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HIGH-SPIN STATES OF $^{174,176}\text{Yb}$ STUDIED IN COULOMB EXCITATION WITH Kr AND Xe BEAMS*

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ABSTRACT

Rotational states up to spin 20^+ (18^+) in ^{174}Yb (^{176}Yb) have been Coulomb excited using beams of ^{136}Xe . Lifetimes up to and including the 14^+ state have been measured using Doppler-broadened lineshape techniques with ^{136}Xe and ^{86}Kr beams. An annular gas-scintillation counter has been developed in order to perform particle- γ coincidence studies. Moments-of-inertia in $^{174,176}\text{Yb}$ behave very regularly, showing no signs of back-bending effects. The measured lifetimes are in agreement with the rotational model predictions, and the measured cross-sections for Coulomb excitation of the high-spin states are in agreement with the semiclassical Winther-deBoer calculation.

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1. INTRODUCTION

The availability of beams of Kr and Xe at energies up to 8.5 MeV/nucleon has opened up the possibility of Coulomb exciting high-spin states in stable and near-stable deformed nuclei. In the actinide region, states up to spin 18^+ for ^{232}Th and 22^+ for ^{238}U have been observed by Coulomb excitation with Kr and Xe beams^(1,2,3). In recent studies of the rare-earth region, Kearns et al⁽⁴⁾ have identified some 12^+ and 14^+ states using ^{84}Kr ions at about 350 MeV. Coulomb excitation of rare-earth nuclei with projectiles sufficiently heavy so that states of angular momentum larger than 16 are populated is quite interesting since:

(i) the method of populating states is different than from a (HI, xn) reaction, so that additional states may be seen. Of particular interest in this region is the study of backbending nuclei. Since backbending usually occurs between spins 14^+ to 18^+ , all studies up to now have involved (HI, xn) reactions, in which the observed levels are almost exclusively yrast (or near-yrast), and there may not be any direct structural connection between levels below and above the backbend. In Coulomb excitation, levels related to the ground band by collective E2 transitions will be populated most strongly; they may or may not be yrast levels.

(ii) some nuclei that cannot be reached by (HI, xn) reactions can be Coulomb excited. Examples of this type would be the actinides and the neutron-rich rare-earth nuclei, including ^{174}Yb and ^{176}Yb . Until recently, there existed essentially no information on high-spin states in such nuclei, although the levels in neutron-rich rare-earth

nuclei may provide a clue to distinguish among the possible origins of backbending.

Another important aspect of Coulomb excitation studies of high-spin states is the evaluation of quantal corrections to the semi-classical calculation of the Coulomb excitation process⁽⁵⁾. So far quantum-mechanical calculations have been performed only up to spin 10^(6, 7); however, they can be estimated from a comparison between the direct measurement of the lifetime of the state of interest and the lifetime deduced from the experimental yields by means of the semi-classical approximation. The analysis of the Doppler-broadened line-shape of the deexcitation γ -rays provides a direct measurement of the lifetime for high-spin states.

2. EXPERIMENTAL PROCEDURE

In a series of experiments, thin ($\sim 1 \text{ mg cm}^{-2}$) and thick ($\sim 30 \text{ mg cm}^{-2}$) foils of $^{174}, ^{176}\text{Yb}$ have been bombarded with beams of ^{86}Kr and ^{136}Xe from the Berkeley Super-HILAC. Various energies in the neighborhood of 380 MeV and 595 MeV respectively, were used. They were chosen to be at least 10% lower than the Coulomb barrier, B , calculated according to the prescription:

$$B = \frac{Z_1 Z_2 e^2}{1.16(A_1^{1/3} + A_2^{1/3} + 2)}$$

so that there should be no effects from the nuclear interaction. The beam energies were determined to $\pm 1\%$ by a time-of-flight technique.

De-excitation γ -rays were detected primarily in two 40 cc coaxial Ge(Li) counters in both singles and γ - γ coincidence modes. However in some experiments, 7.5 x 7.5 cm NaI(Tl) counters were also used in a

variety of multi-coincidence modes with the Ge(Li) counters.

In addition to studying the γ -spectrum in singles and multi-coincidence modes, we have used an annular particle detector and have detected γ -rays in coincidence with specified ranges of the particle scattering angle. A description of this apparatus and some of the problems encountered with more conventional particle detectors is given in the appendix.

In order to avoid contamination of the spectra from lines associated with projectile excitation, we have used the isotopes ^{86}Kr and ^{136}Xe for this study. These nuclei have closed neutron shells, consequently their 2^+ levels are excited less strongly than those of the more abundant Kr and Xe isotopes.

2.1 Singles γ -ray Spectra

Typical singles spectra recorded with a Ge(Li) detector at zero degrees to the beam direction are shown in Figs. 1 and 2. In these experiments, the targets were $\sim 30 \text{ mg cm}^{-2}$ foils of separated Yb isotopes in metallic form, and were sufficiently thick to stop the beam and all recoils. The most noticeable feature in these spectra is the pronounced Doppler broadening of the lineshapes. As would be expected for the Doppler effects in a solid target, the broadening effect becomes progressively enhanced with decreasing lifetime (increasing spin).

Spectra were also recorded at 90° to the beam direction; however, the broadening effects were found to be comparable to those shown at 0° . This is contrary to experience with lighter ions, and

has its origin in the wide range of recoil angles (typically 5° to 50° in the lab) contributing to the high-spin cross-section.

The broadening of lineshapes for the high-spin states considerably decreased the sensitivity of the detection technique and made it difficult to extract reliable values for the relative γ -ray intensities. On the other hand, analysis of the lineshapes gave measurements of the lifetimes as we shall show in section 2.4. The γ -ray relative intensities from these experiments are summarized in Table 1. For the high-spin states we have made a careful comparison of the data with the calculated lineshapes (Figs. 12, 13) so that problems with the integration ranges, background regions and contaminant peaks could be dealt with in the most reliable way. Table 1 also shows a comparison with a Winther-deBoer calculation⁽⁵⁾ which will be discussed in section 3.2.

