Coulomb shifts and shape changes in the mass 70 region

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The technique of recoil β tagging has been developed which allows prompt γ decays in nuclei from excited states to be correlated with electrons from their subsequent short-lived β decay. This technique is ideal for studying nuclei very far from stability and improves in sensitivity for very short-lived decays and for high decay Q-values. The method has allowed excited states in ^{78}Y to be observed for the first time, as well as an extension in the knowledge of $T = 1$ states in ^{74}Rb. From this new information it has been possible to compare Coulomb energy differences (CED) between $T = 1$ states in ^{70}Br/^{70}Se, ^{74}Rb/^{74}Kr, and ^{78}Y/^{78}Sr. The $A = 70$ CED exhibit an anomalous behavior which is inconsistent with all other known CED. This behavior may be accounted for qualitatively in terms of small variations in the Coulomb energy arising from shape changes.

The ability of some atomic nuclei to assume competing mean-field shapes at low excitation energies is a remarkable feature of quantal objects and is called shape coexistence. In certain nuclei, a rearrangement of a few nucleons into different orbitals around the Fermi surface can result in a substantial change in the energetically favored shape. One of the classic examples is ^{186}Pb [1], where configurations resulting in two completely different (prolate and oblate) shapes occur within 700 keV of the spherical ground state configuration. An interplay of nuclear shapes is also found in nuclei with mass (A) around 70 with nearly equal numbers of neutrons (N) and protons (Z), where large shell gaps exist at both oblate *and* prolate shape for $N = Z = 34$ and 36. For example, the moments of inertia of the ground state band of ^{68}Se suggests an evolution from oblate to prolate shape as a function of excitation energy [2]. Conversion electron [3] and Coulomb excitation [4] measurements on ^{72}Kr also indicate shape coexistence. Such coexisting shapes can lead to long lived isomers, which could provide bypass routes for the traditional *rp*-process waiting-points influencing the nucleosynthesis and the timescale of X-ray bursts [5,6]. Thus, understanding the interplay of co-existing shapes provides a sensitive test of our knowledge of nuclear structure and has astrophysical significance.

The study of shape coexistence in $N \sim Z$ nuclei with $A \sim 70$ is challenging, as they lie far from stability and are difficult to synthesize. Radioactive beam Coulomb excitation is a promising approach for their studies [7]. In this Rapid

Communication, we discuss a technique recently developed by us for isolating nuclei in this region through recoil beta tagging [8], and have used it to explore Coulomb energy differences (CED) between isospin $T = 1$ states in odd-odd $N = Z$ nuclei ($T_z = (N-Z)/2 = 0$) and their analog states in their even-even neighbors. The CED is defined as CED $(J) = E_x(J, T = 1, T_{z<}) - E_x(J, T = 1, T_{z>})$, where $T_{z>} = T_{z<} + 1$, E_x is the excitation energy of the states of spin J and $T_{z>} = (N - Z)/2$ which may take values of 0 or 1 in this case [9]. The CED are driven by effects which break charge-symmetry and charge-independence, the dominant contribution to which is expected to come from the Coulomb interaction. They are also exquisitely sensitive to small structural changes and, in the present work, reveal evidence for variations in shapes in analog states in an isospin multiplet.

Over the last decade, the recoil-decay tagging technique [10,11] (RDT) has become one of the principal experimental tools for studying nuclei at the limits of stability with low production cross sections. It employs a recoil separator to separate fusion residues from primary and scattered beam particles, and fission products in the case of heavy nuclei. The residues are subsequently implanted at the focal plane in a silicon strip detector. Exotic nuclei close to the proton drip line are then selected by tagging on their characteristic α-particle or proton emission following implantation events, and are correlated with γ rays detected at the target position $\sim 1 \mu$s earlier, corresponding to the flight time through the separator. The possibility of tagging with electrons (or positrons) from

β-decaying recoils has not been pursued prior to the work described here. This is largely due to β decay being a three-body process where the neutrino (antineutrino) removes some of the energy. There is, therefore, no characteristic β-particle energy to employ as a tag. Instead, there is a Fermi-Kurie distribution of energies which, in general, overlaps with the distribution from other reaction channels. Fermi superallowed β-emitters constitute a special case with exceptionally high β^+ end-point energies (Q(EC) $\sim$10 MeV) and short half lives ($<$100 ms). This Rapid Communication reports on the first use of their properties as a means of channel selection to identify excited states in the odd-odd $N = Z$ nuclei, ^{74}Rb and ^{78}Y.

