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PROBING EXCITED STATES IN NUCLEI AT AND BEYOND THE PROTON DRIPLINE *

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The coupling of a Compton-suppressed Ge (CSGe) detector array to a recoil separator has seen limited use in the past due to the low efficiency for measuring recoil-γ ray coincidences ($< 0.1\%$). With the building of new generation recoil separators and gamma-ray arrays, a substantial increase in detection efficiency has been achieved. This allows for the opportunity to measure excited states in nuclei with cross-sections below 100 nb. In this paper, results from the coupling of a modest array of CSGe detectors (AYE-Ball) and a current generation Ge array (Gammasphere) with a recoil separator (FMA) will be presented.

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1. Introduction

The study of nuclei far from stability has received much attention recently. Indeed, the thrust of the next generation radioactive beam facilities will be to study neutron rich nuclei. However, it is doubtful that the next generation RIB facilities will push all the way to the neutron-drip line except for the lightest elements. On the other hand, nuclei which lie at and beyond the proton-drip have been produced and identified for elements as heavy as Bismuth (Z=83) using either heavy-ion induced fusion evaporation reactions with stable beams and targets or multi-fragmentation reactions. Until recently, many of these isotopes were characterized solely by their decay properties and lifetimes, and little, if anything, was known about their excited states.

This situation has changed somewhat in the last several years with the coupling of modest and large gamma-ray arrays to other detection systems which allow for the isolation of weak channels and their associated γ rays

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from stronger sources of γ radiation, *e.g.* other residue channels, fission, and coulex. Presently, two general techniques are used in γ-ray spectroscopic studies to make isotopic identification of weak channels produced in fusion-evaporation reactions. The first involves the measurement of evaporated particles, *i.e.* neutrons, protons, and/or α particles. The number and type of particles measured give some degree of nuclide identification. The second technique directly detects the residue using either a recoil separator or a recoil detector. Isotopic identification is made by measuring the properties of the residue, *i.e.* mass, energy, time of flight, and/or decay products. In this contribution, the discussion will focus on studies of excited states in nuclei utilizing the second technique. Specifically, results from γ-ray spectroscopy experiments using gamma-ray arrays coupled to a high resolution recoil mass spectrometer will be presented.

2. The Recoil Decay Tagging Technique

A high resolution recoil mass separator is installed on a beam line of the heavy-ion accelerator, ATLAS, at Argonne National Laboratory. This device, named the Fragment Mass Analyzer (FMA), is an 8.2-meter-long mass spectrometer which separates reaction products produced in a heavy-ion fusion reaction and disperses then by Mass/Charge (M/Q) at the focal plane [1]. While the focal-plane detector offers M/Q separation typically of 350:1, it does not provide isotopic (Z) information. Z information is obtained at the FMA by placing ancillary detectors behind the focal-plane. For light and medium mass nuclei ($Z< 50$), it is possible to obtain Z-separation by using an ionization chamber, however, this technique does not work for heavier nuclei.

A technique for isotopic identification of γ rays which is applicable to heavy nuclei far from stability has been developed recently, and it is commonly referred to as Recoil Decay Tagging (RDT). Isotopic identification is made by correlating the characteristic charged-particle radioactivity of an ion implanted in a pixel of a double-sided silicon strip detector (DSSD) with a previously implanted recoil. Fig. 1 shows schematically how the technique works utilizing the DSSD setup at the FMA. Above the closed proton shell at $Z=50$, many nuclei near the proton-drip line decay by the emission of an α particle. Beyond the drip line, odd-Z nuclides are observed to decay by proton emission, and they too are excellent candidates for RDT studies.

RDT is an extremely sensitive technique, and γ rays have been identified in channels produced with cross-section as low as 50 nb. While the technique is quite sensitive, this comes with a cost. Using a device such as the FMA, only about 5-15% of the recoils produced at the target are detected at the focal plane. In addition, only 1/2 of the decay products deposit their full

