PRODUCTION OF NEUTRON-RICH NUCLEI USING DEEP-INELASTIC REACTIONS* **

I.Y. Lee

Lawrence Berkeley National Laboratory
1 Cyclotron Rd, Berkeley, CA 94720, USA

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We have used the reactions ^{48}Ca+^{176}Yb, ^{154}Sm+^{176}Yb and ^{154}Sm + ^{208}Pb to study the feasibility of populating high spin states in neutron-rich nuclei by deep-inelastic reactions. Using Gammasphere, we observed gamma transitions from nuclei with several neutrons richer than the target. Yrast states with spin up to 20 were populated in these reactions. High spin states in ^{175,177,178}Yb were observed for the first time. Back bending behavior in Yb nuclei was studied and compared with cranked shell model calculations. Yields of neutron rich nuclei and high spin states are higher in the Sm induced reactions, But larger Doppler broadening limits the observation of the high spin states.

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1. Introduction

Neutron rich nuclei are of particular interest since they might reveal new aspects of nuclear structure associated with an excess of neutrons, such as a neutron skin and modified shell structure and new modes of excitation. However, these nuclei are difficult to produce, particularly in high-spin states. Currently, nuclear high-spin states are produced almost exclusively by heavy ion induced fusion reactions. With a stable beam and target, only neutron-deficient nuclei can be produced by fusion reactions. So far, high spin states in neutron rich nuclei and most of the odd-even and odd-odd nuclei near the stability line have not been studied due to the lack of suitable nuclear reactions. Neutron-rich radioactive beams would be required if fusion reactions are used. However, using deep inelastic reactions together

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with the new gamma ray detector arrays, one expects to have enough sensitivity, in spite of low cross sections, to reach these nuclei in high spin states. These reactions have been shown to produce a high multiplicity of gamma-rays [1]. In reactions of rare-earth beams with rare-earth targets, a multiplicity of 40 has been observed [2, 3]. In addition, neutron-rich nuclei such as ^{177}Tm, ^{180}Yb, and ^{184}Lu have been identified from β-γ spectroscopy following Xe on W reactions [4]. Attempts have been made to use deep inelastic reactions to produce and study high spin states. States with spin up to 20 have been observed in an in beam study [5], and isomers with spin 10 have been identified in off-beam studies [6]. Since these reactions produce many final nuclei, some of them with a low cross section, a high efficiency gamma-ray detector array, such as Gammasphere, is needed to resolve the cascades through high-fold coincidence measurements.

2. Experimental method

We have carried out the reactions ^{48}Ca + ^{176}Yb at a beam energy of 250 MeV, ^{154}Sm + ^{176}Yb at 950 MeV and ^{154}Sm + ^{208}Pb at 1 GeV. The most neutron rich stable isotopes of projectile and target were used in order to enhance the production of neutron-rich nuclei. Self-supporting metallic targets of enriched isotopes with a thickness of about 1 mg/cm^2 were bombarded with beams of ^{48}Ca and ^{154}Sm from the 88-inch cyclotron at LBNL. Thin targets were used to allow both the projectile- and target-like fragments to decay outside the target so that gamma rays from short lived high-spin states can be observed as sharp lines after Doppler shift correction. An annular Silicon strip detector with an inner diameter of 5 cm and an outer diameter of 10 cm placed downstream from the target was used to detect the scattered fragments. This detector covered polar angle with 16 concentric strips on the front surface and the full range of azimuthal angles with 16 sectors on the back surface. For the Ca beam experiment, the early implementation of Gammasphere with 36 detectors was used to detect the gamma-rays and for the Sm beam reactions Gammasphere had 60 detectors. Coincidence events with at least one fragment and two Compton-suppressed gamma rays were collected. Doppler-shift correction of the gamma rays was based on the direction of the gamma ray and the direction of the detected particle and its velocity calculated assuming a two-body reaction. To study the gamma rays from the target (projectile) like fragments, event-by-event Doppler correction was carried out using the velocity of the target-like (projectile-like) fragments.

