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Study of Nuclei Far from Stability with the AYE-Ball Array

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The coupling of a Compton-suppressed Ge (CsGe) detector array to a recoil mass separator (RMS) 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 approaching 100 nb. In this paper, results from the coupling of a modest array of CsGe detectors (AYE-Ball) with a recoil separator (FMA) will be presented.

I. INTRODUCTION

The wide use of Compton-Suppressed Ge (CSGe) detector arrays for nuclear structure studies began in the 1980's. These arrays held between 10 and 20 detectors and were used initially to measure high-spin states in deformed nuclei. Presently, a large fraction of the measurements performed with current generation CsGe arrays are directed at the study of superdeformed (SD) nuclei. These new spectrometers (Gammasphere, Eurogam and Gasp) are ideally suited for these types of measurements, and there are a still number of open questions involving SD nuclei which require further attention. However, the large segmentation and efficiency of these new arrays also allow for the study of excited states in nuclei situated in regions of the chart of nuclides which were unaccessible using previous generation gamma-ray spectrometers.

Several of these areas lie on the neutron-rich side of stability. While a systematic study of nuclei in this region will have to wait for neutron-rich radioactive beams, certain mass regions are accessible for γ-ray studies using a number of different techniques. For example, gamma-ray spectrometers have been used for a number of years to measure γ rays emitted from fission fragments [1]. These studies have provided a wealth of information on the structure of neutron-rich nuclei. The contribution to this conference by P. Daly [2] illustrates how this technique coupled with the improved sensitivity of Eurogam has allowed for the identification of excited states in neutron-rich nuclei around doubly magic ^{132}Sn. Another recent investigation has examined the feasibility of measuring high-spin states in neutron-rich nuclei with Gammasphere via deep inelastic reactions [3]. Other studies have begun to Coulomb excite neutron-rich radioactive beams produced via a multi-fragmentation reaction. Due to the Doppler broadening of the γ transitions emitted from these fast moving ions (v/c$\sim$0.3), high-resolution measurements are not possible. As a result, these experiments have used arrays of NaI detectors to measure the 2^+-0^+ transition in nuclei around Z=16 and N=24 [4,5].

On the proton-rich side of stability, the large CSGe gamma-ray arrays allow for the opportunity to measure excited states in nuclei at and beyond the proton-drip line. Since the cross-sections for producing the most proton-rich residues via fusion-evaporation reactions are small and compete with channels with much larger cross-sections, nuclide identification becomes essential for associating γ rays to specific isotopes.

Two techniques to identify residues are currently in use for these types of reactions. The first involves the measurement of evaporated particles, *i.e.* neutron, protons, and α particles, in coincidence with γ rays. The number and type of particles measured give some degree of nuclide identification. The contribution by H. Grawe [6] illustrates how this method has been used to identify for the first time states in nuclei near doubly magic ^{100}Sn.

The second technique measures the mass of the residue in coincidence with its emitted γ rays. The following sections will illustrate how this technique has been used to measure excited states in nuclei near the proton-drip line by coupling a modest gamma-ray array (AYE-Ball) to a new generation recoil separator (FMA).

II. THE AYE-BALL ARRAY

Recoil mass separators have a long history of use, however, the coupling of a gamma-ray array to such device has been limited [7]. Some of the pioneering work in this area was performed at Daresbury where the CsGe detector array Tessa was placed at the target position of the Daresbury Recoil Mass Separator [8].

In the 1990's, several new recoil mass separators have come on line. One such device is the Fragment Mass Analyzer (FMA) which is installed on a beam-line of the ATLAS accelerator at Argonne National Laboratory [9]. The device 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. Figure 1 is a schematic diagram of the FMA and shows the configuration of the two electric dipoles and magnetic bending magnet which constitute the mass spectrometer. The FMA has an energy acceptance of ±20% and a M/Q acceptance of ±4%.