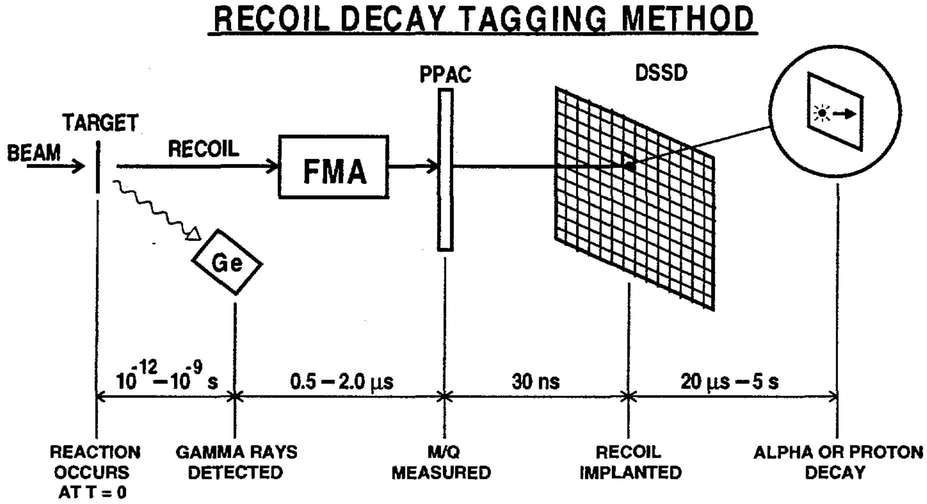

Fig. 1. Schematic diagram of the Recoil Decay Tagging (RDT) method.

energy in the DSSD. As a result, less than 10% of recoils produced at the target are correlated with a decay product (proton or α). This situation can be improved somewhat by using a gas-filled separator like RITU at Jyväskylä where recoil efficiencies as high as 50% are reported [3].

Recoil Decay Tagging was first employed at GSI using an array of NaI detectors and the SHIP velocity filter [4]. However, it was not until the technique was used with a large Ge array (EUROGAM I) that the promise of the method to measure excited states in nuclei at the proton-drip was demonstrated [5]. Since this time, RDT studies have been performed with the FMA, RITU, and the Oak Ridge RMS, a high-resolution mass spectrometer similar to the FMA. In this talk, RDT results using the FMA will be presented. A discussion of the RDT program at RITU can be found in the contribution of M. Leino to this conference.

3. Results from RDT Experiments with Aye-ball

Since its commissioning, a number of experiments have been performed at the FMA using an array of Compton-suppressed (CS) Ge detectors. Initially, an array of 10 CSGe detectors was used (see for example ref. [2]). In order to improve the recoil-γ efficiency at the FMA, a larger array of Compton-suppressed Ge detectors was placed at the FMA-target position in August of 1995. This array, named the Argonne-Yale-European (AYE) Ball, was equipped with a support structure which could hold up to 25

CSGe detectors. Fifteen of the slots were configured for Eurogam phase I detectors, and the remaining 10 slots were configured to hold Ge detectors in Tessa-like suppression shields. For the experiments performed with AYE-ball, nine large Ge ($\sim$ 70%) and ten small ($\sim$ 25%) Ge detectors were available for placement into the array. When fully loaded with detectors, the array had a photo-peak efficiency of 1.1% for 1 MeV γ rays.

Thirteen experiments were performed with the array over a three month period. Nearly all the experiments were directed at nuclei far from stability and covered a mass range from A=24 to A=226 [6]. Several of these experiments utilized the RDT technique, and papers reporting these results on ^{147}Tm [7], ^{156}Hf [8], ^{176,178}Hg [9] and ^{200}Rn [10] have been published. In this section, a summary of the ^{156}Hf and ^{176,178}Hg results will be given.

^{156}Hf is an N=84 nucleus which lies very near the proton-drip line. In an experiment using AYE-Ball coupled to the FMA, excited states in ^{156}Hf were populated with the ^{102}Pd(^{58}Ni,2p2n) reaction at 270 MeV. The charged-particle decay spectrum was measured with a 48x48 double-sided silicon strip detector placed 40 cm behind the FMA focal plane detector. Prior to this experiment, the only identified excited state in ^{156}Hf was an isomeric level at 1959 keV. Both the isomer and the ground state decay predominantly by α emission. In addition, the excited state is known to be populated after the β decay of the $(\pi h_{11/2} \otimes \nu f_{7/2}\})_{9+}$ state in ^{156}Ta suggesting the $(\nu h_{9/2} \otimes \nu f_{7/2})_{8+}$ configuration for the isomeric state [11].