The K130 cyclotron at University of Jyväskylä accelerated beams of ^{36}Ar to 103 MeV and ^{40}Ca to 118 and 121 MeV. These beams of 4 and 5 particle-nA were incident on $\sim$1 mg/cm^2 ^{nat}Ca targets for periods of 90 and 210 h producing ^{74}Rb and ^{78}Y, respectively, via the *pn* fusion evaporation channels. Prompt γ rays were recorded with the JUROGAM array of 43 Compton suppressed high-purity germanium detectors with a total efficiency of 4% at 1.3 MeV. Fusion evaporation residues were separated from the primary beam in the RITU gas-filled recoil separator and were implanted in a 700-μm-thick double-sided silicon strip detector (DSSSD) in the GREAT focal plane spectrometer [12]. Situated behind the DSSSD was a planar germanium detector with a thickness of 15 mm. The combination of these two detectors served as a ΔE-E telescope for recording positrons. In each case, the *pn* evaporation channel involving Fermi superallowed β decay, was selected by demanding the detection of a high energy positron, in a short ($\sim$100 ms) time coincidence with the implanted recoil. By correlating with in-beam γ rays, recorded in JUROGAM $\sim$1 μs earlier, it was possible to study the decay of excited states in ^{74}Rb and *for the first time* in ^{78}Y. We refer to this method as recoil beta tagging (RBT).

Previous in-beam studies of ^{74}Rb have been carried out using charged particle and neutron detection for channel selection [13,14]. This nucleus has a ground state that β decays with a half-life of 65 ms and an end point energy of 9.4 MeV and therefore serves as an excellent test case for the RBT technique. From the ^{36}Ar + ^{40}Ca reaction data, transitions in ^{74}Rb were identified by correlating them with residues implanted at the focal plane, which were succeeded by the detection of a positron within $\sim$100 ms. Such positrons had to record an energy loss in the DSSSD and deposit between 3 and 10 MeV in the planar germanium detector. The strong suppression of contaminating channels by the short correlation time meant that it was possible to set such a low limit (3 MeV) on the positron energy. In this manner, all the γ rays observed in Refs. [13,14] were confirmed, and, in particular, the 575 and 478 keV γ rays establish the energy of the 4$^+$, 2$^+$ states to be 1053 and 478 keV, respectively. In a recent publication, we focus on the technique in detail and explore strategies for optimising the efficiency and cleanliness of the correlations [8]. The use of a ^{36}Ar-induced reaction with a beam energy around the Coulomb barrier, resulted in greater feeding of low-lying nonyrast states. This led to the extension of the $T = 1$ ground state band to $J^\pi = 6^+$ at 1837 keV. A recently published parallel work using more conventional techniques

confirmed this assignment and found a candidate $J^\pi = 8^+$ member of this $T = 1$ analog sequence [15]. The present work has also located a number of additional $T = 0$ states but discussion of these lies beyond the scope of this Rapid Communication.

Prior to this work the knowledge on ^{78}Y was limited to the $T = 1$, $J^\pi = 0^+$ ground state with its characteristic $T_{1/2} = 55(12)$ ms superallowed β-decay with an endpoint energy of 9.4 MeV, and a 5$^+$ isomer with $T_{1/2} = 5.8(6)$ s [16,17]. The isomer receives most of the population in the current study using the ^{40}Ca+^{40}Ca reaction; implant-decay correlations for high energy positrons suggest that as much as 90% feeds the isomer. Although the isomer β decays with a high endpoint energy, the half-life is too long to correctly correlate the decay with the parent implant and its associated prompt γ rays, since the implantation rate per pixel in the DSSSD was $\sim$1/s. However, the superallowed decay of the ground state did allow effective correlations, and identification of prompt γ rays, as was achieved for ^{74}Rb. The data are shown in Fig. 1(a). The lower statistics achieved for the ^{78}Y study can be mainly attributed to population of the isomeric state, as the production cross sections for ^{40}Ca (^{36}Ar, *pn*) ^{74}Rb and ^{40}Ca (^{40}Ca, *pn*) ^{78}Y are expected to be quite similar.