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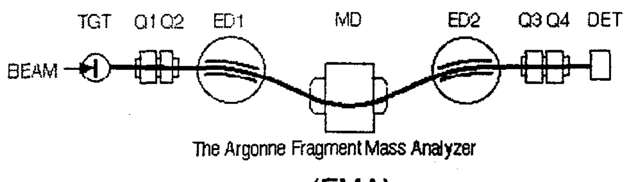

FIG. 1. Schematic diagram of the Fragment Mass Analyzer (FMA).

A number of experiments have been performed with the FMA coupled to an array of 10 Compton-suppressed Ge detectors (see for example ref. [10]). This configuration corresponds to a 2 fold increase in efficiency for measuring recoil-γ coincidences over that of the Daresbury RMS when coupled to the Tessa array.

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. Figure 2 shows a CAD drawing of the support frame indicating where the Eurogam and Tessa shields were placed relative to the beamline and FMA. This support frame was designed at Daresbury laboratory and fabricated at Edinburgh University. For the experiments performed with AYE-ball, nine large Ge detectors ($\sim$ 70%) were available; seven from Eurogam, and one each from Argonne and Yale. Ten small ($\sim$ 25%) co-axial detectors were available for placement into Tessa-like shields, and these detectors came from Daresbury, Yale and Manchester. When fully loaded with detectors, the array had a photo-peak efficiency of 1.1% for 1 MeV γ rays, giving a factor of eight increase in

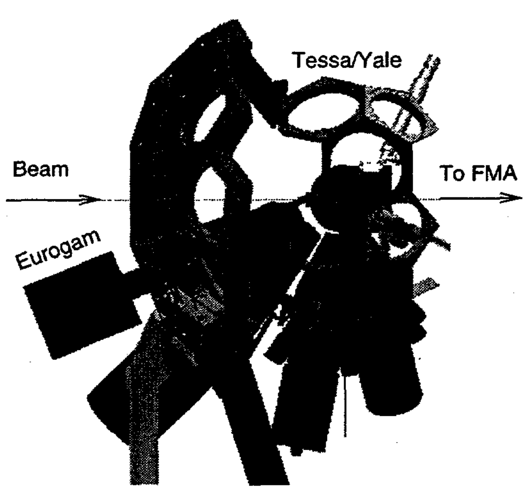

FIG. 2. Diagram of the support frame for AYE-Ball.

efficiency for detecting recoil-γ coincidences over that of the coupling of Tessa to the Daresbury RMS.

A number of other detectors were available for use with this setup. At the target position, two LEPS counters from Yale were at times placed in the array, and evaporated neutrons were detected by a ring of 11 NE213 liquid scintillator counters mounted on the quadrupole immediately in front of the FMA. A variety of detectors were used in conjunction with the PPAC focal plane detector including a split anode ionization chamber, a 48x48 double-sided silicon-strip detector and a 50% Ge detector.

Thirteen experiments were performed with the array over a three month period involving forty scientists from 13 countries. Nearly all the experiments were directed at nuclei at or near the proton-drip line and covered a mass range from A=24 to A=226.

III. N=Z NUCLEI

The N=Z nuclei between Z=28 and Z=50 closely follow the proton-drip line, and offer a particularly interesting laboratory for nuclear structure studies. In this region, the single-particle spectrum shows large gaps as a function of deformation. The N=Z symmetry reinforces these gaps resulting in predictions of large shape changes and shape coexistence in these nuclei. Experiments carried out at the Daresbury RMS measured the $2^+ - 0^+$ transitions in the N=Z nuclei of this region up to ^{84}Mo [11], showing for example that $^{80}_{40}$Zr is highly deformed in its ground state [8]. Other issues to address which are related to the N=Z symmetry include measuring and quantifying the decline of isospin purity [12] and determining the importance of T=0 and 1 n-p pairing [13].

Four of the experiments performed with AYE-Ball were directed at the study of N=Z nuclei. Three were led by groups from Surrey and Daresbury utilizing the reactions: (a) ^{54}Fe + ^{36}Ar at 120 MeV; (b) ^{58}Ni + ^{36}Ar at 120 MeV; and (c) ^{40}Ca + ^{24}Mg at 65 MeV in order to identify for the first time excited states in the N=Z nuclei ^{88}Ru, ^{92}Pd and ^{62}Ga, respectively. The fourth experiment was led by C.J. Lister at Argonne and attempted to confirm and extend the level structure of ^{68}Se using the reaction ^{12}C + ^{58}Ni at 200 MeV. One other experiment on nuclei in this region was led by D. Seweryniak (ANL) and attempted to identify states in ^{103}Sn.