Figure 2a shows the γ-ray spectrum in coincidence with A=156 residues. Nearly all of the strongest transitions are associated with the 4p channel (^{156}Yb). Figure 2d shows the charged particle decay spectrum measured in the DSSD, and the α energies associated with the decay of the ground state (5878 keV) and the isomeric state (7804 keV) in ^{156}Hf are marked in the spectrum. These decay lines confirm that ^{156}Hf is produced in this reaction, and they represent $\sim$ 3% of all α decays measured in the DSSD.

In order to determine whether any of the γ rays observed in the A=156 gated spectrum belong to ^{156}Hf, γ-ray spectra tagged by the two ^{156}Hf α lines were created. These spectra are plotted in figs. 2b and c. The spectrum correlated with the ground-state decay (2b) shows only three γ transitions of equal intensity. Conversely, the spectrum correlated with the α decay of the isomer (2c) shows many more γ rays with varying intensities. None of the γ transitions observed in either spectrum are resolvable in the spectrum gated by A=156 (fig. 2a), thus illustrating the power of the RDT technique in associating γ rays with weakly populated residues. The estimated cross-section for producing ^{156}Hf is 100μb.

The angular distributions of the three γ rays correlated with the ground-state α decay are consistent with E2 multipolarity and establishes the spin and parity of the levels connected by these transitions. As fig. 2e indicates,

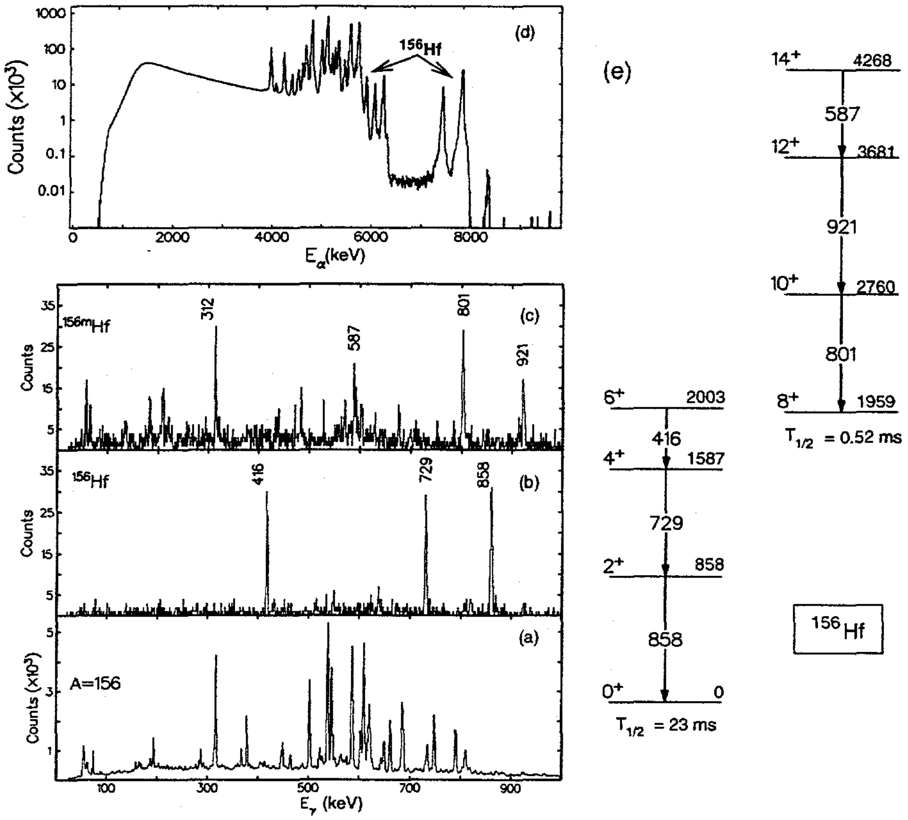

Fig. 2. (a) γ-ray spectrum in coincidence with A=156 residues. (b) γ rays in coincidence with the ground-state α decay of ^{156}Hf. (c) γ rays in coincidence with the α decay of the isomer in ^{156}Hf. (d) Charged particle decay spectrum measured in the DSSD. (e) Deduced level structure for ^{156}Hf.

the 6^+ level lies 44 keV higher in energy than the 8^+ isomer, resulting in a spin inversion of the 6^+ and 8^+ levels. The lowering of the 8^+ state $(\nu f_{7/2} \otimes \nu h_{9/2})$ with respect to the 6^+ $(\nu f^2_{7/2})$ state arises from the closing of the energy gap between the $f_{7/2}$ and $h_{9/2}$ orbitals. In the lighter N=84 isotones, the systematic lowering of the 8^+ level has been associated with the strong attractive interaction between $\hbar_{11/2}$ protons and $h_{9/2}$ neutrons.