2.2 Particle-Gamma coincidences (thick target)

We have performed a particle-gamma coincidence experiment in which scattered ^{86}Kr ions were detected in the angular range $100^\circ \leq \theta \leq 150^\circ$. The annular counter described in the appendix was employed for this purpose. Two Ge(Li) detectors were used at 0° and 90° . Typical spectra are shown in Figs. 3-6. The 90° spectra were used to determine γ -ray energies up to $14^+ \rightarrow 12^+$ and the corresponding stopped-peak positions are indicated on the 0° spectra. Analysis of the 0° lineshapes is discussed in section 2.4. Relative intensities are shown in Table 2.

In this experiment it was not possible to make a precise comparison with the Coulomb excitation calculation because there were many uncertainties in calculating the effective penetration depth of the Kr ions in the target. Our best estimate of the calculated yield is shown in Table 2.

2.3 Particle-Gamma coincidences (thin target)

The very highest spin states can be observed only if the Doppler-broadening problem can be solved. To accomplish this we have performed experiments with thin Yb foils in which the recoiling nuclei escaped the foil with very little energy loss, thus eliminating Doppler attenuation. To make the lineshape narrow also required that the range of recoil velocities and angles be defined kinematically; that is, by selecting a relatively narrow band of scattered Xe ions. This was done by particle-gamma coincidences, detecting scattered Xe ions in the annular counter described in the appendix.

We will briefly review the factors influencing the choice of geometry. To maximize the yield in this experiment requires that the detection annulus should subtend angles close to the peak of the differential cross section for the interesting states. This is indicated in Fig. 7. For a given projectile detection annulus of width $\Delta\theta$ positioned at θ , the spread of recoil velocities becomes greater and the cone of the recoils opens up to larger angles, as θ is moved forward. This makes the smearing effect of the γ ray detector size considerably worse. Also at angles approaching 90° the recoils correspond to forward scattering of Xe ions, so that their number is several orders of magnitude larger than that of the Xe ions detected at the same angle, but, as can be seen in Fig. 7, the energy of these recoils at the detection annulus goes down very rapidly as θ increases towards 90° . Consideration of these factors led us to believe that the detection annulus $80^\circ \leq \theta \leq 100^\circ$ is probably optimal for the Xe on Yb system. To do this requires that the target be tilted out of the plane perpendicular

to the beam direction. There will then be two small dead regions of azimuth shadowed by the target foil and its frame.

Results obtained in this configuration are shown in Fig. 8. It is interesting that the $4 \rightarrow 2$ and $6 \rightarrow 4$ transitions of the ground band, and the $2 \rightarrow 0$ transition in ^{136}Xe were doublets. The lower energy components of the $4 \rightarrow 2$ and $6 \rightarrow 4$ transition were due to γ -coincidence with recoiling ^{176}Yb nuclei detected in the particle counter. In that case ^{176}Yb nuclei were moving in a plane almost perpendicular to the γ -detector, so that the lines appeared close to their unshifted energy. The same effect was responsible for the splitting of the ^{136}Xe line; however, in that case it was the higher energy component which was in coincidence with the Yb recoils.

The sensitivity of the method was improved further by demanding an additional γ -ray event to be detected in either of two 7.5×7.5 cm NaI(Tl) detectors placed at $\pm 90^\circ$. All events in the range $100 \leq E_\gamma \leq 900$ keV were accepted from the NaI(Tl) detectors. This additional γ -ray condition had the effect of suppressing low-multiplicity events, whilst γ -rays in paths of high multiplicity (e.g. $20^+ \rightarrow 18^+$) were not affected. The spectra are shown in Figs. 9 and 10. Comparison of the γ -p coincidences and γ - γ -p coincidence for ^{176}Yb (Figs. 8 and 9) shows that multiplicity selection suppressed some of the background and γ -peaks corresponding to detection of Yb recoils. This is to be expected since they correspond to very forward Xe scattering ($\sim 10^\circ$ in the center-of-mass system) which only weakly excites the nucleus, i.e., has low multiplicity.

True γ -ray energies were obtained from these spectra by calculating the Doppler shift based on kinematics, and the differential cross sections

obtained from the Winther-deBoer program. The uncertainty in the procedure was estimated to be ± 5 keV for the highest energy transitions. Results are shown in Table 3.

We have compared the relative γ -ray yields observed in these experiments with the Coulomb excitation calculation shown in Table 3. The uncertainty in the calculation arises in knowing precisely the range of scattering angles seen by the particle detector. Also since the recoils escaped the foil at very high recoil velocity, there could be marked deorientation effects which also introduce uncertainties up to the 20% level⁹⁾. In principle, with tighter control of the beam-spot size, and better masking of the particle detector, these problems could be solved if the deorientation effect could be determined empirically.

2.4 Extraction of lifetimes from lineshape analysis

Several groups have recently studied γ -ray lineshapes in multiple Coulomb excitation^{3,4,10,11)}. The computer code used here is a modified version of the one developed at Chalk River, and since in general principles it is very similar to that described in detail by Inamura et al.¹²⁾, we shall mention only some of the important differences.

The electronic stopping powers were taken from the tables of Northcliffe and Schilling¹³⁾ (N-S) but were normalized to include the medium dependences given by Ziegler and Chu¹⁴⁾ (Z-C). This was done by scaling the Yb in Yb value given by N-S, at a given E/A, by the discrepancy between the N-S and Z-C tables for ⁴He ions, at the same value of E/A. For the Yb stopping medium this was a fairly small correction; however, for the lighter rare-earths the correction is appreciable at low

velocities. Nuclear stopping powers were taken from a parametrization of the LSS theory¹⁵⁾ given by Winterbon et al.¹⁶⁾. The prescription of Blaugrund¹⁷⁾ was used to take into account effects of large-angle scattering.