For all these experiments both the neutron detectors and ionization chamber were in place. The ionization chamber provided Z-identification to the mass identified ions. While the data from these experiments are still under analysis, an example of the Z-selectivity is given in fig. 3 where it is shown that Z=30 (^{61}Zn) lines from the 2pn channel can be cleanly separated from the dominating 3p lines associated with ^{61}Cu in the A=61 gated spectrum.

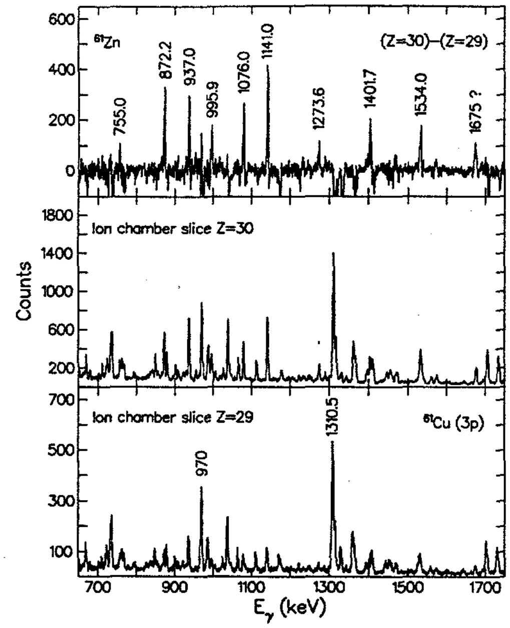

FIG. 3. Spectrum showing the Z discrimination from the ionization chamber for A=61 recoils in the ^{24}Mg+^{40}Ca experiment. The $^{61}_{30}$Zn (2pn) lines can be clearly separated from the dominant $^{61}_{29}$Cu (3p) lines.

IV. RECOIL DECAY TAGGING EXPERIMENTS

Above the closed shell at Z=50, many nuclei near the proton-drip line decay by the emission of an α particle. Beyond the proton-drip line, odd-Z nuclei are observed to decay via the emission of a proton, and the identification of new proton emitters using the FMA has been a major focus of study at ATLAS over the last several years (see for example ref. [14]). A number of experiments with AYE-Ball were performed on Z> 50 nuclei which are near or at the proton-drip line. For these experiments, nuclide identification of γ rays was made using the Recoil-Decay Tagging (RDT) method. This technique correlates 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 allowing for isotopic identification of the mass separated residue and its associated prompt γ rays. The method was first employed at GSI using an array of NaI detectors and the SHIP velocity filter [15]. However, it was not until the technique was used with a CSGe array that the promise of the method to measure excited states in nuclei at the proton-drip was demonstrated [16].

One of the experiments performed with AYE-ball was on ^{156}Hf [17], an N=84 nucleus which lies very near the proton-drip line. In this experiment, 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 [19].

Figure 4a 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 4d 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, however, these lines represent less than 3% of all α decays measured in the DSSD.

