High-Spin Lifetime Measurements in the N=Z Nucleus ^{72}Kr

C. Andreoiu,[1,2] C.E. Svensson,[1] R.A.E. Austin,[3,*] M.P. Carpenter,[4] D. Dashdorj,[5] P. Finlay,[1] S.J. Freeman,[4] P.E. Garrett,[6,†] J. Greene,[4] G.F. Grinyer,[1] A. Görgen,[7] B. Hyland,[1] D. Jenkins,[8] F. Johnston-Theasby,[8] P. Joshi,[8] A.O. Machiavelli,[9] F. Moore,[4] G. Mukherjee,[4] A.A. Phillips,[1] W. Reviol,[10] D.G. Sarantites,[10] M.A. Schumaker,[1] D. Seweryniak,[4] M.B. Smith[11], J.J. Valiente-Dobón,[1,‡] R. Wadsworth,[8] and D. Ward[9]

[1]*Department of Physics, University of Guelph, Guelph, ON, Canada N1G 2W1*
[2]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 3BX, UK*
[3]*McMaster University, Hamilton, Ontario L8S 4K1, Canada*
[4]*Physics Division, Argonne National Laboratory, Argonne, IL 60436*
[5]*North Carolina State University, Raleigh, NC 27695*
[6]*Lawrence Livermoore National Laboratory, Livermoore, CA 94551*
[7]*CEA Saclay, Daphnia/SphN, 91191 Gif-sur-Yvette Cedex, France*
[8]*Department of Physics, University of York, Heslington, York YO105DD, UK*
[9]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[10]*Department of Chemistry, Washington University, St. Louis, MO 63130*
[11]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada V6T 2A3*

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High-spin states in the $N = Z$ nucleus ^{72}Kr have been populated in the ^{40}Ca(^{40}Ca,2α)^{72}Kr fusion-evaporation reaction at a beam energy of 165 MeV and using a thin isotopically enriched ^{40}Ca target. The experiment, performed at Argonne National Laboratory, USA, employed the Gammasphere array for γ-ray detection coupled to the Microball array for charged particle detection. The previously observed bands in ^{72}Kr were extended to higher excitation energy of ∼24 MeV and higher angular momentum of 30$\hbar$. Using the Doppler shift attenuation method the lifetimes of high-spin states were measured for the first time in order to investigate possible deformation changes associated with the $g_{9/2}$ proton and neutron alignments in this $N = Z$ nucleus. Excellent agreement with theoretical calculations including only standard $t = 1$ np pairing was observed.

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I. INTRODUCTION

$N = Z$ nuclei are of particular interest regarding np correlations which are expected to be significant in these nuclei due to the large spacial overlap of proton- and neutron-wavefunctions. These correlations can have either an isoscalar or an isovector character, and in principle might form a static pair condensate in either channel. Experimental evidence from pair-transfer reactions [1] and binding energy systematics [2, 3] establish an isovector ($t = 1$) pair field in $N \approx Z$ nuclei with a magnitude consistent with that expected from the systematics of $t = 1$ nn and pp pair gaps throughout the chart of the nuclides. For the $T = 0$ states of the $N = Z$ nuclei, isospin symmetry requires the contribution from $t = 1$ np pairing to be equal to those from nn and pp pairing [4]. The situation concerning the role of $t = 0$ np interaction in $N = Z$ nuclei is less clear. The ground-state binding energy systematics leave little room for a collective $t = 0$ pair gap [3]; a result understood in terms of the disruptive influence of the spin-orbit splitting on $t = 0$ np pairing [5, 6], and consistent with the analysis [7] of pairing vibrations around ^{56}Ni which indicates that the effective $t = 0$ pairing strength represents only a small fraction (∼0.2) of the critical value required for condensate formation. These analyses do not, however, rule out the possibility that the state-dependent $t = 0$ np interactions might have important effects on the properties of $N \approx Z$ nuclei. In particular, such interactions may influence the pattern of rotation alignments associated with the breaking of $t = 1$ pairs.