Two- and three-fold gamma-ray-coincidence data were analyzed. One dimensional spectra were obtained by single and double gating on transitions belonging to a gamma cascade. Figure 1 shows the spectra of even-even Yb

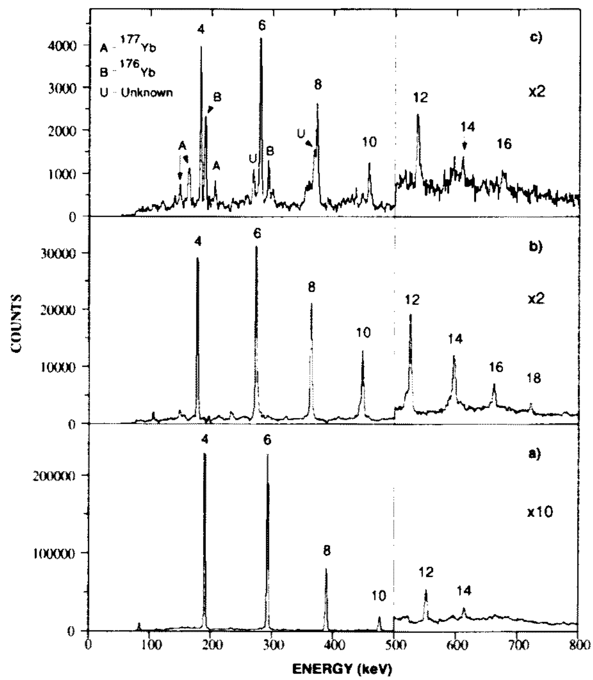

Fig. 1. Spectra from double-γ-coincidence data of ^{48}Ca+^{176}Yb reaction corrected for the Doppler shift of the target-like fragement for a) ^{176}Yb, b) ^{174}Yb and c) ^{172}Yb.

nuclei from the two-fold data of the ^{48}Ca + ^{176}Yb experiment. The low spin transitions of ^{176}Yb have more than 10^5 counts and the highest line observed is the $14 \to 12$. The spectrum of ^{174}Yb has ten times fewer counts but the highest spin observed is 18. This indicates that the yield of ^{176}Yb drops faster as a function of spin than the yield of ^{174}Yb. The spectrum of ^{172}Yb has ten times fewer counts than the spectrum of ^{174}Yb and because of the low yield the spectrum is not clean. The main impurity peaks are due to ^{176}Yb and ^{177}Yb. Figure 2 compares the spectra of ^{178}Yb from single gated two-fold and double-gated triple data. The transitions belonging to ^{178}Yb are clearly identified in the triples spectrum which is much cleaner than the doubles spectrum but with 1/6 of the counts. The identified impurity peaks in the double spectrum are from ^{176}Yb and ^{177}Yb. It is obvious that in order to study the weakly populated nuclei such as ^{178}Yb the three-fold data are essential. Figure 3 shows the double coincidence spectra of ^{175,177}Yb nuclei. From this experiment, high-spin levels in ^{175,177,178}Yb were observed for the first time up to 33/2 in the odd nuclei and 12 in the even nucleus.

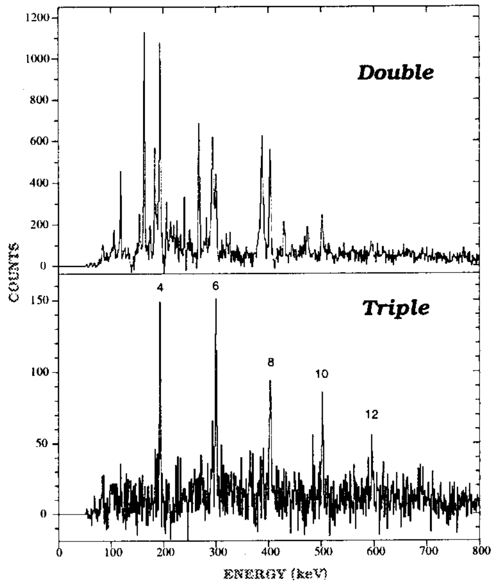

Fig. 2. Spectra of ^{178}Yb from double (top) and triple (bottom) γ-coincidence data with the Doppler correction for the target-like fragment.