States up to and including the 20^+ member of the ground band were included in the Winther-deBoer calculation of the differential cross section. Cascade feeding of up to six levels ($J_{\max} \leq 20$) were taken into account in the lineshape calculation.

In the first analysis we used rotational matrix elements in the Winther-deBoer calculation. Uncertainties in these matrix elements affect the calculation in two ways. Firstly, changes in the matrix elements at the 10% level produce small effects on the angular distribution of excited recoils; however, this has negligible effect on the derived lifetimes. More important is the direct change in the feeding intensities resulting from changes in the matrix elements. In cases where there was a discrepancy between the experimental populations and those calculated by the Winther-deBoer program, the weighting of the various recoil angles for that state were scaled overall by a factor to make the total intensities agree with experiment. Since the calculated yields were always close to those measured, cf. Tables 1 and 2, these changes were expected to have negligible effects on the derived lifetimes.

The program calculated the lineshape expected for a γ -detector of perfect resolution. This spectrum was then convoluted with the detector response. The response function of the detector was taken from the $4^+ \rightarrow 2^+$ transitions which do not have lineshape broadening due to Doppler effects. But because the full-width at half-maximum of the

photopeak in a Ge(Li) detector changes with increasing γ -ray energy, these lineshapes were not appropriate for γ -rays of higher energy. Using a simple convolution procedure on the $4 \rightarrow 2$ lineshapes we were able to reproduce the observed changes in resolution (FWHM) from a ^{152}Eu source and thereby "tailor" the standard lineshape to a given γ -ray energy.

The final step in the calculation was normalization of the experimental and calculated lineshapes to the same total intensity, and calculation of χ^2 for the fit. The lifetime was taken to be that value which gave minimum χ^2 . Analysis proceeded from the highest spin transition observed, using rotational lifetimes for its feeding γ -rays. This experimental result could then be applied in analysing the next highest transition, and so on down the band.

Results for singles γ -ray spectra with ^{86}Kr and ^{136}Xe are shown in Figs. 11-14. Contaminating γ -rays which were obviously not part of the lineshape structure were excluded from the χ^2 of the fit. These points are indicated by open symbols in Figures 11-14.

A test of our ability to describe the recoil distribution was provided by γ -ray lineshapes encountered for recoils from a thin foil. A typical example is shown also in Figure 11. The calculated fit was obtained using the DBLS program with the lifetime of that state and all precursors set to $< 10^{-15}$ seconds. The calculated lineshape agrees very closely with that observed indicating that the "mix" of recoil angles in the calculation was close to the actual situation.

Results for the coincidence lineshapes shown in Figures 15 and 16, were obtained in a similar manner as for the singles spectra. However, in these cases the integration over scattering angle and bombarding

energy was performed only over those regions observed in the annular particle detector. The uncertainty in this part of the calculation is difficult to estimate, but if the "mix" of recoil angles and energies is crudely correct, then the uncertainty in the lifetime should be small, provided the feeding intensities are correct. A check on this assumption is provided by the agreement (within 20%) of the experimental relative γ -ray intensities (Table 2) with those calculated with the "mix" used in the DBLS calculation. Furthermore, in experiments with thin foils (section 2.3), we found that the lineshapes observed even for very high-spin states are much narrower than those observed in the thick-target coincidence experiment (Figs. 15 and 16). This shows that we are far from the limit $\tau = 0$ for the lifetimes and therefore less sensitive to the "mix" used in the calculation.

Results are shown in Table 4. The uncertainty in the electronic stopping power is believed to be $\leq 10\%$, which translated to $\sim 10\%$ uncertainty in the lifetime at these high recoil velocities. The uncertainty in the nuclear stopping can be neglected at the high recoil velocity. The statistical error was obtained in the usual way from the χ^2 plot. For the lowest spin states, we have included effects due to uncertainties in the feeding life-times.

It is difficult to assign final uncertainties to the lifetimes. The consistency of the three sets of measurements shown in Table 4 is reasonably good and checks certain aspects of the method. For example, the singles Kr and Xe results involve rather different energy regions of the stopping-power curve, and their agreement indicates that the stopping power used must have the correct dependence on recoil energy.

The relative importance of the feeding corrections also changes quite significantly between the three sets of data.

3.1 Comparison of the lifetimes with the rotational model

A summary of the experimental lifetimes is shown in Figure 17, where they are compared to the rotational values. For the $^{174}\text{Yb } 8^+ \rightarrow 6^+$, $10^+ \rightarrow 8^+$ and $12^+ \rightarrow 10^+$ transitions, the present measurements agree with the second set of Manchester values¹⁸⁾ (Table 4) within their combined errors; however, the present adopted values tend to be systematically about 8% higher. The Manchester data were obtained using a ^{84}Kr beam with γ -rays detected in singles, and if we make the comparison with the present ^{86}Kr singles data only, the systematic discrepancy is reduced to +5%, of which about +3% can be attributed to the different choice of stopping powers.

To within an accuracy of $\sim 13\%$ the average of the measured transitions in both ^{174}Yb and ^{176}Yb are consistent with the rotational model. However, there might be a systematic trend for the measured ratios to decrease with increasing spin.

3.2 Comparison of the yields with the semiclassical calculation

Primary γ -ray yields normalized to the $6^+ \rightarrow 4^+$ transition are shown in Table 1. The only correction applied in the experimental column is for the relative efficiency of the detector. Other corrections such as conversion coefficients, γ -ray angular distributions and feeding from higher states were included in the calculated numbers.