The low cross section for population of states built on the ^{78}Y ground state made the breakthrough in channel selection using RBT more apparent than in the ^{74}Rb study. In this case, it was demanded that the β particle energy was between 4.5 to 10 MeV within a correlation time of 150 ms. After eliminating known transitions from interfering contaminants, including ^{74}Rb produced via the αpn channel, three new γ lines were identified as belonging to the short lived, high endpoint reaction product, ^{78}Y. They were strong enough for it to be established that they are in prompt coincidence (inset to Fig. 1(a)). The intensity of the 281 keV γ ray is consistent with it being the strongest transition and hence it is most likely to decay to the ground state. This could be shown to be associated
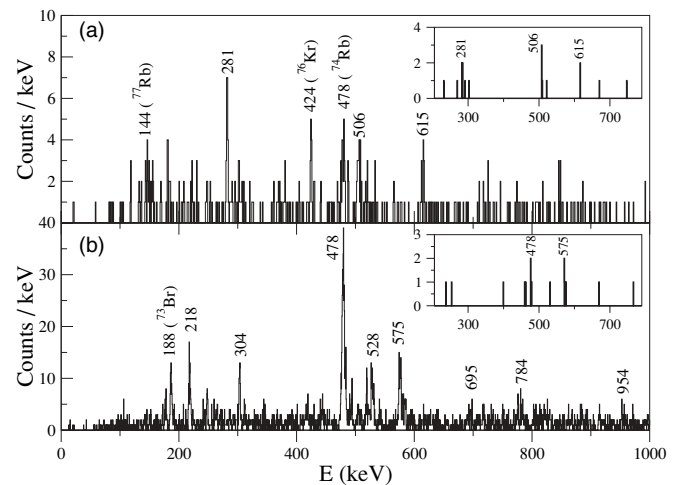

FIG. 1. Recoil-β tagged γ ray spectra for (a) ^{78}Y and (b) ^{74}Rb [8]. The insets show a sum of gates on the 281, 506, and 615 keV, and a gate on the 784 keV transitions, in their respective recoil-β tagged E_γ-E_γ matrices. Details of the time correlations and positron energy limits are given in the text.

with positrons decaying with a half-life of 47(5) ms, in good agreement with the known ^{78}Y ground state decay. The angular distributions of the two stronger lines were consistent with quadrupole multipolarity although with large uncertainties due to poor statistics. It is also a common practice in studies of isobaric analog nuclei to assume that the analog states have a similar structure at a given spin [18]. Thus, we tentatively assign the 506 and 281 keV transitions as the analogs of the 504 and 278 keV γ rays corresponding to the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in the $T = 1$ ground state band in ^{78}Sr. Unfortunately, we are unable to determine the multipolarity of the 615 keV γ ray. Moreover, we note that if this is assumed to be the $T = 1$, $6^+ \rightarrow 4^+$ transition, then it would result in a large negative CED of -92 keV compared to the small positive values for the 2^+ and 4^+ states (see Fig. 2). While the systematics suggest that such an abrupt change is not impossible, it could also be that the 615 keV γ decay does not originate from the 6^+ member of $T = 1$ sequence.

The new CED data on $A = 74$ and 78 nuclei can now be compared to the published $A = 70$ trend [19,20], as shown in Fig. 2(b). They show a remarkable contrast. The CED falls for $A = 70$, rises smoothly for $A = 74$ and is near-zero (at least up to spin 4) for $A = 78$. The $A = 70$ trend was previously attributed [19] to the Thomas-Ehrman effect; the loosely bound proton in ^{70}Br was anticipated to have an unusually extended radial wave function and thus have a lower Coulomb energy than the equivalent state in ^{70}Se. In the light of the new data, this cannot be the complete explanation, as all the three systems have similar differences in binding energy between the $T_z = 0$ and $T_z = 1$ nuclei, and so should all exhibit the same trend. Moreover, these states are all well bound so are unlikely to have significantly extended wave functions.