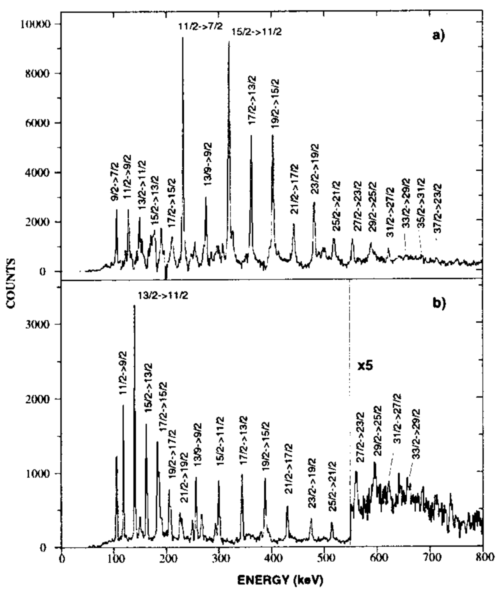

Fig. 3. Double-γ-coincidence spectra similar to Figure 1 for a) ^{175}Yb, and b) ^{177}Yb.

3. Results and discussion

The production cross sections of the target-like nuclei, determined from the gamma-ray yields of the low spin states are shown in Figure 4 for the ^{48}Ca+^{176}Yb reaction. About 10 nuclei around the target ^{176}Yb have been identified. From the current data set, we were able to study nuclei produced with a cross section as low as 0.1 mb/sr. So far, a number of even-odd and odd-odd nuclei, such as ^{173}Yb and ^{171,172}Tm which are expected to be produced from the systematics of the yield distribution, were not identified because very little is known about their level schemes. Including these nuclei, it is estimated that about 20 projectile-like nuclei and a comparable number of target-like nuclei are produced with cross section greater than 0.1 mb/sr. So far, we have identified about 60% of the γ-ray lines in the total projection spectra.

The gamma-ray yield of observed Yb nuclei as a function of spin is shown in Figure 5. The sensitivity of the current setup allowed states with spin as high as 20 to be observed in this reaction. The yields decrease when the spin increases at about the same rate for all nuclei except for ^{176}Yb. The latter nucleus has a higher yield at low spin and the yield drops by a factor about 1000 from spin 6 to 18, while the yield of other nuclei drops by a factor about 100. This difference is most likely due to additional contributions from quasi-elastic reactions (*e.g.* Coulomb excitation) in ^{176}Yb. Figure 5 also shows the calculated Coulomb excitation yield of ^{176}Yb. The steep drop of the yield of the states with spin below 12 is well reproduced by the calculation. The extra yield at higher spin which has a flatter spin dependence similar to the other Yb isotopes is most likely due to deep inelastic reactions, since few nucleon transfer reactions do not bring in large amount of angular momentum. Therefore, the yield curve of Coulomb excitation

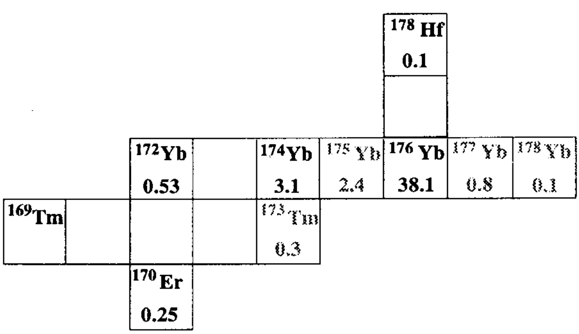

Fig. 4. Production cross sections in mb/sr of target-like nuclei deduced from gamma-ray yields of the ^{48}Ca+^{176}Yb reaction.

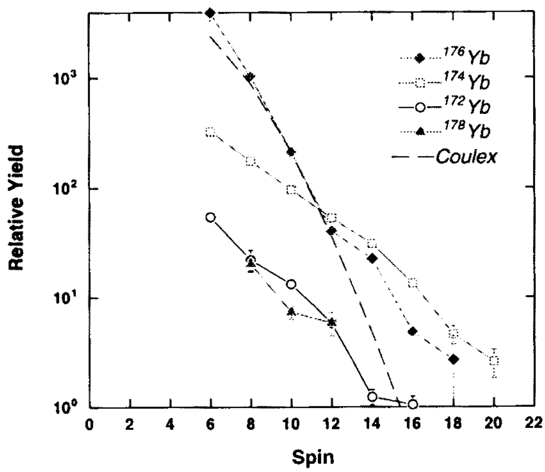

Fig. 5. Gamma-ray yield of Yb nuclei as a function of spin.