Excitation probabilities and total cross sections were obtained from the Winther-deBoer program including levels up to the 20^+ member of the ground band. E2 and E4 matrix elements were calculated according to the usual rotational expressions

$$M(E2; I_i \rightarrow I_f) = \sqrt{\frac{5}{16\pi}} (2I_i + 1)^{\frac{1}{2}} \langle I_i^{200} | I_i^{2I_f 0} \rangle. Q_0^{\lambda=2}$$

$$M(E4; I_i \rightarrow I_f) = \sqrt{\frac{9}{16\pi}} (2I_i + 1)^{\frac{1}{2}} \langle I_i^{400} | I_i^{4I_f 0} \rangle. Q_0^{\lambda=4}$$

based on the values shown in table 3. Since the vibrational levels of $^{174,176}\text{Yb}$ are known to be high lying and only weakly collective ¹⁹⁻²¹, they were not included in the calculation.

Integration over the thick target was performed from results of several separate runs of the program at bombarding energies spanning significant excitation in the foil. Stopping powers for the projectile were taken from the table of Northcliffe and Schilling corrected for material dependence as described in section 2.4.

In the present experiments there was very strong excitation of the target nucleus, so that the cross sections depend on many matrix elements. For example it is not possible to relate the cross section for exciting the 10^+ level to $B(E2; 8 \rightarrow 10)$ alone. The ratios of γ -ray intensities can be approximately related to $B(E2)$ values as follows:

$$r_{\text{exp}}(J) = I_{\gamma}(J + 2 \rightarrow J)_{\text{exp}} / I_{\gamma}(J \rightarrow J-2)_{\text{exp}}$$

$$r_{\text{calc}}(J) = I_{\gamma}(J + 2 \rightarrow J)_{\text{calc}} / I_{\gamma}(J \rightarrow J-2)_{\text{calc}}$$

and

$$R(J) = \frac{r_{\text{exp}}(J)}{r_{\text{calc}}(J)} \approx \frac{B(E2; J \rightarrow J + 2)_{\text{exp}}}{B(E2; J \rightarrow J + 2)_{\text{calc}}}$$

This approximation works rather well for states of sufficiently large J such that $\sigma_J > \sigma_{J+2}$ where σ refers to the direct excitation cross section. This happens at about spin 10^+ with Xe and spin 8^+ with Kr bombardments in the present cases. Tables 1 and 2 give values for the quantities $R(J)$ which according to the above analysis are approximately equal to

$B(E2; J \rightarrow J + 2)_{\text{exp}}$; $B(E2; J \rightarrow J + 2)_{\text{rotational}}$, since rotational matrix elements were used in the calculation, Figure 17 shows the results from table 1 compared with the lifetime measurements.

It has been pointed out^(6,22) that the quantal correction for the semi-classical calculation would be large for high multiplicity excitations. Exact quantum mechanical calculations have only been performed for spins up to 10^+ , but the corrections for the next higher spin states can be estimated by extrapolating the low-spin results⁽²³⁾. The corrections are estimated to be about -7% for the 12^+ and -11% for the 14^+ states in the ^{86}Kr experiment and -10% for the 16^+ and -14% for the 18^+ states in the ^{136}Xe experiment. By comparing the lifetimes or $B(E2)$ values obtained using the Winther-deBoer program with the results from the lifetime measurement, it is possible to determine the quantal correction from experiment. However, the results of the present measurements have uncertainties of the same magnitude as the estimated quantal corrections. Therefore it is not possible to determine the exact values of the quantal corrections, but it seems that the estimates are the upper limit of the quantal effect. Within their experimental errors, both types of measurements yield reduced transition probabilities in agreement with those for a rigid rotor, although the values from the line-shape analysis seem to show a slight downward trend with increasing spin.

3.3 Backbending in Yb nuclei

There is now considerable interest in high-spin states, due to the pronounced anomalies (backbendings) that have been observed around $I = 16$ in the ground-state rotational bands of some rare-earth nuclei. At least three explanations have been considered for these effects :

1) a collapse of the pairing correlations²⁴⁾; 2) a change in shape of the nucleus²⁵⁾; and 3) an alignment of the angular momenta of two particular high-j nucleons ($i_{13/2}$ neutrons in the light rare-earth region) with the rotational angular momentum of the core²⁶⁾. Most of the information on these high-spin states has come from studies of the gamma-ray de-excitation of (HI,xn) products. The present work has, however, provided the first data on neutron-rich rare-earth nuclei. The information on the high-spin states of the Yb nuclei from mass 164 to 176 is shown on the usual backbending type of plot in Fig. 18. Two interesting features are apparent in these plots. The first is that ^{168}Yb shows less backbending than its neighbors, ^{166}Yb and ^{170}Yb . This has been previously noted by Faessler²⁷⁾ and ascribed by him as a pairing effect due to the lower level density at just this neutron number (98). This kind of pairing effect was previously suggested²⁸⁾ to be responsible for the somewhat larger moments of inertia (compared with the neighboring nuclei) of the 98-neutron Hf and W isotopes. This explanation of the reduced backbending in ^{168}Yb is still consistent with the generally accepted idea that the backbending in this mass region is caused mainly by the alignment of two $i_{13/2}$ neutrons; since, in the alignment mechanism, the moment of inertia plays a strong role, and a larger groundband moment of inertia would certainly go in the direction of weakening the backbending. Thus a pairing explanation for the weak backbending of ^{168}Yb seems likely to be correct, although it is not clear whether the weaker pairing in ^{168}Yb prevents the alignment of the $i_{13/2}$ neutrons in the yrast states or just modifies it somewhat.