Many more γ rays are observed in the spectrum correlated with the decay of the 8^+ isomer, and these transitions connect states which lie above the isomer. Unfortunately due to the low efficiency for detecting γ-γ-recoil coincidences, only the strongest transitions could be placed in the level scheme as indicated in fig. 2e.

In light Hg isotopes ($100 \geq N \geq 108$), shape co-existence has been established close to the ground state where rotational bands built on collective oblate and prolate shapes are observed. Recent Nilsson-Strutinsky calculations [12] indicate that for neutron number N<100, the oblate ground state evolves steadily as a function of decreasing N towards a spherical shape, while the prolate minimum disappears and gives way to a new minimum at large deformation ($\beta_2 \sim 0.5$) located 3.5–5 MeV above the ground state.

With this recent calculation in mind, a series of measurements were performed with AYE-ball to identify for the first time γ transitions in $^{176-179}$Hg using the ^{78}Kr(^{103}Rh,pxn) reaction. The assignment of γ-ray transitions to a particular nuclide was made using RDT. The left side of fig. 3 summarizes the results for ^{178}Hg. The top panel shows the γ-ray spectrum in coincidence with A=178 residues. This spectrum is dominated by the 3p channel, ^{178}Pt. The γ-ray spectrum in the middle panel was produced by requiring correlations between γ rays and ^{178}Hg α decay ($E_\alpha = 6.43$ MeV). On the basis of the α-γ correlations, the transitions labeled by their energy in the middle panel are assigned to the de-excitation of levels in ^{178}Hg. Their placement in the ^{178}Hg level scheme was confirmed from the analysis of the $\gamma - \gamma$ matrix gated on residues. This is illustrated in the bottom panel where the sum of γ-ray coincidence spectra gated on the strongest ^{178}Hg transitions is seen to be nearly identical to the RDT gated spectrum.

The right side of Fig. 3 summarizes the results for ^{176}Hg. The γ-ray spectrum in coincidence with $A = 176$ residues is shown in the upper panel and it is dominated by transitions in ^{176}Pt. The inset to this panel shows the α-decay spectrum measured in the DSSD. It is worth noting that the ^{176}Pt α line dominates the ^{176}Hg one by a ratio of ~ 300:1. Nevertheless, transitions were unambiguously assigned to ^{176}Hg from the $\alpha - \gamma$ correlations. This is demonstrated in the bottom panel where three γ rays correlated with ^{176}Hg are observed. The data set was not sufficient to confirm the ordering of the transitions based on γ-ray coincidences, rather, the three γ rays (615, 756, and 551 keV) were ordered in the level scheme based on their intensities.

The excitation energy of the first 2^+ level in the even Hg isotopes ranges between 350-425 keV for $180 \leq A \leq 196$. From the newest data, the excitation of the 2^+ level exceeds 550 keV in ^{178}Hg and 600 keV in ^{176}Hg indicating a transition from the well established weakly deformed oblate structures for A>180 ($\beta_2 = -0.15$) towards a spherical shape as predicted in ref. [12]. The present data also provide new information about the evolution of the excitation energy of the prolate band with mass. In most even-even Hg isotopes with $N < 110$, the presence of the prolate band is readily visible from the inspection of the yrast sequence: the energy of the γ-ray transition decreases drastically at the point where this band (with its larger moment of inertia) crosses the ground band. This is clearly evident in ^{178}Hg, and the