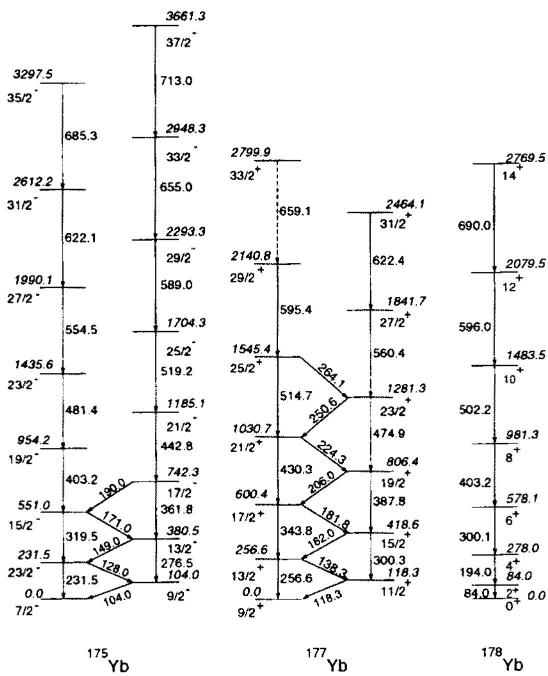

Fig. 6. The level schemes of ^{175,177,178}Yb determined from this experiment. Previously, only three levels were known in each of these nuclei.

plus transfer reaction is expected to be similar to that of Coulomb excitation. The flatter yield curves of other nuclei also indicates that Coulomb excitation plus transfer are not important for the population of these nuclei.

Before this study, only three levels in the yrast band were known in ^{175,177}Yb and ^{178}Yb. This work extends the yrast band of ^{178}Yb to spin 12 and yrast bands in ^{175,177}Yb to spin 37/2 and 33/2 respectively. These new transitions are placed in the level schemes shown in Figure 6. The structure of the yrast band of ^{175}Yb is assigned [8] to be [514]7/2 and the yrast band of ^{177}Yb is based [9] on $i_{13/2}$[624]9/2. One of the interesting properties of yrast levels with spin below about 20 in rare-earth nuclei is the alignment of a pair of neutrons in the $i_{13/2}$ orbital. In the even-even nuclei, the aligned band crosses the ground state band at a rotational frequency about 0.35 MeV. The interaction strength between the bands is expected to show an oscillatory behavior as the Fermi level moves through the multiplets of the $i_{13/2}$ orbitals with different K-values. In the odd neutron nuclei, if the odd neutron occupies an $i_{13/2}$ orbital, the alignment is blocked. If the odd neutron does not occupy $i_{13/2}$ orbitals, a band crossing similar to that of the even-even nuclei is observed.

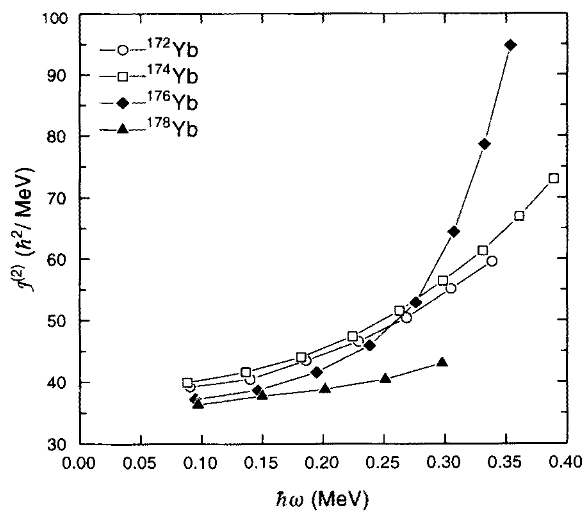

Fig. 7. Dynamic moment of inertia of even-even Yb nuclei.