The other interesting feature in Fig. 18 is the very regular behavior of the high-spin states in $^{174,176}\text{Yb}$ compared with that of the lighter Yb isotopes. This behavior is easy to understand in the alignment model, and

was predicted to occur²⁶⁾. It happens because the alignment requires the low- Ω components from a j-shell, and (for a prolate shape) these essential components lie higher in energy as the shell fills. For example, the Fermi level is near the $\Omega = 5/2$ component of the $i_{13/2}$ shell in ^{167}Yb ; whereas, it is up to $\Omega = 9/2$ in ^{177}Yb . Thus one can easily understand why the alignment of two $i_{13/2}$ neutrons would be difficult in ^{174}Yb or ^{176}Yb . However, backbending does recur in the W and Os nuclei having neutron numbers similar to $^{174,176}\text{Yb}$. In these cases, it has been shown that the alignment of two $h_{9/2}$ protons play a major role in the backbending, and this process is less likely to occur in $^{174,176}\text{Yb}$ because: 1) Yb has fewer protons; 2) the moment of inertia is larger in the Yb region; and 3) ϵ_4 is less positive (β_4 less negative) for the Yb isotopes²⁹⁾. Thus the lack of backbending in $^{174,176}\text{Yb}$ seems quite consistent with our present understanding of this process.

4. CONCLUSION

Coulomb excitation with Kr and Xe ions appears to be a promising technique for the study of high-spin states in medium and heavy nuclei. Doppler-broadening effects severely limit the sensitivity of simple γ -ray techniques; on the other hand, these same broadening effects can be used to extract lifetimes which could not be obtained in any other way.

By allowing the recoils to escape into the vacuum and defining a relatively narrow band of recoil angles with particle coincidence, it is possible to obtain γ -ray peaks with a resolution of ~ 10 keV. With this technique we have shown that it is possible to see up to the transition $20^+ \rightarrow 18^+$ in ^{174}Yb .

Lifetimes measured by analysis of Doppler-broadened lineshapes in $^{176,174}\text{Yb}$ are in agreement with the rotational model up to the $14^+ \rightarrow 12^+$ transition. They are also in agreement with the lifetimes deduced from the experimental yields using the semiclassical Winther-deBoer calculation. This shows that the quantal corrections are small within the experimental uncertainty. The $B(E2)$ deduced from the Coulomb excitation yields are in agreement with the rotational model up to the $18^+ \rightarrow 16^+$ transition.

The absence of backbending in $^{174,176}\text{Yb}$ is consistent with the present theoretical understanding of the backbending process.

APPENDIX

A GAS-SCINTILLATION COUNTER FOR DETECTION OF VERY HEAVY IONS IN CLOSE GEOMETRY

In Coulomb excitation, the quality of gamma spectra can be improved by demanding coincidences with a specific range of particle scattering angles, chosen to maximize the differential cross section for the interesting states. In the present case, these are the high-spin states. With ions of $A < 40$ this was usually done by means of an annular silicon detector to cover the range $150^\circ - 170^\circ$. However, with very heavy ions, difficulties arise, and this method is no longer convenient. Coulomb excitation is strongest for the closest collisions, i.e., backward scattering in the center-of-mass system. With very heavy projectiles ($A > 100$), however, the optimum orbits correspond to a considerable shifting forward in the laboratory system. For example, with Xe on rare-earth targets, $d\sigma/d\theta$ for spin $18+$ peaks at $\theta_{\text{lab}} = 80^\circ$ (Fig. 7). Therefore a system allowing some flexibility in geometry is needed. In this range of detection angles, the rate of particles to be detected can be very high, limiting the lifetimes of silicon detectors to a few hours. A system allowing the detection of a high flux of particles during long periods of time is necessary.

We have therefore developed a gas-scintillation system (shown schematically in fig. 19), which covers efficiently angles where the maximum cross section is expected. The target can be placed anywhere inside the annulus, and it is a simple matter to arrange masks so that the detector is open to any desired range of particle trajectories in θ and ϕ .

The technology of gas scintillators is already fully documented³⁰⁾. The inside of the chamber was coated with a white reflecting paint and a

wave-shifter (quaterphenyl) was evaporated over the paint to a thickness of 50-100 $\mu\text{gm}/\text{cm}^2$. The wave-shifter was necessary since we used regular photomultiplier tubes which were not sensitive to the primary ultra-violet radiation from argon scintillations. Xe ions of less than 17 MeV were stopped in the $\sim 6.5 \mu\text{m}$ aluminized mylar window. This window was supported on longitudinal bars $\sim 0.5 \text{ mm}$ thick spaced 6.2 mm apart, and could withstand a pressure of 1 atm. All particle events were expected to produce a coincidence in the PM tubes because of the dispersing effect of the wave-shifter. In typical experiments the coincidence rate between the tubes was $\sim 80 \text{ kHz}$.

REFERENCES

1. E. Grosse, J. DeBoer, R. M. Diamond, F. S. Stephens, and P. Tjom, Phys. Rev. Lett. 35 (1975) 565.
2. P. Colombani, J. C. Jacmart, N. Poffé, M. Riou, P. P. Singh, C. Stephan, and A. Weidinger, Phys. Lett. 48B (1974) 315.
3. M. W. Guidry, P. A. Butler, P. Colombani, I. Y. Lee, R. M. Diamond, D. Ward, F. S. Stephens, E. Eichler, N. R. Johnson and R. Sturm (to be published, 1976).
4. F. Kerns, G. Dracoulis, T. Inamura, J. C. Lisle, and J. C. Willmott, J. Phys. A7 (1976) L11.
5. A. Winther and J. DeBoer, "Coulomb Excitation", Academic Press, New York, (1966) Pg. 303.
6. U. Smilansky, Nucl. Phys. A112 (1968) 185.
7. F. Rosel, J. X. Saladin and K. Alder, Computer Physics Communications 8 (1974) 35.
8. eg. D. Ward, International Conference on Reactions between Complex Nuclei, Nashville 1974, Pg. 417, North-Holland.
9. eg. D. Ward, H. R. Andrews, R. L. Graham and J. S. Geiger, Nucl. Phys. A234 (1974) 94 and references therein.
10. R. G. Stockstad, I. A. Fraser, J. S. Greenberg, S. H. Sie, and D. A. Bromley, Nucl. Phys. A156 (1970) 145.
11. S. H. Sie, H. R. Andrews, J. S. Geiger, R. L. Graham, and D. Ward, Bull. Am. Phys. Soc. II, 18 (1973) 629, and II 18 (1973) 1597.
12. T. Inamura, F. Kearns and J. C. Lisle, Nucl. Inst. and Methods 123, (1975) 529.
13. L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables A7 (1970) 23.