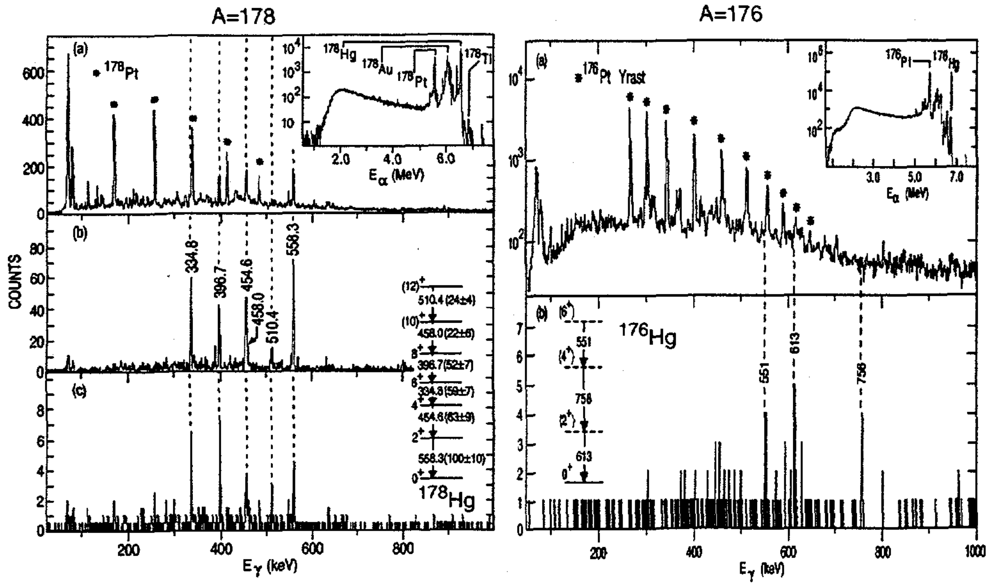

Fig. 3. Left panel: relavent spectra for ^{178}Hg. (a) γ-rays in coincidence with A=178 residues. (b) γ rays correlated with the ^{178}Hg α decay (the charged-particle decay spectrum is shown in the top inset). (c) Sum of coincidence spectra gated on transitions assigned to ^{178}Hg. Right panel: relavent spectra for ^{176}Hg. (a) γ-rays in coincidence with A=176 residues. (b) γ rays correlated with the ^{176}Hg α decay (the charged-particle decay spectrum is shown in the top inset).

states above the 4^+ level have been associated with the prolate structure. By performing a two-band mixing calculation, the unperturbed prolate band head is estimated to lie $\sim$ 710 keV above the ground state. This can be compared to 334 keV for ^{180}Hg and 264 keV for ^{182}Hg [13], indicating a clear rise in energy for the prolate band head with decreasing neutron number as again predicted in ref. [12]. While only three transitions are observed in ^{176}Hg, a lower limit has been placed on the prolate band head at 1300 keV. New data from RITU on higher lying members in the ^{176}Hg yrast band has allowed for the identification of the prolate structure [14]. This new data also suggests that the prolate band head is at $\sim$ 1300 keV in ^{176}Hg.

4. Study of Proton Emitters with Gammasphere

The two preceding talks by C. Davids and K. Rykaczewski have reviewed the current status of proton decay studies and illustrated the type of nuclear structure information which can be deduced from these measurments. By studying the excited states which lie above the proton-emitting states, additional information becomes available on nuclei at the edge stability, *e.g.* (i) independent confirmation of the single-particle nature of the proton decaying state, (ii) mapping out of the proton-bound region as a function of spin and excitation energy, and (iii) the possibility to study the mixing of bound with continuum states in these loosely bound systems. Unfortunately, the cross-sections for producing proton emitters are quite low with the most favorable cases ranging between 10 and 100 μb. As was demonstrated from an AYE-ball experiment on the proton-emitting nucleus ^{147}Tm [7], gamma-ray arrays with efficiencies on the order of 1% only allow for recoil-γ measurements when using the FMA to study nuclei with production cross sections $< 100\mu$b. In order to perform detailed spectroscopic studies of proton-emitters, γ-ray coincidence data is necessary.

With the move of Gammasphere to Argonne in the fall of 1997, an order of magnitude gain in singles efficiency was realized for γ-ray spectroscopy measurements at the FMA. More importantly, however, is the 100 fold gain in $\gamma-\gamma$-recoil efficiency, and the near 1000 fold gain in $\gamma-\gamma-\gamma$-recoil efficiency. Gammasphere is sited at the FMA target position, allowing the opportunity to perform recoil$-\gamma-\gamma$ measurements on proton-emitters using RDT. Several such experiments have been performed at Gammasphere on proton emitters [15-19], and I will briefly discuss the results from two of them, namely, ^{167}Ir [17] and ^{141}Ho [18].