The experimental results and comparison to the calculations are shown in Figures 7 to 10. Figure 7 shows the moment of inertia of the even-even Yb nuclei as a function of rotational frequency. The curves of ^{172}Yb and ^{174}Yb are similar to each other and ^{176}Yb shows an increase of the moment of inertia at frequency above 0.25 MeV. The new results of ^{178}Yb

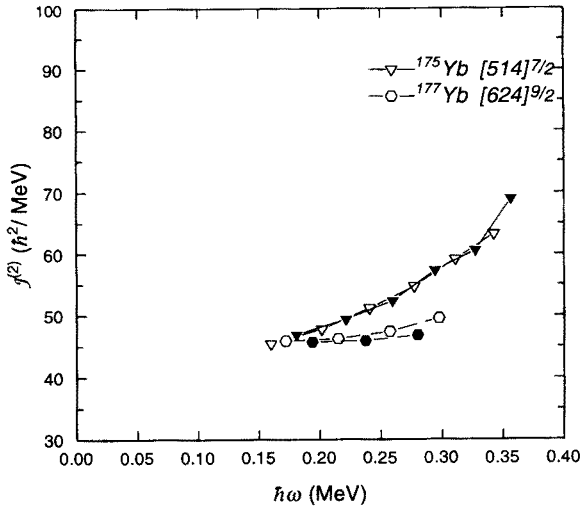

Fig. 8. Dynamic moment of inertia of ^{175,177}Yb.

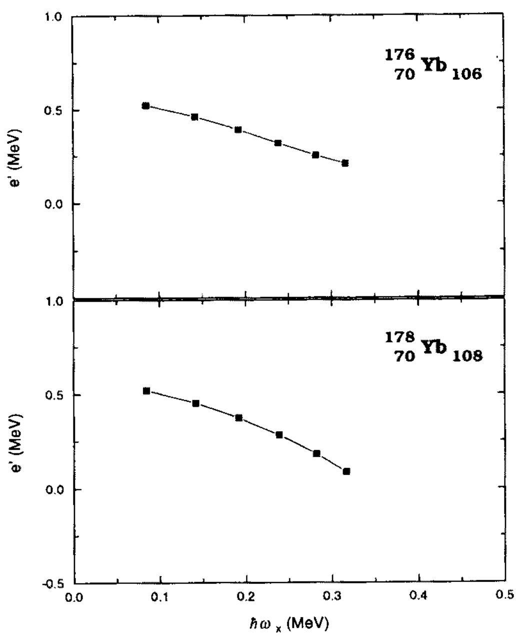

Fig. 9. Experimental Routhians for ^{176,178}Yb as a function of ω_x. They are obtained from the energy differences of yrast levels in even-even nuclei and the $i_{13/2}$ band in ^{175}Yb.

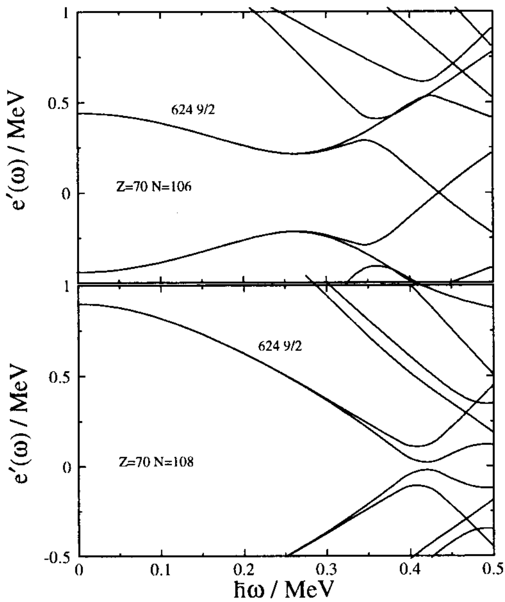

Fig. 10. Routhians from cranked shell model calculations for ^{176,178}Yb.

give a rather flat moment of inertia curve which suggests a smaller value for the interaction strength of the $i_{13/2}$ neutron AB crossing than for the lighter Yb nuclei. The expected sharp backbend is likely to occur just above spin 12. It would be interesting to observe higher spin states with more statistics or using a reaction which makes products with higher angular momentum. Figure 8 shows the moment of inertia of the odd mass ^{175,177}Yb. The different behavior between these two nuclei is because in ^{177}Yb the odd neutron is occupying $i_{13/2}$ orbital and the alignment is blocked which produces a flat moment of inertia curve. For ^{175}Yb the alignment of $i_{13/2}$ orbital is not blocked and its moment of inertia curve is similar to that of ^{174}Yb.

