Proton-Neutron Pairing Correlations in the Self-Conjugate Nucleus ^{38}K Probed via a Direct Measurement of the Isomer Shift

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A marked difference in the nuclear charge radius was observed between the $I^\pi = 3^+$ ground state and the $I^\pi = 0^+$ isomer of ^{38}K and is qualitatively explained using an intuitive picture of proton-neutron pairing. In a high-precision measurement of the isomer shift using bunched-beam collinear laser spectroscopy at CERN-ISOLDE, a change in the mean-square charge radius of $\langle r_c^2\rangle(^{38}\mathrm{K}^m) - \langle r_c^2\rangle(^{38}\mathrm{K}^g) = 0.100(6)$ fm^2 was obtained. This is an order of magnitude more accurate than the result of a previous indirect measurement from which it was concluded that both long-lived states in ^{38}K have similar charge radii. Our observation leads to a substantially different understanding since the difference in charge radius is, moreover, opposite in sign to previously reported theoretical predictions. It is demonstrated that the observed isomer shift can be reproduced by large-scale shell-model calculations including proton and neutron excitations across the $N, Z = 20$ shell gaps, confirming the significance of cross-shell correlations in the region of ^{40}Ca.

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Since the early days of nuclear physics, it has been known that protons and neutrons favor the formation of $I = 0$ pairs with antialigned spins. In 1935, the first parametrization of the Bethe-Weizsäcker mass formula [1] included a term that took $\pi\pi$ and $\nu\nu$ pairs into account by enhancing the binding in even-even nuclei. Only one year later an analysis of nucleon-nucleon scattering data demonstrated that, within experimental errors, the strong interaction between nucleons can be considered charge independent [2]. This discovery led directly to the application [3] of Heisenberg's concept of "isotopic spin" (isospin) to finite nuclei. As a direct consequence, $\pi\nu$ pairs with $T = 1, T_z = 0$ should be treated on an equal footing to the $T = 1$ $\pi\pi$ and $\nu\nu$ pairs with $T_z = +1, -1$, respectively. While this charge independent treatment of isovector pairing remains a standard feature of modern shell model calculations and is under development in mean-field approaches [4,5], the experimental investigation of the $\pi\nu$ pairing interaction remains an active area of interest [6,7]. Specifically, theoretical debate [8–11] on the role of $\pi\nu$ pairing in the microscopic origins of the nuclear symmetry energy has wide ranging consequences not only for nuclear structure, but also nuclear astrophysics [12–14]. Consequently, an experimental constraint on the strength of isovector pairing correlations is vital. Here, we demonstrate that, when $\pi\nu$ pairing correlations are considered on an equal footing to $\pi\pi$ and $\nu\nu$ correlations, then the increase in mean square charge radius of $^{38}\mathrm{K}^m$ can be successfully described. Furthermore, the isomer shift is shown to provide a highly sensitive test of the strength of isovector pairing employed in modern nuclear structure calculations.

The setup for collinear laser spectroscopy [15], located at CERN-ISOLDE, was used to obtain the hyperfine spectra (hfs) of $^{38,39,42,44,46-51}$K isotopes. During the experiment, protons bombarded a UC_x target producing a wide range of radioactive nuclei. The ions of interest were cooled and bunched in a helium filled radio-frequency quadrupole ISCOOL [16] after mass separation by the high-resolution mass separator. These ions were then neutralized in a potassium-filled charge exchange cell (CEC) located in front of the detection region and resonant excitation of the $4s^2S_{1/2} \rightarrow 4p^2P_{1/2}$ atomic transition was obtained using a cw Ti:sapphire laser. With the laser frequency kept constant, Doppler tuning of the ions was performed by applying an additional voltage to the CEC. The background from scattered light was reduced by only accepting signals

from the detectors (four photomultiplier tubes) when bunches of K atoms arrived in the detection region. More detailed descriptions of the experimental setup may be found in Papuga *et al.* [17] and Kreim *et al.* [18] reporting, respectively, on spins and magnetic moments of ^{49,51}K and charge radii of the K isotopes between $N = 27$ and $N = 32$.

Here, we focus only on the discussion of the isomer shift between the two observed states in ^{38}K. As the mass difference between the two states is small, systematic uncertainties on the kinematic shift arising from an imperfect knowledge of the ion beam energy [19] are negligible. An example frequency spectrum containing both the ground state and isomer of ^{38}K is presented in Fig. 1. Simultaneous fitting of the four ^{38}K^g hfs components and the single ^{38}K^m component was performed using a χ^2 minimization procedure. The fitting employed asymmetric line shapes associated with collisional ion energy loss [20] and the relative positions of the ^{38}K^g components to the hfs centroid were constrained by the usual relations [21].