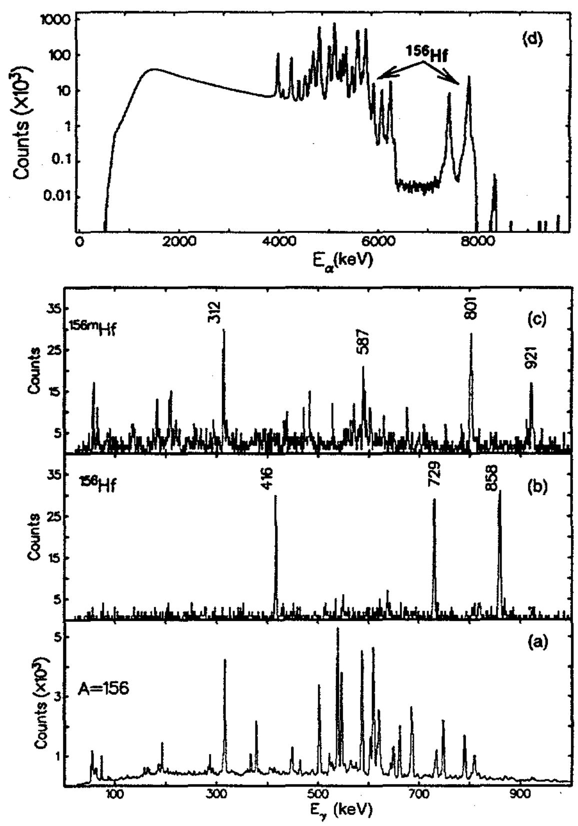

FIG. 4. (a)Gamma-ray spectrum in coincidence with A=156 residues. (b) Gamma-rays in coincidence with the ground-state α decay of ^{156}Hf. (c) Gamma-rays in coincidence with the α decay of the isomer in ^{156}Hf. (d) Charged particle decay spectrum measured in the DSSD.

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. 4b and c. The spectrum correlated with the ground-state decay shows only three γ transitions of equal intensity. Conversely, the spectrum correlated with the α decay of the isomer 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. 4a), 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. 5 indicates, the 6^+ level lies 44 keV higher in energy than the

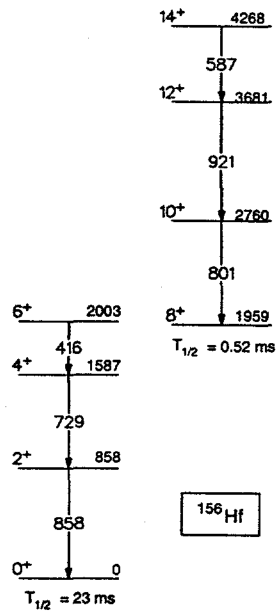

FIG. 5. Preliminary level structure for ^{156}Hf.

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 $h_{11/2}$ proton and $h_{9/2}$ neutrons coupled to I=1.

Many more γ rays are observed in the spectrum correlated with the decay of the 8^+ isomer, and these must correspond to transitions between 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. 5.

Another region examined with AYE-Ball concentrated on Hg isotopes with $N < 100$. For Hg isotopes between N=100 and 108, shape coexistence has been established close to the ground state where rotational bands built on weakly-deformed oblate ($\beta_2 \sim -0.15$) and moderately deformed prolate ($\beta_2 \sim 0.25$) shapes are observed. In addition, a recent paper presented results from Nilsson-Strutinsky calculations [20] which predict the existence of strongly deformed oblate states with $\beta_2 \sim -0.35$ at excitation energies around 2.5 MeV for $N \leq 104$ for Pb isotopes as well as excited SD minimum with $\beta_2 = 0.5-0.56$ for Hg and Pb isotopes with $N \leq 98$. The SD minima are calculated to be between 3.5 and 5 MeV above the ground state which is comparable to the excitation energy calculated for the SD well in Hg-Pb nuclei with $N \geq 110$.

With these past results and 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 at beam energies of 340, 360 and 380 MeV [21]. The assignment of γ-ray transitions to a particular nuclide was made using the RDT method described above. As an example,

