of 19° to 57° the yield for the $2_3^+ \rightarrow 2_1^+$ transition is moderately reduced by about 20% and still sufficiently high to reach our main goals.
The yield estimations for higher lying states shown in table 2 are not substantially reduced by shielding the inner two rings of the CD detector, which would limit the total count rate and help to prevent radiation damages.

Summary of requested shifts:
Based on our yield calculations we estimate that a total of **21 shifts** will be sufficient for the proposed goals. For our main goals, the determination of the Coulomb excitation yield to higher lying states including non-yrast states and the measurement of the multipolarity of the de-exciting transitions, we request **18 shifts** at 4.15 MeV/u. This would lead to about 10^4 counts for the $2_3^+ \rightarrow 2_1^+$ transitions in the total γ-ray spectrum. With an angular

Table 2: Expected γ-ray yields **per shift** for the transitions of interest in ^{88}Kr. The calculations were performed with the Coulomb excitation code CLX for 1 mg/cm^2 targets and the given angular ranges for the detection of scattered projectiles. The yields were also calculated for the case where the two innermost rings of the CD detector are shielded. In the calculations additional buffer states were used which are not substantially populated.

Target	E_{beam} [MeV/u]	Transition	E_γ [keV]	N_γ [Counts]	N_γ [Counts] CD partially shielded
^{196}Pt	3.00	$2_1^+ \to 0_1^+$	775.28	17360	16195
		$2_2^+ \to 0_1^+$	1577.41	0	0
	lab. ang.	$2_2^+ \to 2_1^+$	802.14	2	2
	16° - 53°	$4_1^+ \to 2_1^+$	868.4	10	10
		$\mathbf{2_3^+ \to 0_1^+}$	**2216.3**	**1**	**1**
		$\mathbf{2_3^+ \to 2_1^+}$	**1440.5**	**10**	**10**
^{196}Pt	4.15	$2_1^+ \to 0_1^+$	775.28	58159	50791
		$2_2^+ \to 0_1^+$	1577.41	8	8
	lab. ang.	$2_2^+ \to 2_1^+$	802.14	48	48
	16° - 53°	$4_1^+ \to 2_1^+$	868.4	193	193
		$\mathbf{2_3^+ \to 0_1^+}$	**2216.3**	**73**	**73**
		$\mathbf{2_3^+ \to 2_1^+}$	**1440.5**	**592**	**590**
^{196}Pt	4.0	$2_1^+ \to 0_1^+$	775.28	55314	46656
		$2_2^+ \to 0_1^+$	1577.41	8	8
	lab. ang.	$2_2^+ \to 2_1^+$	802.14	45	44
	19° - 57°	$4_1^+ \to 2_1^+$	868.4	187	183
		$\mathbf{2_3^+ \to 0_1^+}$	**2216.3**	**60**	**57**
		$\mathbf{2_3^+ \to 2_1^+}$	**1440.5**	**481**	**464**

binning of 15° this translates into an relative uncertainty of about 5% for each datapoint in its angular distribution. Further we request **3 shifts** for the re-measurement of the $B(E2, 0_1^+ \to 2_1^+)$ which will be used for normalisation of the other transition strengths at 3.0 MeV/u.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: MINIBALL + only CD

Part of the	Availability	Design and manufacturing
MINIBALL + only CD	☒ Existing	☒ To be used without any modification
MINIBALL	☐ 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
CD	☐ 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

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed MINIBALL + only CD installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of 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 (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
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]		

Hazard identification:

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]: ... kW