The difference in hyperfine structure centroid of two isotopes or nuclear states $\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}$ may be related to the difference in mean square charge radii $\delta\langle r_c^2\rangle^{A,A'} = \langle r_c^2\rangle^{A'} - \langle r_c^2\rangle^{A}$ via

$$\delta\langle r_c^2\rangle^{A,A'} = \frac{1}{F}\left(\delta\nu^{A,A'} - \mathrm{K_{MS}}\frac{m_{A'} - m_A}{m_{A'}m_A}\right), \qquad (1)$$

where m_A and $m_{A'}$ are the masses of relevant isotopes or nuclear states taken from Wang *et al.* [22]. $\mathrm{K_{MS}}$ is the total mass shift factor given by the sum $\mathrm{K_{MS}} = \mathrm{K_{SMS}} + \mathrm{K_{NMS}}$, in which the specific mass shift $\mathrm{K_{SMS}} = -15.4(38)$ GHz u from Martensson-Pendrill *et al.* [23] and the normal mass shift $\mathrm{K_{NMS}} = \nu^A m_e = 213.55$ GHz u. The electronic factor $F = -110(3)$ MHz fm^{-2} was also taken from Ref. [23].

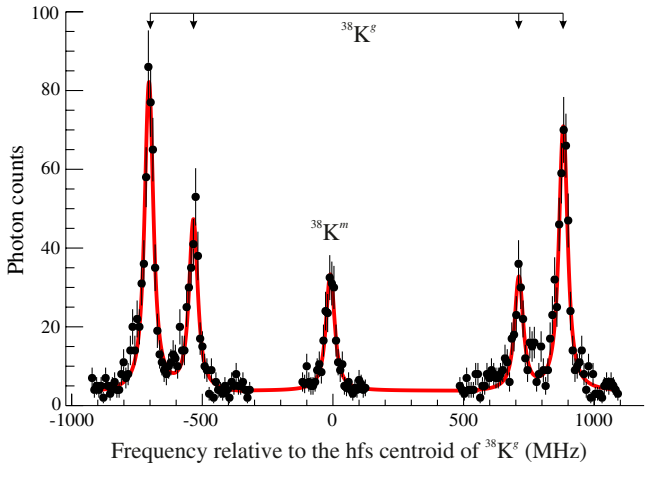

FIG. 1 (color online). Observed hyperfine spectra of ^{38}K^{g,m}. Four peaks are obtained for $I = 3$ (ground state) and only one for $I = 0$ (isomer).

Behr *et al.* [24] measured the isotope shift $\delta\nu^{38m,39}$ and combined this with $\delta\nu^{38g,39}$ measured by Touchard *et al.* [25]. From this approach, they found that, within errors, the ground and isomeric state had the same charge radii. In Table I, excellent agreement can be seen between the ^{38m,39}K isotope shift measured in this work and that of Behr *et al.* and agreement within errors between our ^{38g,39}K isotope shift and that of Touchard *et al.* It is only possible to conclude that the cumulative effect of the relatively large uncertainties in [24] and [25] led to the conclusion that the ground state and isomer are of the same size. Here the advantages of performing a direct isomer shift measurement are most clearly visible.

The authors of [24] also performed a detailed calculation of the difference in charge radius of the two states. Their Hartree-Fock calculation constrained by shell model orbital occupancies concluded that the ground state should be larger than the isomer by 0.014 fm^2. This evaluation clearly contradicts the measurement reported in this work in both magnitude and sign.

To develop an understanding of the origins of the difference in size of these two nuclear states, we begin by comparing with the $\delta\langle r_c^2\rangle^{38g,A'}$ of neighboring nuclei in Fig. 2. Clearly, the increase in size of the isomeric state is larger than the normal ground-state odd-even staggering by about a factor of 2. An alternative view of this effect can be obtained by plotting the differences in charge radii as a function of A along the line of $N = Z$. The results of this process are shown in Fig. 3. Here, it is seen that the larger charge radius of the isomer is consistent with a smooth increase in size along the $N = Z$ line, while the ground state is somewhat smaller than the average of its two neighbors.