The two α-emitting states in ^{167}Ir were recently found to proton decay [20]. Based on the partial half-lives for proton decay, the ground state was given a $\pi s_{1/2}$ assignment while the isomeric state at 175 keV was assigned to the $\pi h_{11/2}$ configuration. The spectroscopic factors deduced for these states agree with low-seniority shell model calculations which assume that all states are spherical. In this measurement performed at the FMA, the ^{92}Mo(^{78}Kr,p2n) reaction at a beam energy of 358 MeV was used to produce ^{167}Ir. The cross sections for producing the isomeric and ground states were found to be 100μb and 10μb, respectively.

In order to study excited states via RDT, the same reaction was used at a slightly higher beam energy of 360 MeV. γ-recoil coincidences were measured with Gammasphere coupled to the FMA. Figure 4a shows the γ-ray spectrum correlated with the α decay of the isomeric level in ^{167}Ir. The inset shows the partial level scheme deduced from the γ-ray coincidence data (all spins are tentative). An E2 sequence (672, 801, 865 keV) is built on top of the isomer, and the γ-ray energies are consistent with a spherical or weakly deformed structure, confirming the interpretation from the proton-decay data. The first three transitions in ^{166}Os, the core to ^{167}Ir, have energies of 433, 589, and 704 keV, indicating a rather substantial change in deformation with the addition of one proton. The level scheme also indicates that another structure becomes yrast around I=21/2, and its single-particle

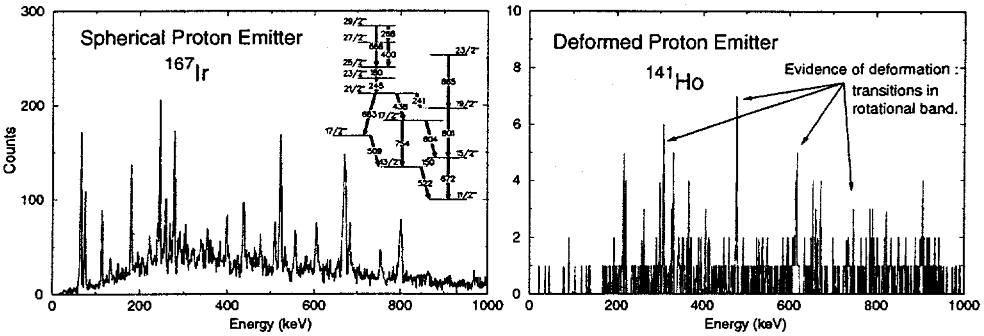

Fig. 4. (a) γ-ray spectrum correlated with the decay of the $\pi h_{11/2}$ isomer state in ^{167}Ir. The inset shows the partial level structure built on top of the isomer. (b) γ-ray spectrum correlated with the proton-decay of ^{141}Ho.

nature is unclear at this time.

Until recently, the lifetimes of all proton emitters could be well reproduced by WKB calculations using spectroscopic factors derived from spherical shell model calculations [20]. Recently, proton radioactivity has been observed in ^{141}Ho and ^{131}Eu, however, the decay lifetimes cannot be reproduced by the WKB calculations [21]. This has been interpreted in ref. [21] as evidence for the onset of large deformation. The proton rates can be reproduced using the formalism of Bugrov and Kademskii [22] developed for proton decay from deformed nuclei, and these calculations predict a deformation $\beta_2 \sim 0.3$ for both nuclei in agreement with the Nilsson-Strutinsky calculations of ref. [23].

An independent confirmation of the deformation of these bands can be obtained by measuring the excited states built on top of the proton-emitting states. An experiment to measure excited states in ^{141}Ho was carried out with Gammasphere coupled to the FMA, despite the fact that the production cross section was found to be only 250 nb [21]. The ^{92}Mo(^{54}Fe,p4n) reaction was used to produce ^{141}Ho, and Fig. 4b shows the proton correlated γ-ray spectrum produced using RDT. A number of γ rays are observed in the spectrum and are assigned to ^{141}Ho. Assuming that the transitions marked in fig. 4b form a rotational band, the deformation extracted from the moment of inertia agrees well with that deduced from the proton-decay half-life [21]. However, due to the low statistics and lack of γ-ray coincidence information, the grouping of these transitions into a rotational sequence is tentative.