14. J. F. Ziegler and W. K. Chu, Atomic and Nuclear Data 13 (1974) 463.
15. J. Lindhard, M. Scharff and H. E. Schiott, Kgl. Danske Viv.Selsk.Mat. Fys. Medd. 33 (1963) #14.
16. K. B. Winterbon, P. Sigmund, and J. B. Sanders, Kgl. Danske Viv.Selsk. Mat.Fys. Medd. 37 (1970) #14.
17. A. E. Blaugrund, Nucl. Phys. 88 (1966) 501.
18. T. Inamura, F. Kearns, J. C. Lisle, G. Varley and J. C. Willmott. Annual Report 1974 Schuster Lab., University of Manchester, pg. 75.
19. R. O. Sayer, P. H. Stelson, F. K. McGowan, W. T. Milner and R. L. Robinson, Phys. Rev. C1 (1970) 1525.
20. Alan H. Shaw and J. S. Greenberg, Phys. Rev. C10 (1974) 263.
21. R. S. Simon, Thesis, Sektion Physik, Ludwig-Maximilians-Universität München, 1974.
22. K. Alder and H.K.A. Pauli, Nucl. Phys. A128 (1969) 193.
23. K. Alder, F. Roesel, and J. X. Saladin, Proc. Intl. Conf. of Reactions between Complex Nuclei, Nashville (1974) Vol. 1, p. 28.
24. B. R. Mottelson and J. G. Valatin, Phys. Lett. 5 (1960) 511.
25. P. Thieburger, Phys. Lett. 45B (1973) 417.
26. F. S. Stephens and R. S. Simon, Nucl. Phys. A138 (1972) 257.
27. A. Faessler, F. Grümmer, L. Lin, and J. Urbano, Phys. Lett. 48B (1974) 87.
28. F. S. Stephens, N. Lark, and R. M. Diamond, Phys. Rev. Lett. 12 (1964) 225.
29. F. S. Stephens, P. Kleinheinz, R. K. Sheline, and R. S. Simon, Nucl. Phys. A222 (1974) 235.
30. J. B. Birks, "Theory and Practice of Scintillation Counting" Pergamon Press 1964.

Table 1. Relative γ -ray intensities observed in Coulomb excitation of thick targets with a ^{136}Xe beam at 595 MeV. The experimental values refer to the actual γ -ray intensity corrected only for the efficiency of the detector. The effects of conversion, γ -ray angular distributions, and feeding from higher levels are included in the calculation.

Transition ^{174}Yb	E_γ (keV)	Total Con- version co- efficient	<u>Xe 595 MeV</u>				$R = \frac{r_{\text{exp}}}{r_{\text{calc}}} = \frac{I_\gamma(J)/I_\gamma(J-2)_{\text{exp}}}{(\text{calc})}$	
			Relative γ -ray Intensity					
			0 degrees		90 degrees		0 degrees	90 degrees
Exp.	Calc..	Exp.	Calc..					
6 $\rightarrow$ 4	272.9	0.098	100	100	100	100		
8 $\rightarrow$ 6	363.1	0.042	44	44.9	42	41.8	0.98 $\pm$ 0.06	1.01 $\pm$ 0.06
10 $\rightarrow$ 8	447.2	0.024	20	20.3	20	18.1	1.01 $\pm$ 0.08	1.08 $\pm$ 0.08
12 $\rightarrow$ 10	524.4	0.016	9	9.0	8	7.68	0.97 $\pm$ 0.15	0.93 $\pm$ 0.15
^{176}Yb								
6 $\rightarrow$ 4	293.1	0.079	100	100	100	100		
8 $\rightarrow$ 6	389.3	0.035	41	42.7	39	39.9	0.96 $\pm$ 0.06	0.99 $\pm$ 0.06
10 $\rightarrow$ 8	477.1	0.020	18	18.4	17	16.3	1.00 $\pm$ 0.08	1.05 $\pm$ 0.08
12 $\rightarrow$ 10	553.5	0.014	7	7.68	6	6.56	0.93 $\pm$ 0.15	0.94 $\pm$ 0.15
14 $\rightarrow$ 12	617	0.011	2	2.86	—	—	0.82 $\pm$ 0.25	—

Table 2(a). Relative γ -ray intensities observed in Coulomb excitation with ^{86}Kr and ^{136}Xe beams. The ^{86}Kr results were obtained in coincidence with ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$ from a thick target. The ^{136}Xe results were from a 1 mg.cm^{-2} target in coincidence with ions scattered in the annulus $80^\circ \leq \theta \leq 100^\circ$. The effects of conversion, γ -ray angular distribution and feeding from higher levels are included in the calculation.