To interpret these observations, one may begin by considering the origins of the ubiquitous normal odd-even staggering (OES) in nuclear charge radii [27–29]. This phenomenon may be readily explained by considering $\pi\pi$ or $\nu\nu$ $I = 0$ pairs scattering to a large number of states near the Fermi surface in the even N or Z nuclei. The addition of an odd proton or neutron "blocks" a specific orbit, thus,

TABLE I. Isomer and isotope shifts determined in this work compared with literature values. The second uncertainty contained within the square brackets corresponds to the systematic contribution associated with the atomic parameters $\mathrm{K_{SMS}}$ and F.

A'	A	$\delta\nu^{A,A'}$ (MHz)	$\delta\langle r_c^2\rangle^{A,A'}$ (fm^2)	Reference
38 g	39	−123.4(10)	−0.089(9)[23]	This work
		−127.0(53)	−0.057(48)[23]	[25]
38 m	39	−134.5(11)	0.011(10)[23]	This work
		−132(3)	−0.02(3)[2][a]	[24]
38 m	38 g	−11.03(56)	0.100(5)[3]	This work
		−4(6)	0.04(6)	[24,25]

[a]Measured in the $4s^2S_{1/2} \rightarrow 4p^2P_{3/2}$ transition assuming the same F and $\mathrm{K_{SMS}}$ as in the $4s^2S_{1/2} \rightarrow 4p^2P_{1/2}$ transition.

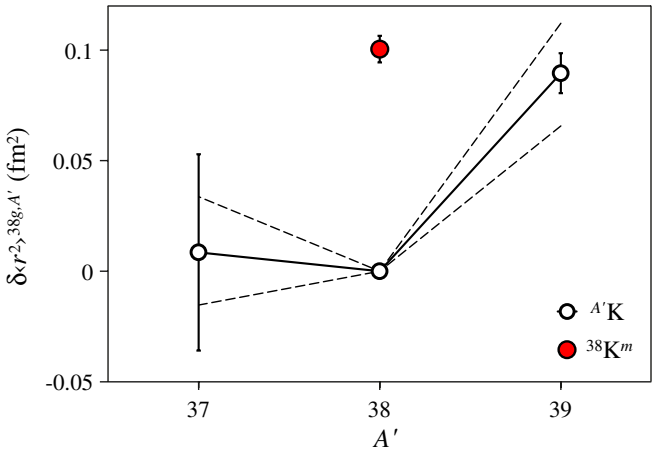

FIG. 2 (color online). Changes in mean square charge radius referenced to ^{38}K. The systematic uncertainty related to the atomic specific mass shift is represented by the two dotted lines. Datum for ^{37}K taken from [24].

reducing the scattering of pairs. As less bound orbitals naturally have a larger spacial extent, $\langle r_c^2 \rangle$ of odd N or Z nuclei are consistently found to be smaller than the average of their even neighbors. In the case of isotopic OES, an increase in neutron orbital correlations translates into a change in charge radius either by a global broadening of the proton distribution in mean-field calculations or via a direct enhancement of the scattering of valence $\pi\pi$ pairs. Although such pairing arguments are typically employed when considering pairs of protons or neutrons, charge independence of the nucleon-nucleon interaction effectively results in the possibility of $\pi\nu$ pairing correlations. Indeed, in ^{38}K, it would appear that, for the $T = 1$ isomer, the $\pi\nu$ pair coupled to $I = 0$ is free to scatter into a range of orbitals. Conversely, the $\pi\nu$ pair making up the $T = 0$, $I^\pi = 3^+$ ground state is heavily restricted in the number of states with which it can mix, significantly reducing the proton occupancy in the fp shell.

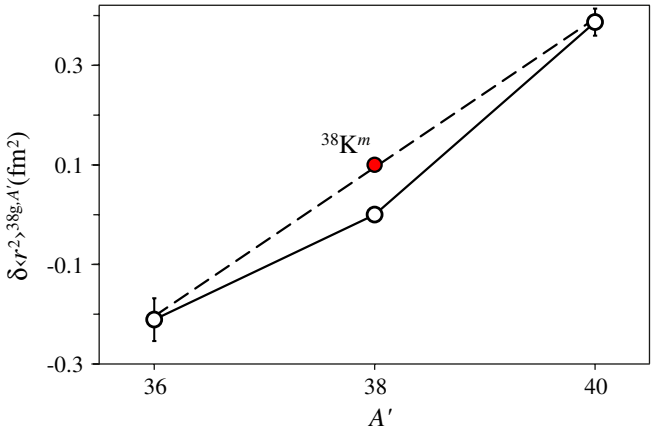

FIG. 3 (color online). Changes in mean square charge radii between the self-conjugate nuclei ^{36}Ar, ^{38}K, and ^{40}Ca from this work and [26].