Previous studies of $N = Z$ nuclei from ^{72}Kr to ^{80}Zr [8, 9] have indicated delays in the rotational alignments of $g_{9/2}$ protons and neutrons relative to their $N \neq Z$ neighbours, with ^{72}Kr appearing to show the largest effect. More recent experimental work in ^{72}Kr [10] and theoretical calculations [11] show that the delay is not as large as originally thought. A similar phenomenon, involving $g_{9/2}$ particles, appears to occur in the yrast superdeformed (SD) band of the $N = Z$ nucleus ^{60}Zn [12], where the simultaneous proton and neutron $g_{9/2}$ alignment occurs at higher rotational frequency than the neutron alignment in the yrast SD band in ^{59}Cu [13] or the proton alignment in the yrast SD band of ^{61}Zn [14]. Numerous attempts to interpret these results in terms of np interactions have been presented, with a clear understanding yet to emerge. For example, a delay in the alignment frequency in $N = Z$ nuclei relative to their

* Present address: Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada
† Present address: Department of Physics, University of Guelph, Guelph, ON, Canada N1G 2W1
‡ Present address: INFN, Laboratori Nazionali di Legnaro, I-35020, Legnaro, Italy

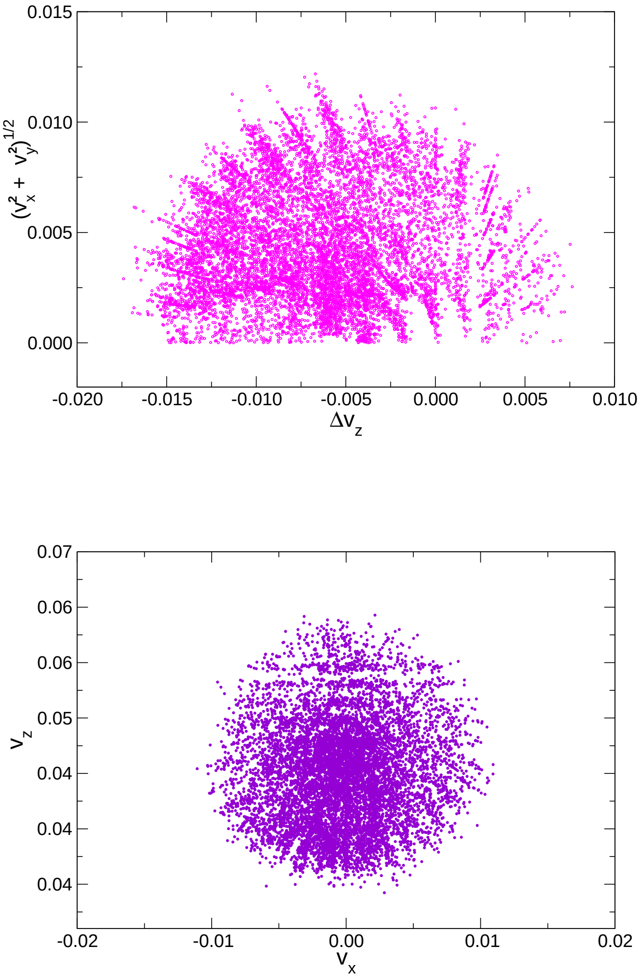

FIG. 1: Upper panel shows the boost given to the recoil by the particle evaporation perpendicular to the beam (z) axis in the center-of-mass frame. Lower panel shows the initial velocity of the ^{72}Kr recoils in the $v_x - v_z$ plane in the 2α-gated data set, as reconstructed from the measured alpha-particle momenta.

neighbours was found in the calculations of Ref. [15] employing a full $t = 1$ and $t = 0$ δ-interaction between high-j protons and neutrons in the presence of a deformed, rotating mean-field potential. This delay was ascribed to the $t = 1$ component of the δ-interaction, although the mechanism at work was not clear. Reference [16], on the other hand, predicts a transition from $t = 1$ to $t = 0$ pairing with increasing angular momentum in the case of ^{80}Zr. By increasing the np pairing strength by 30% relative to the pp and nn strengths, the calculations of Ref. [17] provide an acceptable reproduction of the data for $N = Z$ nuclei reported in Ref. [8], albeit at the admitted expense of the agreement with the $N \neq Z$ cases. Clearly, additional experimental data related to rotational alignments in $N \approx Z$ nuclei, including lifetime measurements to constrain the deformation degree of freedom in theoretical models, is essential to unravel the respective role of isovector and isoscalar residual interaction in the structure of these nuclei.