Transitions in ^{174}Yb	E_γ (keV)	Relative γ -ray Intensities ^{86}Kr 365 MeV			Relative γ -ray Intensities ^{86}Kr 593 MeV		
		Exp.	Calc.	Ratio R.	Exp.	Calc.	Ratio R.
6 $\rightarrow$ 4	272.9 $\pm$ 0.4	100	100		100	100	—
8 $\rightarrow$ 6	363.1 $\pm$ 0.5	89	85.7	1.04 $\pm$ 0.07	91	90	1.01 $\pm$ 0.05
10 $\rightarrow$ 8	447.2 $\pm$ 1.0	79	76.1	1.00 $\pm$ 0.09	68	74	0.91 $\pm$ 0.06
12 $\rightarrow$ 10	524.4 $\pm$ 1.3	54	54.4	0.95 $\pm$ 0.15	55	62	0.97 $\pm$ 0.08
14 $\rightarrow$ 12	595.9 $\pm$ 1.7	22	26.3	0.84 $\pm$ 0.19	39	44	1.00 $\pm$ 0.11
16 $\rightarrow$ 14	660 $\pm$ 2.0				18	22.3	0.91 $\pm$ 0.16
18 $\rightarrow$ 16	719 $\pm$ 3.0				7.5	8.1	1.15 $\pm$ 0.22
20 $\rightarrow$ 18	774 $\pm$ 5.0				—	—	—

Table 2(b). Relative γ -ray intensities observed in Coulomb excitation with ^{86}Kr and ^{136}Xe beams. The ^{86}Kr results were obtained in coincidence with ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$ from a thick target. The ^{136}Xe results were from a 1 mg.cm^{-2} target in coincidence with ions scattered in the annulus $80^\circ \leq \theta \leq 100^\circ$. The effects of conversion, γ -ray angular distribution and feeding from higher levels are included in the calculation.

Transitions in ^{176}Yb	E_γ (keV)	Relative γ -ray Intensities ^{86}Kr 365 MeV			Relative γ -ray Intensities ^{136}Xe 593 MeV		
		Exp.	Calc.	Ratio R.	Exp.	Calc.	Ratio R.
6 $\rightarrow$ 4	293.1 $\pm$ 0.3	100	100		100	100	—
8 $\rightarrow$ 6	389.3 $\pm$ 0.6	92	85.5	1.08 $\pm$ 0.07	90	86	1.05 $\pm$ 0.07
10 $\rightarrow$ 8	477.1 $\pm$ 1.1	76	73.6	0.96 $\pm$ 0.10	69	72	0.92 $\pm$ 0.10
12 $\rightarrow$ 10	553.6 $\pm$ 1.5	44	47.4	0.88 $\pm$ 0.17	70	59	1.24 $\pm$ 0.13
14 $\rightarrow$ 12	617 $\pm$ 2.0	16	20.4	0.82 $\pm$ 0.22	35	36	0.82 $\pm$ 0.16
16 $\rightarrow$ 14	668 $\pm$ 3.0				15	15.6	0.99 $\pm$ 0.22
18 $\rightarrow$ 16	709 $\pm$ 4.0				—	4.8	—

Table 3. Intrinsic quadrupole and hexadecupole moments
used in the yield calculations

Nucleus	$Q_0^{\lambda=2}$ eb	$Q_0^{\lambda=4}$ eb ²
¹⁷⁴ Yb	7.73 ^{20,21)}	0.59 ²⁰⁾
¹⁷⁶ Yb	7.28 ¹⁹⁾	0.35 [†]
[†] Estimated from trends given in ref. 20).		

Table 4. Summary of lifetimes for rotational transitions in ^{174}Yb and ^{176}Yb

Transition ^{174}Yb	E_γ keV	Previous Lifetime, ^{4,18)} (ps)	Present Lifetime from DBLS (ps)				Rotational Lifetime (ps)
			^{86}Kr Singles	^{86}Kr Coinc.	^{136}Xe Singles	Present Average	
6 $\rightarrow$ 4	272.9	--	19 $\pm$ 7.0	—	21 $\pm$ 7.0	20 $\pm$ 5.0	26
8 $\rightarrow$ 6	363.1	6.3 $\pm$ 0.6 [5.6 $\pm$ 0.5]	5.5 $\pm$ 1.2	4.9 $\pm$ 1.2	5.3 $\pm$ 1.1	5.2 $\pm$ 0.7	6.33
10 $\rightarrow$ 8	447.2	2.48 $\pm$ 0.25 [2.36 $\pm$ 0.24]	2.15 $\pm$ 0.35	2.05 $\pm$ 0.3	2.25 $\pm$ 0.3	2.15 $\pm$ 0.2	2.22
12 $\rightarrow$ 10	524.4	1.03 $\pm$ 0.10 [1.00 $\pm$ 0.10]	0.98 $\pm$ 0.15	0.90 $\pm$ 0.15	0.95 $\pm$ 0.15	0.95 $\pm$ 0.10	1.00
14 $\rightarrow$ 12	596.0	--	—	0.60 $\pm$ 0.15	—	0.60 $\pm$ 0.15	0.52
<u>^{176}Yb</u>							
6 $\rightarrow$ 4	293.1	—	18.5 $\pm$ 6.0	—	—	18.5 $\pm$ 6.0	21
8 $\rightarrow$ 6	389.3	—	4.4 $\pm$ 1.2	4.5 $\pm$ 1.0	4.50 $\pm$ 1.2	4.45 $\pm$ 0.7	5.10
10 $\rightarrow$ 8	477.1	—	1.70 $\pm$ 0.25	1.75 $\pm$ 0.25	1.75 $\pm$ 0.7	1.73 $\pm$ 0.15	1.82
12 $\rightarrow$ 10	553.5	—	0.85 $\pm$ 0.15	0.85 $\pm$ 0.15	0.84 $\pm$ 0.15	0.85 $\pm$ 0.09	0.88
14 $\rightarrow$ 12	617	—	—	0.45 $\pm$ 0.15	0.65 $\pm$ 0.15	0.55 $\pm$ 0.10	0.50

FIGURE CAPTIONS

Fig. 1. Gamma spectra recorded in and out of the beam bursts for Coulomb excitation of thick foils of $^{174,176}\text{Yb}$ with ^{86}Kr ions at 372 MeV. Transitions above the $6^+ \rightarrow 4^+$ show considerable broadening on the high-energy side due to the Doppler effect during the finite slowing-down time of the recoils. Arrows indicate the expected stopped-peak positions as determined in later experiments.