In this blocking picture, it is readily apparent that the isomer shift should be larger than the normal isotopic OES. As the even $N^{37,39}$K isotopes have proton distributions which remain blocked by the single $\pi d_{3/2}^{-1}$, the scale of the OES remains somewhat smaller than in the neighboring even Z isotopic chains. The formation of an $I = 0$ $\pi\nu$ pair in ^{38}K^m effectively removes this blocking, thus, enhancing the πfp occupancy. Under the assumption of charge independence, this $\pi\nu$ pair should be free to scatter on an equal basis to $\pi\pi$, $\nu\nu$ pairs removing the OES along the line of $N = Z$. Precisely this behavior is observed in the experimental $\delta\langle r_c^2 \rangle^{A,A'}$ presented in Fig. 3.

As the observed radii differences can be understood with a simple intuitive model, it remains to investigate how the previous detailed theoretical calculation failed to predict both the sign and magnitude of the isomer shift. It was shown by Caurier *et al.* [28] that the isotope shifts in Ca could be reproduced with a reasonable accuracy if one calculates the occupancy of the πfp shell as a function of A. In this work, the expression

$$\delta\langle r_c^2 \rangle^{A,A'} = \frac{1}{Z} \Delta n_{fp}^{\pi}(A, A') b^2, \tag{2}$$

was used, where b is the oscillator parameter and n_{fp}^{π} refers to the number of protons lifted across the $Z = 20$ shell closure. The choice of oscillator parameter b remains a subject of much interest. While a number of approaches exist within the literature [30–33], it should be noted that all produce values of b within a few percent of each other. In the following, we assume $b^2(^{38}\mathrm{K}) = 3.944$ fm^2 as determined by the equation of Duflo and Zuker [32]. With this value and Eq. (2), it is immediately obvious that, for a successful reproduction of the isomer shift, one would require the isomer to have an average πfp orbital occupancy, n_{fp}^{π}, of the order of 0.48 protons larger than the corresponding ground state occupancy.

To test the validity of this conclusion, shell model calculations were performed in the model space comprising $1s_{1/2}, 1d_{3/2}, 0f_{7/2}, 1p_{3/2}$ orbitals for neutrons and protons, with the ZBM2 interaction from Ref. [28]. Full space diagonalization in this model space has been achieved using the shell model code ANTOINE [34]. The results of the calculations are reported in Table II, where the summed

TABLE II. Proton occupancies of the $f_{7/2}p_{3/2}$ orbitals, and the difference in charge radii between 0^+ isomer and 3^+ ground state, calculated within the shell model. See text for details.

	$n_{fp}^{\pi}(38m)$	$n_{fp}^{\pi}(38g)$	$\delta\langle r_c^2 \rangle^{38g,38m}$ (fm^2)
ZBM2	0.86	0.50	0.075
ZBM2 modified	0.82	0.41	0.085
Experiment			0.100(6)

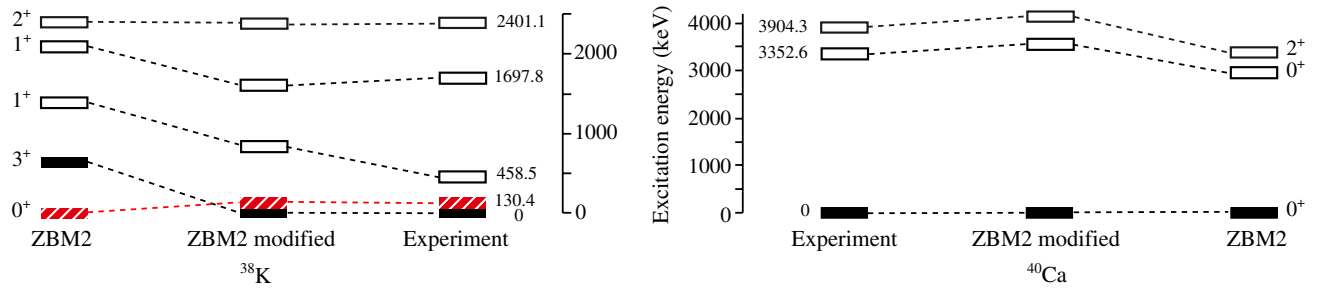

FIG. 4 (color online). Low energy excitation spectra of ^{38}K (left) and ^{40}Ca (right) calculated with the ZBM2 interaction before and after modification of the $V^{0,1}_{d_{3/2},d_{3/2}}$ centroids (see text for details).