The trend in CED across the sd and fp shell has been investigated in considerable detail in recent years. New data have been obtained and interpreted using large scale shell model calculations [9,22,23]. As shown in Fig. 2(a), the CED have a positive trend in the sd and fp shells. The microscopic
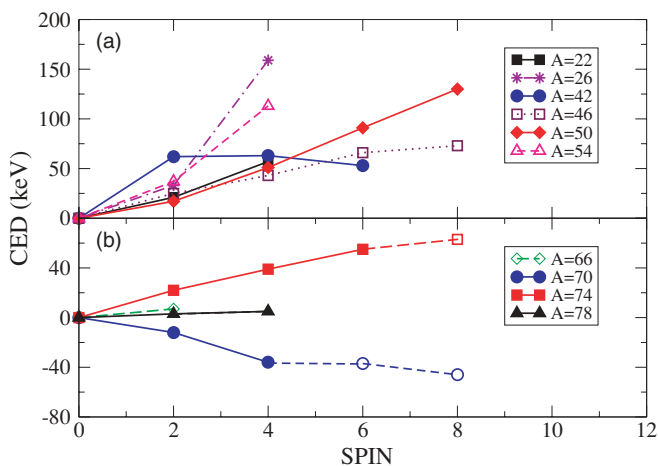

FIG. 2. (Color online) CED between $T_z = (0, 1)$ pairs as a function of spin for the cases: (a) $A =$ 22, 26, 42, 46, 50, and 54 and (b) $A = 66$, 70, 74, and 78. Data for (a) and $A = 66$ were taken from Refs. [9] and [21], respectively. Open symbols and dashed lines for (b) represent tentatively assigned levels in the $N = Z$ system considered.

explanation for this ubiquitous trend lies in the destruction of pairing correlations by angular momentum, i.e., Coriolis antipairing. For perfect charge independence, this destruction should be exactly the same in $T_z = 0$ and $T_z = 1$ nuclei of same mass; the generation of angular momentum reduces the occupation of exactly time reversed orbits and the overlap of wave functions is diminished. For proton pairs, this lowers the Coulomb energy. Depending on how many proton-proton pairs are being destroyed, there can be a small difference in the Coulomb energy change between analog nuclei. For the $N = Z$, $T_z = 0$ nuclei, it is expected that neutron-proton $T = 1$ pairing correlations are important. For the $N = Z + 2$ nuclei with $T_z = 1$ only nn and pp pairs are expected to play a significant role [22–24]. Thus, there are always more proton-proton pairs in the $N = Z + 2$ nuclei, and consequently a larger reduction in Coulomb energy with spin. In a large shell model space, or a single j-shell with many pairs of particles and a high level density, the CED would rise smoothly with spin. Empirically, this effect is 10–15 keV per unit of angular momentum. However, in the restricted spaces for intermediate mass nuclei with several orbitals of differing j, the effect can become irregular depending on the microscopic construction of the pairs, particularly the angular momentum of the underlying single particle states.

The $A = 70$ case, with its unique negative CED needs a new explanation. The interpretation of the CED behavior in the fp-shell assumes that the nuclear shapes are fixed and that $T = 1$ np-pairing is important only in $N = Z$ nuclei. If either of these considerations are not valid, then the CED can assume a different behavior. Experiments on ^{68}Se and ^{72}Kr show evidence for the presence of an oblate shape at low excitation energy [2–4]. In the neighboring nuclei, ^{70}Se [25,26] and ^{74}Kr [27,28], shape changes have also been suggested to play an important role. With the assumption of charge independence, the shape coexistence *must be* exactly the same for the $T = 1$ states in the odd-odd $N = Z$ nuclei, ^{70}Br and ^{74}Rb. To lowest order, the spectra should then be identical. However, this does not imply the CED will be zero, as the Coulomb monopole cancellation obtained by aligning the ground state energies, only remains exact if the shapes remain frozen. Any evolution of shape with spin (including stretching or changes in shape) will perturb the CED. Specifically, big increases in deformation with spin lead to negative CED. Thus, negative CED provide new and sensitive information on shape evolution.