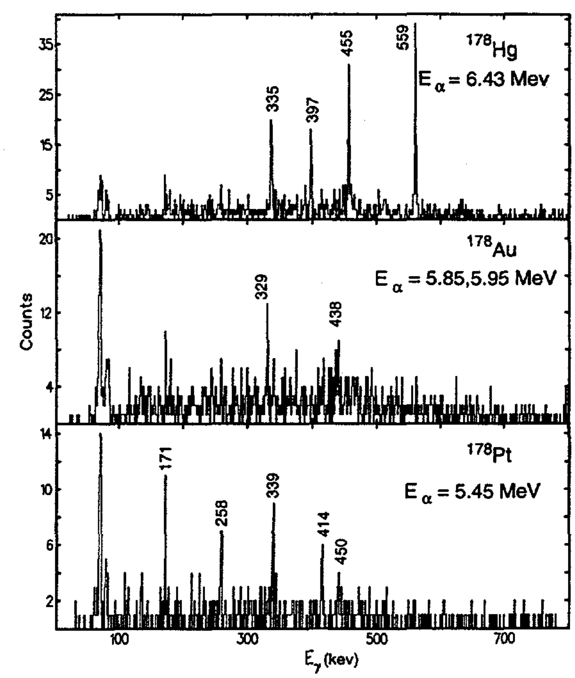

FIG. 6. RDT gated spectra for A=178.

fig. 6 shows the γ-ray spectrum produced when tagging on the α decays of ^{178}Pt, ^{178}Au and ^{178}Hg. The transitions correlated with the decay of ^{178}Pt agree with those previously measured. The four transitions associated with ^{178}Hg are presumably members of the yrast rotational band with the sequence 397, 355, 455, 559 keV defining the $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade. The ordering in based on the intensity of transitions determined from the RDT gated spectrum. The γ-γ-recoil data confirm that these four transitions are in coincidence with each other, however, the lack of statistics makes it difficult to confirm the proposed sequence. In ^{176}Hg, only one γ ray (615 keV) was observed to be correlated with the ground-state α decay of ^{176}Hg, and this γ ray is assigned to the $2^+ - 0^+$ transition in ^{176}Hg.

Figure 7 plots the excitation energies of the 2^+ and

4^+ states in a series of even-even Hg isotopes centered around N=102. The open circles correspond to levels newly identified with AYE-Ball. The minimum in excitation energy observed at N=102 is not due to an increase in deformation of the ground-state, rather it results from the crossing of the excited prolate band with the oblate ground state configuration. Two trends can be inferred from the newest data. In ^{178}Hg, the prolate band does not cross the oblate band until I=6. This also implies that the 2^+ levels in ^{176,178}Hg are not influenced by the prolate band, and thus the continual increase in excitation energy of this level suggests an evolution from an oblate deformed to spherical ground state as N decreases.

Several other RDT measurements were performed with AYE-Ball. For example, γ-ray transitions correlated with the proton decay of the ground state and an isomeric state in ^{147}Tm have been measured [17], as well as γ rays correlated with the α decay of ^{200}Ra [22].

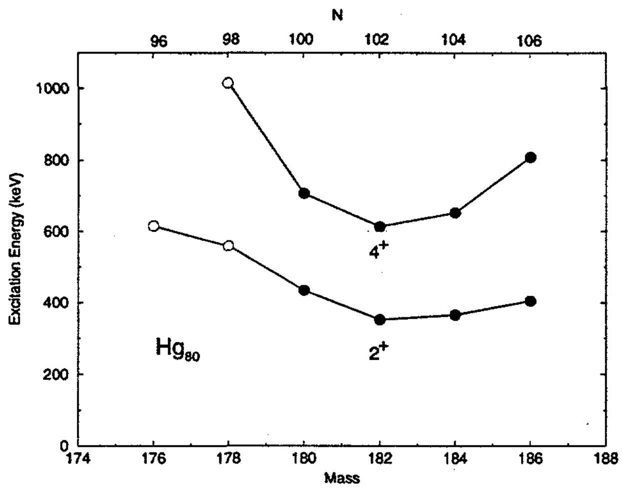

FIG. 7. Systematics of 2^+ and 4^+ excitation energies in Hg nuclei around N=102. The open circles correspond to states measured with AYE-Ball.

V. SUMMARY

This contribution has described results from experiments using a modest array of CsGe detectors coupled to a recoil mass spectrometer. These experiments have shown the viability of measuring excited states in nuclei at and beyond the proton-drip line. The minimum cross-sections measured were on the order of 1μb. Gammasphere, a 110 CSGe detector array, will operate at ATLAS in 1998. The coupling of this device to the FMA will increase the γ-recoil sensitivity down to 100 nb and should allow for a mapping out of excited states in nuclei at the proton-drip line.

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