In ref. [21], the proton emitting state of ^{141}Ho was assigned to the $7/2^-$[523] Nilsson configuration. Two rotational sequences forming a signature partner pair would be expected to be built on top of this state. Unfortunately, the data does not indicate the presence of a signature partner band having transitions which lie between the marked γ-rays in fig. 4b. If these transitions were observed, this would provide strong support for the interpretation of ref. [21].

5. In-Beam Gamma-ray Studies for Z>100

In the preceding sections, the discussion centered on studies of nuclei far from stability utilizing the RDT technique. In this section, the prospects of performing γ-ray spectroscopy experiments on the heaviest elements will be discussed. The push to produce and measure the properties of new elements is an ongoing activity in nuclear structure physics. Presently, elements up to Z=112 have been identified, and the talk at this school by S. Hofmann summarizes the recent work that has been carried out in this area.

The experimental quantities extracted from heavy-element decay studies, *i.e.* α-decay energies and α-decay lifetimes, can be reproduced by theoretical calculations which predict that the identified nuclei between Z=100 and Z=112 are deformed. A more direct determination of the deformation of these nuclei can be obtained by measuring their excited states, however, this is extremely difficult due to the fact that the production cross sections for making these very heavy nuclei are are at most a few 100 nb and typically much less. There is one exception to this: reactions using a ^{48}Ca beam to bombard a ^{208}Pb target give a maximum cross section for producing ^{254}No (Z=102) via the 2n channel of 3 μb [24].

In order to identify excited states in ^{254}No, a Gammasphere experiment at the FMA was recently performed using the reaction ^{208}Pb(^{48}Ca,2n) at the optimal beam energy of 215 MeV [25]. In the measurements discussed in the previous sections, the residue survival cross sections are on the order of 10 mb, and the RDT technique identifies γ rays in the weakest channels. For this experiment, the ^{254}No channel is the dominant channel and the FMA is used to separate these residues from the fission background produced at a rate 10^4 higher than for ^{254}No. Unambiguous identification of ^{254}No comes from the α-decay spectrum measured in the DSSD.

The upper panel in Fig. 5 shows the γ-ray spectrum gated on A=254 residues while the lower panel gives the γ-ray spectrum correlated with ^{254}No α-decays. The strongest γ rays in (a) are also observed in (b) which confirms there placement in ^{254}No. In addition, coincidence relationships between these γ rays can also be established. Assuming these transitions form a rotational band, they can be ordered by their intensity after taking into account the γ-ray intensity lost to conversion. Due to the large conversion coefficients for low energy transitions, it is most likely that the level fed

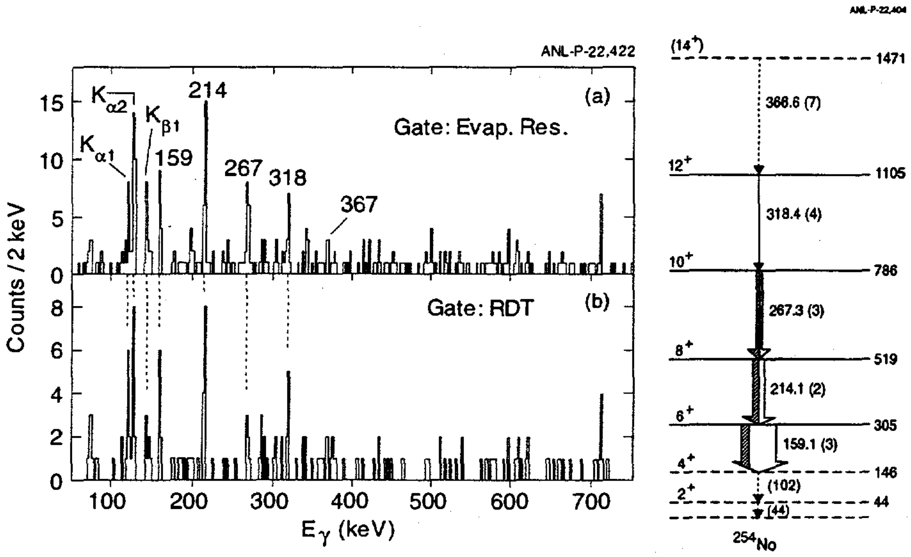

Fig. 5. ^{254}No spectra and level structure.