We have investigated the effects of shape change on the CED using a deformed liquid drop model [29] and calculated the effects for $A = 70$. Shape changes in ^{70}Se are clear experimentally from the very irregular yrast line and lifetime measurements, which indicated a strong reduction in $B(E2)$ transition strengths near $J = 4$ [25]. A recent Coulomb excitation measurement favors a prolate shape for the 2^+ state consistent with $\beta_2 = 0.25$ [7] and is in agreement with a configuration mixing shell model calculation which predicts a ground state band with $\beta_2 = 0.18$ crossed by a more deformed band with $\beta_2 = 0.33$ near $J = 6$ [30]. For such a shape change, the deformed liquid drop model suggests a $\sim$75 keV decrease in CED, in good agreement

with that observed in the present work. Historically, the shape coexistence in ^{70}Se has been described as a competition between an oblate ground state configuration and an excited prolate configuration; this interpretation being supported by total Routhian surface calculations [26]. However, for such a shape change, i.e., β_2 from -0.3 (oblate) to 0.35 (prolate), the CED should only decrease by $\sim$7 keV, which does not account for the observed trend. Only a significant change in elongation can make sufficient change to the Coulomb energy.

The $A = 74$ CED reveal a monotonically positive trend. This seems to imply that in the $T = 1$ band the deformation up to $J = 8$ is always large and does not change significantly (supported by $B(E2)$ data [31]), so the CED evolution is due to Coriolis antipairing as in the case of $f_{7/2}$ nuclei. Beyond the coexistence region, in the middle of the fpg shell at $A \sim 80$, very large and stable prolate deformation is known to be stabilized by a gap in the single particle sequence at $N = Z = 38$ [27]. The gap is sufficiently large that all scattering across the Fermi surface is suppressed and the odd-A nuclei appear as near rigid rotors [32]. With stable shapes and all pairing effects reduced the very small CED found in the ^{78}Y-^{78}Sr pair at low spin are perhaps not surprising. However, as the proton backbend, which occurs at $J = 8$ [13], is approached in ^{78}Sr one may well expect a change in CED to appear. This could explain the CED of -92 keV discussed earlier if the 615 keV transition in ^{78}Y originates from the decay of the $T = 1$, 6^+ state.

In summary, information on Coulomb energy differences in $T = 1$ multiplets has been extended using recoil beta tagging.

The CED derived for $A = 70$ are quite different from the expectations based on our knowledge of the behavior in the *fp*-shell. We suggest that the pronounced decrease in CED as a function of spin is due to subtle differences in the Coulomb energy as shapes evolve with spin. If this is the correct explanation, it will be manifested in the $T_z = -1$ member of the isobaric triplet through a further lowering of the ground state band of ^{70}Kr, by an amount equal to that observed between the ^{70}Br/^{70}Se pair, as the effect is linear with Z. Currently nothing is known about the excited states in ^{70}Kr, but clearly this becomes an important measurement. From a theoretical stand point, these measurements provide a definitive test case for state-of-the-art shell model calculations. Even though the 2^+ level assignment in ^{66}As is tentative, it is also interesting to note that for the $A = 66$ pair (^{66}As/^{66}Ge – see Fig. 2(b)) the CED for the $T = 1$, 2^+ states is about zero, suggesting a trend similar to that for ^{78}Y. Clearly, extending these data for the $T = 1$ states in ^{66}As will be important, since if the CED remains near zero as a function of spin in this case then a different explanation to that given above for the mass 78 pair will be required. During the preparation of this Rapid Communication, we learned about studies of ^{82}Nb and ^{86}Tc [33], which promise further insight into the issues discussed here.

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