II. EXPERIMENT

The experiment, performed at Argonne National Laboratory, employed the ^{40}Ca(^{40}Ca,2α)^{72}Kr fusion-evaporation reaction at a beam energy of 165 MeV. The 0.350 mg/cm^2 thin isotopically enriched ^{40}Ca target was sandwiched between two thin layers of Au to prevent oxidation. The experimental set-up consisted of the Gammasphere array [18] at the time comprising 99 Compton-suppressed HPGe detectors in combination with the 95-element CsI(Tl) Microball detector [19]. The event trigger required the detection of at least four Compton suppresed γ rays. To provide γ-ray multiplicity and sum-energy measurements [20], and additional selectivity by total energy conservation requirements [21] the Hevimet collimators were removed from the Gammasphere detectors. Based on the charged-particle energies and directions detected in Microball, the momenta of the recoiling residual nuclei were determined for each event, allowing for a more accurate Doppler-shift correction of the γ-ray energies, leading to a significantly improved energy resolution. The events were sorted off-line into various E_γ projections, E_γ-E_γ matrices, and E_γ-E_γ-E_γ cubes by selecting events in which 2α particles corresponding to ^{72}Kr were detected in the Microball. The events belonging to the 2α1p channel populating ^{71}Br were carefully suppressed from this data set by the total energy conservation requirements. The analysis employed the Radware software package [22] and the spectrum-analysis code Tv [23].

The main focus of this work was the lifetimes of high-spins states determined using the centroid-shift Doppler shift attenuation method [24]. The states at the top of the rotational bands have lifetimes of the order of tens of femtoseconds, thus they decay while the recoils are slowing down in the thin ^{40}Ca target. A Doppler correction is applied to the events with a recoil velocity β_0 corresponding to the velocity of the ^{72}Kr recoil at the time of formation as deduced on an event-by-event basis from the measured evaporated charged particles. As a result, the peaks are slightly shifted in the γ-ray spectra of the Germanium detectors at forward and backward angles. From the shift measurement the mean velocity, β_t, at the time when the transition was emitted is obtained. The fractional Doppler shift defined as $F(\tau) = \beta_t/\beta_0$ for each transition is experimentally obtained and plotted as a function of angular momentum. These $F(\tau)$ values are fit to extract the best transitional quadrupole moment Q_t for each band. The program takes into account the initial momenta of the ^{72}Kr recoil and a velocity history of the recoils including their directions in time steps of 0.05 fs. The beam and recoil stopping power in the target were simulated using the SRIM-2003 code Ref. [25]. The upper panel in Fig. 1 shows the boost given to the recoil by the 2α particle evaporation perpendicular to the beam axis, z, in the center-of-mass frame. The lower panel in Fig. 1 shows the initial velocity in the $v_x - v_z$ plane of the ^{72}Kr recoils in the 2α-gated data set, as reconstructed from the measured energies and directions of the detected alpha particles. These effects were accounted for in the off-line analysis. Additional experimental details can be found in Refs. [26, 27].

III. RESULTS

Previously high-spin states in ^{72}Kr were known up to an angular momentum of $28\hbar$ [10]. Figure 2 shows the level scheme of ^{72}Kr obtained from the present experiment. The level scheme was extended up to excitation energy of ∼24 MeV and an angular momentum of $30\hbar$. Figure 3 shows 2α-gated γ ray spectra generated by summing coincidence gates set on in-band transitions. At low energies, in panels (a) and (b) of Fig. 3 the transitions belonging to the ground state band up to the 14^+ state are shown at 710, 612, 792, 996, 1186, 1356, and 1510 keV. In the upper panel, the transition belonging to band 2 at 1665, 1741, 1832, 1917 keV are shown. In addition, a linking transition to band 4 at 1816 keV was observed. The inset in the upper panel of Fig. 3 shows the high energy transitions in band 2 at 2038 keV and 2143 keV, and two newly identified transitions at 2440 and 2706 keV, extending the band to an excitation energy of 23.64 MeV and an angular momentum of $30\hbar$. The middle panel of Fig. 3 shows the transitions belonging to band 4 at 1586, 1021, 1467, 1949 keV. The transitions at 1241 and 1368 keV, which are placed on a parallel branch with band 2 are also shown. The inset in the middle panel of Fig. 3 shows the transition at 2468 keV, confirms the transition at 3059 keV and the linking transition between band 2 and 4 at 2836 keV, and tentatively continues band 2 with a transition at 3717 keV, extending the band to an excitation energy of 22.43 MeV and an angular momentum of $28\hbar$. The lower panel of Fig. 3 shows the transitions in the side band at 960, 1292, 1116, 1435, 1447, 1497, 1600, and 1778 keV, and the linking transitions into the ground state band at 1653 and 1685 keV. The inset in the lower panel shows the transition at 2062 keV, and two newly identified transitions at 2515 and 3068 keV, extending the band to an excitation energy of 22.57 MeV. Although intensively searched for, no other linking transitions between the bands were found.