Fig. 2. Gamma spectra recorded in and out of the beam bursts for Coulomb excitation of thick foils of $^{174,176}\text{Yb}$ with ^{136}Xe ions at 595 MeV. Transitions above the $6^+ \rightarrow 4^+$ show considerable broadening on the high-energy side due to the Doppler effect during the finite slowing-down time of the recoils. Arrows indicate the expected stopped-peak positions as determined in later experiments.

Fig. 3. Gamma spectrum at 0° for ^{176}Yb (thick target) in coincidence with ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. Known stopped-peak positions are indicated with arrows.

Fig. 4. Gamma spectrum at 90° for ^{176}Yb (thick target) in coincidence with ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. Known stopped-peak positions are indicated with arrows.

Fig. 5. Gamma spectrum at 0° for ^{174}Yb (thick target) in coincidence with ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. Known stopped-peak positions are indicated with arrows.

Fig. 6. Gamma spectrum at 90° for ^{174}Yb (thick target) in coincidence with ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. Known stopped-peak positions are indicated with arrows.

Fig. 7. Kinematics for the Coulomb excitation of ^{176}Yb with ^{136}Xe ions.

Note that the 18^+ yield is expressed for the complete annulus at a given laboratory angle θ .

Fig. 8. Gamma rays in coincidence with ^{136}Xe ions scattered in the annulus $80^\circ \leq \theta \leq 100^\circ$. The target of ^{176}Yb was about 1 mg cm^{-2} and inclined at 45° to the beam direction. The quasi-stopped peaks for the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions, and the quasi-moving peak for the $^{136}\text{Xe } 2^+ \rightarrow 0^+$ transition arise from ^{176}Yb recoils having been detected in the annular counter as explained in the text.

Fig. 9. The effect of an additional γ -ray coincidence (NaI) requirement on the spectrum shown in figure 8.

Fig. 10. Gamma-rays in coincidence with ^{136}Xe ions scattered in the annulus $80^\circ \leq \theta \leq 100^\circ$ for ^{174}Yb . The arrangement was the same as that described for figures 8 and 9.

Fig. 11. Doppler-broadened lineshape (direct singles) for 372 MeV $^{86}\text{Kr} + ^{176}\text{Yb}$. The best fits are shown, obtained with the lifetimes indicated. Open circles correspond to data points which were not included in the fit. Also shown is the gamma-ray lineshape obtained for the $8 \rightarrow 6$ transition when the excited nuclei is recoiling into the vacuum from a $\sim 1 \text{ mg cm}^{-2}$ thin foil with little energy loss; in that case the calculated fit was done assuming the 8^+ lifetime and those of all feeding states were less than 10^{-15} ps.

Fig. 12. Doppler-broadened lineshapes (direct singles) for $^{136}\text{Xe} + ^{176}\text{Yb}$ at 595 MeV. The best fits are shown, obtained with the lifetimes indicated. Open circles correspond to data points which were not included in the fit.

Fig. 13. Doppler-broadened lineshapes (direct singles) for $^{86}\text{Kr} + ^{174}\text{Yb}$ at 372 MeV. The best fits are shown, obtained with the lifetimes indicated. Open circles correspond to data points which were not included in the fit.

Fig. 14. Doppler-broadened lineshapes (direct singles) for $^{136}\text{Xe} + ^{174}\text{Yb}$ at 595 MeV. The best fits are shown, obtained with the lifetimes indicated. Open circles correspond to data points which were not included in the fit.

Fig. 15. Doppler-broadened lineshapes for $^{86}\text{Kr} + ^{176}\text{Yb}$ in coincidence with 372 MeV ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. The best fits are shown, obtained with the lifetime indicated.

Fig. 16. Doppler-broadened lineshapes for $^{86}\text{Kr} + ^{174}\text{Yb}$ in coincidence with 372 MeV ^{86}Kr ions scattered in the annulus $100^\circ \leq \theta \leq 150^\circ$. The best fits are shown, obtained with the lifetime indicated.

Fig. 17. Comparison of the lifetimes obtained by Doppler-broadened lineshape analysis with the rotational model. The yield ratio R (defined in the text) is also approximately equal to $B(E2)_{\text{exp}}/B(E2)_{\text{Rotational}}$ as explained in the text.

Fig. 18. Plots of the moment-of-inertia versus rotational frequency (squared) for the Yb isotopes.

Fig. 19. Schematic of an argon gas scintillation counter. The target may be positioned anywhere inside the band; masks are used to define the range of particle angles accepted.

XBL757-3621

Fig. 1

Fig. 2

XBL757-3619

Fig. 3

XBL757-3623

Fig. 4

XBL757-3622

Fig. 5

XBL757-3620

Fig. 6

XBL757-3616

Fig. 7

XBL757-3627

Fig. 8

Fig. 9

Fig. 10

XBL 7512-9932

Fig. 11

Gamma ray lineshapes $^{136}\text{Xe} + ^{176}\text{Yb}$ 595 MeV

-40-

Fig. 12

XBL757-3631

00004404491

Fig.13

XBL757-3629

Fig. 14

XBL 757-3632

$^{86}\text{Kr} + ^{176}\text{Yb}$ (372 MeV) GAMMA-RAYS IN COINCIDENCE WITH Kr IONS

Fig. 15

$^{86}\text{Kr} + ^{174}\text{Yb}$ (372 MeV) GAMMA-RAYS IN COINCIDENCE WITH Kr IONS

Fig. 16

XBL763-5228

Fig. 17

0 0 0 0 0 0 0 0 0 0 0 0

Fig. 18

00004404494

Fig. 19

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