by the 159 keV transition is not the ground state. In order to estimate the spins of the levels connected by the observed transitions and the energies of the missing transitions, the dynamic moment of inertia was fit using the Harris parameterization, $\mathcal{J}^{(2)} = J_0 + 3J_1\omega^2$, where $\mathcal{J}^{(2)} = 4\hbar/\Delta E_\gamma$ and $\omega = E_\gamma/2$. The spins of the emitting states were then assigned using the expression $I = J_0\omega + J_1\omega^3 + 1/2$. Following this prescription, it was deduced that the 159 keV transition fed the 6^+ level, and the two missing transitions had energies of 44 and 102 keV. The proposed level scheme with deduced spins is given in fig. 5, and it is interpreted as a rotational band with β_2 estimated to be 0.27 which is consistent with the theoretical predictions. The results from this experiment have been confirmed using the SARI array with RITU (see the contribution from M. Leino to this conference).

6. Summary

In this contribution, results obtained from RDT studies on nuclei which lie far from stability have been presented. While detailed studies of the excited states in proton-emitters and nuclei with Z> 100 have just begun, they have already provided valuable information on the evolution of nuclear structure at the limits of stability.

I would like to extend my gratitude to the many collaborators who have taken part in the experiments discussed above. In particular, I would like to acknowledge C.N. Davids, R.V.F. Janssens, T.L. Khoo, C.J. Lister, P. Reiter, D.S. Seweryniak, and P.J. Woods for numerous discussions as well as their permission to present results from their work to this conference. This work is supported by the U.S. Department of Energy, Nuclear Physics Division under contract W-31-109-ENG-38.

REFERENCES

[1] C.N. Davids *et al.,* Nucl. Inst. Meth. Phys. Res. **B70**, 358 (1992).

[2] A. Baxter *et al.,* Phys. Rev. C **48**, R2140 (1993).

[3] M. Leino, see proceedings to this conference.

[4] R. Simon *et al.,* Z. Phys. **A325**, 197 (1986).

[5] E.S. Paul *et al.,* Phys. Rev. C **51**, 78 (1995).

[6] M.P. Carpenter *et al.,* Z. Phys. **A358**, 261 (1997).

[7] D. Seweryniak *et al.,* Phys. Rev. C **55**, R2137 (1997).

[8] D. Seweryniak *et al.,*, in *Proc. of the Conf. on Nuclear Structure at the Limits*, Argonne, Illinois, 1998, Vol. II, p. 247.

[9] M.P. Carpenter *et al.*, Phys. Rev. Lett. **78**, 3650 (1997).

[10] R.B.E. Taylor *et al.,* Phys. Rev. C **54**, 2926 (1996).

[11] S. Hofmann *et al.,* Z. Phys. **A333**, 107 (1989).

[12] W. Nazarewicz, Phys. Lett. **B305**, 195 (1993).

[13] G. Dracoulis, Phys. Rev. C **49**, 3324 (1994).

[14] M. Muikku *et al.,* Phys. Rev. C **58**, R3033 (1998).

[15] C.-H. Yu *et al.,* submitted to Phys. Rev. C.

[16] C. Gross *et al.,* in *Proc. Int. Conf. on Exotic Nuclei and Atomic Masses*, AIP Conf. Proc. Vol. **455**, 444 (1998).

[17] M.P. Carpenter *et al.,* in *Proc. Conf. Nuclear Structure '98*, Gatlinburg, Tennessee, 1998, Vol. **I**, p. 13.

[18] D. Seweryniak, Bull. Am. Phys. Soc. **43**, 1545 (1998).

[19] J. Uusitalo *et al.,* Bull. Am. Phys. Soc. **43**, 1572 (1998).

[20] C.N. Davids *et al.,* Phys. Rev. C **55**, 2255 (1997).

[21] C.N. Davids *et al.,* Phys. Rev. Lett. **80**, 1849 (1998).

[22] V.P. Bugrov and S.G. Kadmenskii, Sov. J. Nucl. Phys. **49**, 967 (1989).

[23] P. Möller *et al.,* At. Data Nucl. Data Tables **66**, 131 (1997).

[24] H.W. Gaggeler *et al.*, Nucl. Phys. **A502**, 561c (1989).

[25] P. Reiter *et al.,* Phys. Rev. Lett. **82**, 509 (1999).