The main focus of this work was the lifetimes of high-spins states determined using the centroid-shift Doppler shift attenuation method [24]. Previous to this study no lifetimes of high-spin states were known. The experimental $F(\tau)$ values of band 2 and 4 and the side band, as a function of angular momentum are shown in Figs. 4(a), (b) and (c), respectively. In order to extract a quadrupole moment from these measurements, the decay of the band was modeled assuming a constant in-band Q_t and the

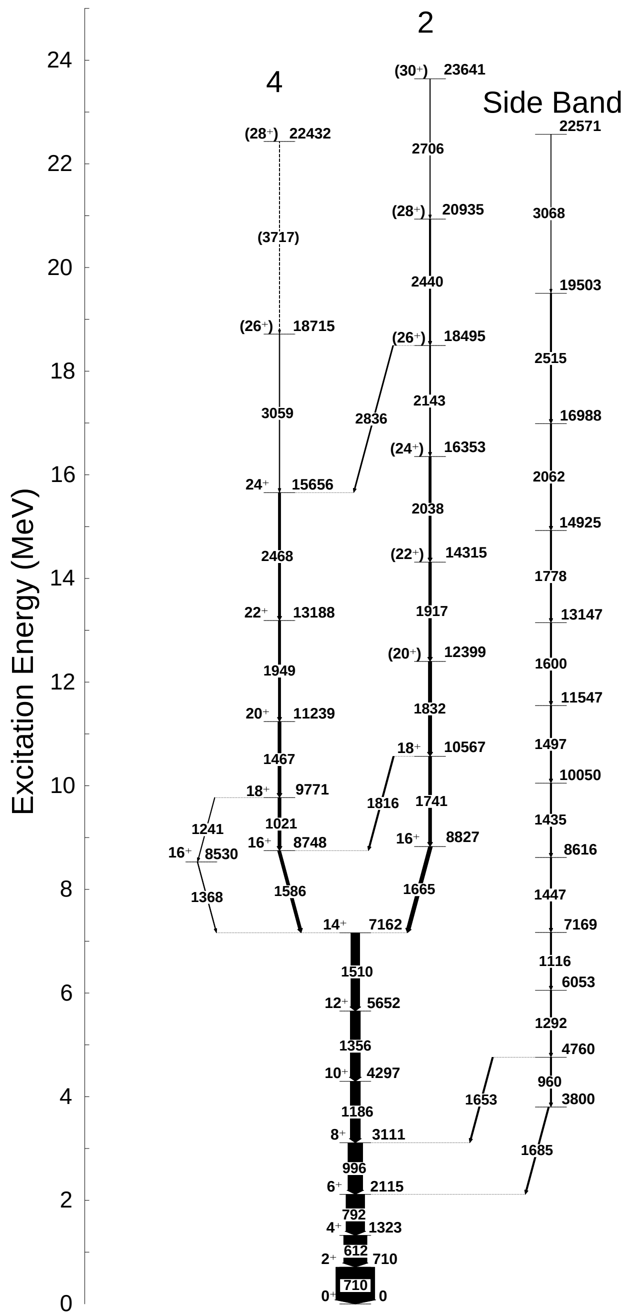

FIG. 2: Proposed high-spin level scheme of ^{72}Kr from the present experiment. Energy labels are in keV. The widths of the arrows are proportional to the relative intensities of the γ rays. Tentative transitions are dashed.

feeding of the band and the slowing down of the recoils in the target were treated as in Ref. [28]. The best fit to the data is obtained with $Q_t = 2.87(^{23}_{19})\ eb$ for band 2, $Q_t = 2.06(^{44}_{33})\ eb$ for band 4, and $Q_t = 2.39(^{24}_{31})\ eb$ for the side band. The uncertainties in the quadrupole moments do not include the systematic uncertainties due to the stopping power, which are typically 10%. It is clear