To analyze the response of the $i_{13/2}$ quasiparticles to rotation we compare the experimental Routhians with the ones calculated by means of the cranked shell model (CSM). The experimental quasiparticle Routhians are obtained by subtracting from the experimental Routhian of the $i_{13/2}$ band in the odd N nucleus the experimental Routhian of the even N neighbor, which is called the "yrast reference". This is different from the commonly used reference of a fourth order curve fitted to the low frequency part of the measured Routhians (Harris fit). As discussed in detail in Ref. [7], such a "g-band reference" is only useful if one can sufficiently clearly distinguish

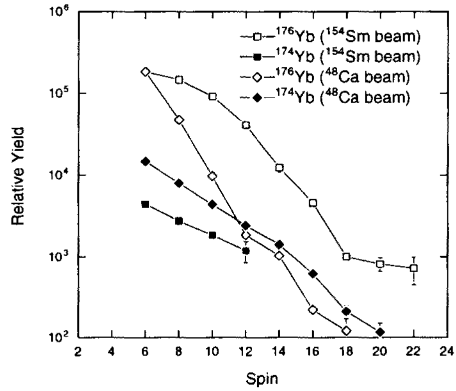

Fig. 11. Gamma-ray yield of ^{174,176}Yb as a function of spin from Ca and Sm induced reactions.

between the pieces of the band before and after the alignment of the pair $i_{13/2}$ quasiparticles. For very gradual structural changes, as the ones in the heavy Yb - isotopes, it is more appropriate to apply the yrast reference. Fig. 10 shows the experimental quasiparticle Routhians of ^{176,178}Yb which is obtained from the yrast levels of ^{176,178}Yb and the $i_{13/2}$ band in ^{177}Yb. Fig. 11 shows the calculated Routhians calculated by means of cranked shell model with a modified oscillator potential [7].

For ^{176}Yb the Routhian stays far from the zero line, whereas for ^{178}Yb the experimental Routhian seems to head for an intersection with the zero line, both in accordance with the calculations. The comparison between calculated and experimental Routhians seems to indicate that the CSM which is able to account for the quasiparticle response at low pairing in a quantitative way, if one compares directly the odd with the even N bands (yrast reference), without trying to extrapolate the low spin part of the even N bands as a Harris reference. This finding is certainly of interest for superdeformed bands where a similar weak pairing regime seems to be present.

It is expected that beams with a larger N/Z ratios than the target favor the production of neutron-rich target-like nuclei, and heavier beams could produce fragments with higher spins. The reactions ^{154}Sm + ^{176}Yb and ^{154}Sm+^{208}Pb were carried out to determine whether neutron-rich nuclei with high spin can be produced with larger cross sections than those produced in the ^{48}Ca+^{176}Yb reaction. Fig. 11 compares the yield of two Yb isotopes produced in the Ca induced reaction with that from the Sm induced reactions. The yield of high spin states of ^{176}Yb are indeed higher in the reactions induced by Sm. However, only a few more high spin states were observed. It is due to the larger Doppler broadening from the larger recoil velocity of the fragments and the finite angular resolution of the particle detector. A particle detector with an angular resolution compariable to that of the Ge detector (± 5 degrees) would improve the energy resolution by a factor of 2 which would allow higher spin discrete lines to be resolved.

4. Conclusion

We have established that with a high efficiency gamma-ray array, it is possible to study high-spin states in neutron rich nuclei produced in deep inelastic reactions. These reactions extended the range of nuclei for high spin structure study in the neutron rich direction by about 10 neutron numbers. The observed variation in the experimental Routhians of the neutron-rich Yb nuclei raise the question of whether the pairing strength is reduced in these nuclei. Reactions with beams of larger N/Z values produce high-spin states in neutron-rich fragments with larger cross sections. However, in the current experiments, Doppler broadening limits the highest spin states that can be resolved. The yields of the high spin states is sufficiently high. Therefore, using particle detectors with a higher position resolution would enable us to observe higher spin states.

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