pf-shell proton occupancies are listed for ground and isomeric states along with the corresponding $\delta\langle r^2\rangle^{38g,38m}$ obtained from Eq. (2). As can be seen, the ZBM2 interaction gives a fair agreement with the experimental value, supporting the realistic character of the wave functions obtained. However, as demonstrated in Fig. 4, it fails to produce a correct order of the $T = 1$ versus $T = 0$ states. This problem can be traced back to the uncertainty on the adjustments of $d_{3/2}$-$d_{3/2}$ monopole matrix elements: since ^{28}O is unbound, the strength of the $T = 1$ monopole cannot be precisely determined in a purely neutron system. As appears here, the $T = 1$ matrix elements of the ZBM2 interaction are too strong with respect to the $T = 0$ elements producing an inversion of the 0^+ and 3^+ levels.

In the isospin formalism, the centroids V_{ij} enter the monopole Hamiltonian through the coefficients a_{ij} and b_{ij}, where $a_{ij} = \frac{1}{4}(3V^{T=1}_{ij} + V^{T=0}_{ij})$ and $b_{ij} = V^{T=1}_{ij} - V^{T=0}_{ij}$. While the b_{ij} coefficient fixes the position of the configurations with a given isospin T value, the a_{ij} component fixes the position of configurations dependent on the particle number involved. It is thus always possible to modify the position of the $T = 0$ versus $T = 1$ states via t he b_{ij} parameter, leaving the position of particle-hole excited states versus zero-particle–zero-hole configuration unchanged. In our case, we have modified the $V^{0,1}_{d_{3/2},d_{3/2}}$ centroids to reproduce the spectrum of ^{38}K in the ZBM2 calculation as shown in Fig. 4. This modification leads to a proper behavior of the two-neutron separation energies along the oxygen chain. At the same time, the a_{ij} value is left invariant, preserving the description of the isotope shifts in calcium and other results from the original ZBM2 interaction as illustrated for ^{40}Ca in Fig. 4. From Table II, it can be seen that ZBM2 and the modified version of the interaction provide a similar composition of the ground and isomeric state wave functions, the latter giving $\delta\langle r^2_c\rangle^{38g,38m} = 0.085$ fm^2, even closer to the experimental value of 0.100(6) fm^2.

Finally, we have quantified the role of pairing correlations in the description of the ground and isomeric states by taking the expectation value of the $T = 1$ pairing Hamiltonian in the wave functions of the 3^+ and 0^+ states obtained from the shell-model diagonalization. The absolute value of the pairing contribution to the 0^+ state is 5 MeV larger than to the 3^+. On the contrary, taking the pairing Hamiltonian restricted to proton-proton and neutron-neutron pairs only, one obtains a small and nearly equal expectation value for both states. Therefore, these are, indeed, the $T = 1, I = 0$ proton-neutron pairs that constitute the essential difference in the building of the 0^+ and 3^+ states.

Returning to Behr *et al.*'s shell-model occupancy constrained spherical Hartree-Fock calculations, it is likely that the exclusion of cross-shell correlations and the resulting small difference between the orbital occupancies of the two states is the origin for the incorrect sign of the isomer shift.

It is intriguing to note that the only other odd-odd self-conjugate isomer shift measured to date [21] in ^{50}Mn [35] results in a $\delta\langle r^2\rangle$ which is identical in magnitude and opposite in sign to that measured here. The sign can be easily understood when one recalls that the $T = 0$ and $T = 1$ levels are inverted after $A = 40$ for all known cases with the exception of ^{58}Cu. While it is too early to draw direct conclusions from this similarity, the measurement of other isomer shifts in odd-odd self-conjugate nuclei such as ^{26}Al and ^{42}Sc could map the evolution of proton-neutron pairing correlations along the line of $N = Z$.

To conclude, both the direction and magnitude of the isomer shift in ^{38}K^m can be described phenomenologically when isovector proton-neutron pairing correlations are considered. Furthermore, a detailed study within the shell model framework has demonstrated good agreement with the observed isomer shift, confirming the significance of these cross-shell correlations in the region of ^{40}Ca.

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