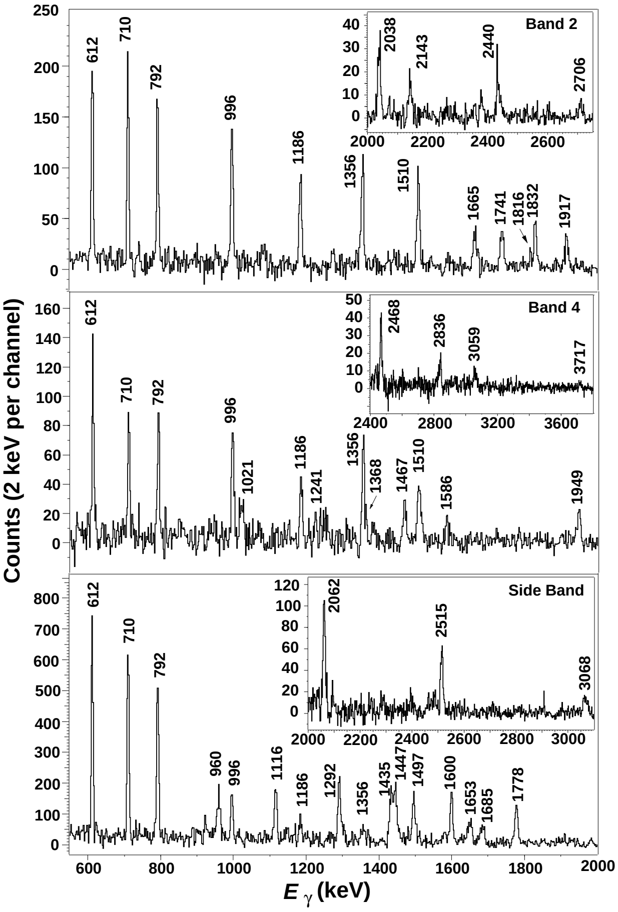

FIG. 3: 2α-gated γ-ray spectra generated by summing coincidence gates set on in-band transitions in band 2 (upper panel), band 4 (middle panel), and side band (lower panel). The insets show the higher energy transitions in each band.

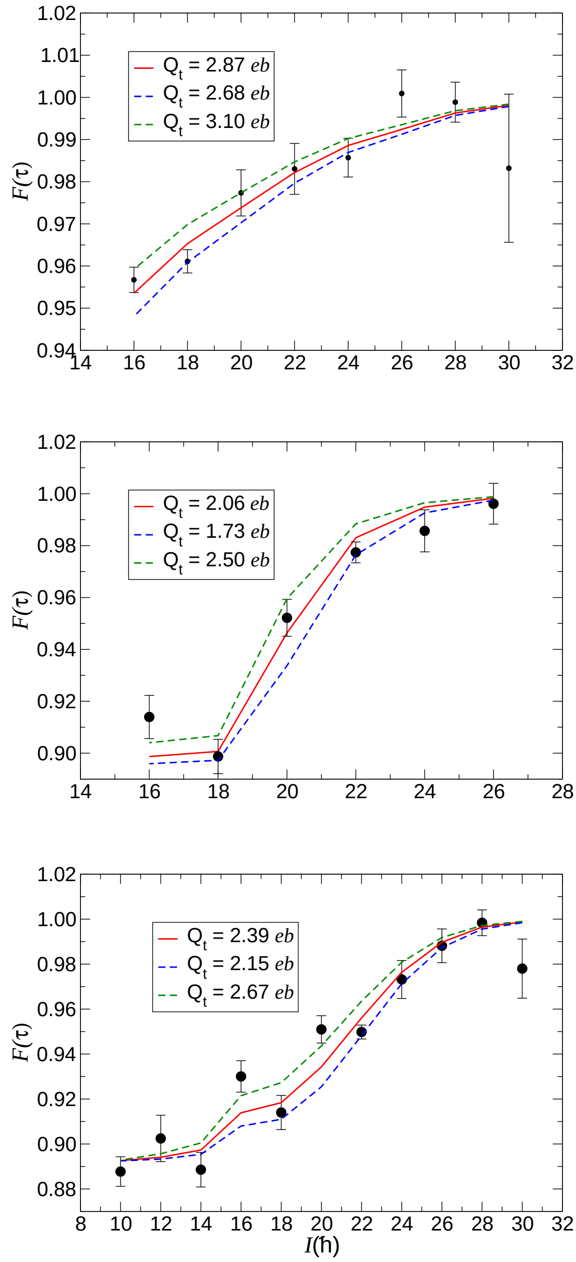

FIG. 4: Experimental $F(\tau)$ values (symbols) and transition quadrupole moments, Q_t (lines), for band 2, 4, and side band as a function of angular momentum are shown in (a), (b), and (c), respectively. The middle curves show the best fit to the experimental data and correspond to an average quadrupole moment of 2.87 eb for band 2, 2.06 eb for band 4, and 2.39 eb for the side band, respectively.

from the results that band 2 has a higher Q_t than band 4. With the current experimental uncertainties on the $F(\tau)$ measurements investigations with variable Q_t's do not provide a significantly better description of the bands.

IV. DISCUSSION

Theoretical calculations for ^{72}Kr have been performed with Cranked Nilsson Strutinsky (CNS), the cranked relativistic mean field (CRMF) and the cranked relativistic Hartree-Bogoliubov (CRHB) [11]. At high spins the pair correlations are neglected in the CRMF and the CNS calculations. The D1S Gogny force and the Lipkin-Nogami (LN) method for particle number projection have been used in conjunction with the CRHB theory. In the CNS calculations, the bands are labelled by the number of $g_{9/2}$ protons and neutrons, as [p,n]. In Ref. [11] band 4 was assigned to the [2,2] configuration (i.e the double S-band). Band 2 was assigned to the [3,3] configuration, with two possible signatures [3,3]a and [3,3]b, obtained by exciting a proton and a neutron from the $\mathcal{N} = 3$ $\alpha = + - 1$ orbitals into the second $g_{9/2}$ $\alpha = +1/2$ orbital. Figure 5(a) shows the experimental excitation energies relative to a rigid rotor versus angular momentum for band 2 and 4

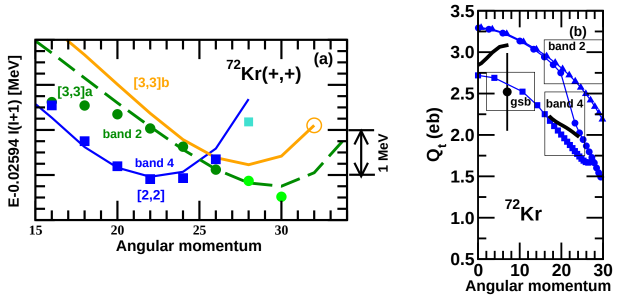

FIG. 5: (a) Lowest configurations calculated within the CNS model (lines) and experimental values (symbols), given relative to a rigid rotor. (b) Transition quadrupole moments as a function of angular momentum. The data point at $I = 8\hbar$ is from Ref. [29], while boxes represent the measured transition quadrupole moments and their uncertainties within the measured spin range from the present work. The CRMF calculations are shown by filled symbols connected by lines and the CRHB calculations using the Lipkin-Nogami method for particle number projection are shown by thick lines. See Ref. [11] and text for details.

(filled symbols) and the CNS calculations (lines). The CRMF calculations are very similar and for this reason are not shown here. There is excellent agreement between the experimental data and the theoretical calculations, especially in the unpaired regime for $I > 20\hbar$. Figure 5(b) shows the experimental and calculated transition quadrupole moments as a function of angular momentum. The data point at $I = 8\hbar$ is obtained from a previous experiment using conventional Doppler shift attenuation techniques [29]. The boxes show the measured transition quadrupole moments and their uncertainties within the measured spin range obtained from the present experiment. They are in good agreement with both the CRMF (filled symbols connected by lines) and CRHB + LN calculations (thick lines). These agreements, in terms of both energies and quadrupole moments provide firm assignments for band 4 and band 2 to the [2,2] and [3,3] configurations, respectively. It should also be noted that the good agreement between experiment and theory is achieved with only the standard $t = 1$ pair field.

V. SUMMARY

An experiment to populate high-spin states in the $N = Z$ nucleus ^{72}Kr was performed with Gammasphere and Microball. The level scheme was extended up to an excitation energy of ~24 MeV and an angular momentum of $30\hbar$. The lifetimes of high-spin states were measured for the first time using the DSAM method and transitional quadrupole moments for each band were determined. The experiment is in good agreement with theoretical calculations (CRHB + LN) involving standard $t = 1$ pairing [11].

VI. ACKNOWLEDGEMENTS

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