High spin states in ^{128}Ce

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Properties of high spin states in ^{128}Ce have been measured following the reaction $^{112}Cd(^{20}Ne, 4n)$ ^{128}Ce induced by 103-MeV ^{20}Ne ions. High efficiency γ-γ coincidence measurements and angular distribution measurements showed a series of stretched $E2$ transitions that form the yrast sequence up to $I=24^+$, six stretched $E2$ transitions which form one sideband, and four transitions of undetermined multipolarity forming a second sideband.

An inspection of both the energy level spacings and the lifetimes of excited states in the light cerium nuclei reveals a region of pronounced collective behavior. An examination of the data in Refs. 1–4 shows that this collective pattern evolves rapidly in moving from ^{134}Ce to ^{132}Ce to ^{130}Ce. Ward *et al.*[5] carried out measurements on the yrast sequence in ^{128}Ce up through the 16^+ state and found a level sequence indicative of enhanced collective behavior. To further clarify the collective behavior in this light cerium region we have carried out detailed γ-γ coincidence measurements on ^{128}Ce. Preliminary accounts of this work are contained in Refs. 6 and 7 while a more detailed treatment can be found in Ref. 8.

For the present studies the reaction $^{112}Cd(^{20}Ne,4n)$ ^{128}Ce was utilized by employing a beam of 103-MeV ^{20}Ne ions from the Oak Ridge Isochronous Cyclotron (ORIC). Self-supporting target foils of ^{112}Cd used in these experiments were 1.0 mg/cm^2 thick and were 98.5% enriched. The beam energy, selected after carrying out excitation function measurements, brought about $45\hbar$ of maximum angular momentum into the compound system according to calculations that assume sharp nuclear surfaces. The experimental apparatus consisted of seven large volume germanium detectors in the horizontal plane and two 25 cm $\times$ 25 cm NaI detectors located above and below the reaction chamber. The NaI detectors served as a total γ-ray energy spectrometer and, thus, provided a means for selective gating in the total energy spectrum with a resulting enhancement of the desired 4n reaction channel. However, since ^{128}Ce lies somewhat close to the proton drip line, it was necessary to contend with several charged particle reaction channels (e.g., α3n, p3n, and 2p2n) which are not well separated from the 4n channel with a total energy selection device. Nevertheless, because much of the cross section went into the 4n channel, the coincidence spectra were of good quality.

The coincidence event count rate was approximately 2 kHz, while the average count rate for the NaI detectors was around 80 kHz and for the Ge detectors it was about 8 kHz. About 240 million pairs of γ-γ coincidence events were stored in list mode on magnetic tape. Regions of the total energy spectrum were selected that gave enhancement of the dominant reaction channels and with these restrictions, the tapes were scanned for prompt γ-γ coincidence events which were constructed into 4096$\times$4096 channel coincidence matrices. From these matrices, one-dimensional spectra for any γ-ray energy gating interval of interest could be extracted. To illustrate these data, the coincidence spectrum from summed gates in the yrast band is shown in Fig. 1. From the coincidence data it was possible to develop the yrast sequence up to $I=24^+$ and to assign with less certainty two partially developed side bands. The level scheme shown in Fig. 2 summarizes these results. An additional 429.9-keV transition identified with sideband 2 is not shown in Fig. 2, but it probably depopulates the 2418.7-keV level. Angular distribution data showed that the yrast seqeuence in this scheme consisted of stretched $E2$ transitions, as does sideband 1. However, since we were unable to determine the multipolarities of the interband transitions between sideband 1 and the ground band, it was not possible to assign spins to these sideband states. Also, the data were not of sufficient statistical quality for a determination of the multipolarities in sideband 2.

At spin 10^+ in this nucleus, a backbend similar to the ones seen in $^{130,132,134}Ce$ is observed. Assuming $K=0$ in both the ground and s bands, we plot in Fig. 3 the angular momentum along the rotation axis, I_x, ($I_x=I+\frac{1}{2}$) as a function of the rotational frequency ($\hbar\omega$) for all four of these nuclei. Inspection of these curves shows that in moving to the lighter cerium isotopes the backbending sets in at a lower rotational frequency. However, $^{128,130,132,134}Ce$ show very similar crossing frequencies of ~ 0.3 MeV and have

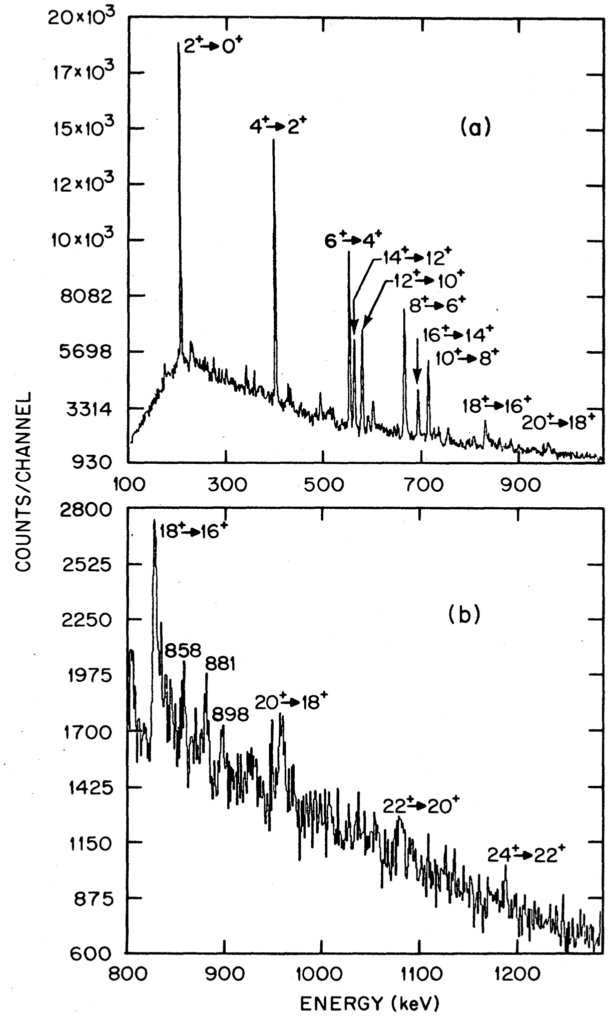

FIG. 1. Coincidence spectrum from summed gates on transitions in the yrast sequence of ^{128}Ce.

very similar alignment gain (ΔI_x) values of 8, 9, 10, and 9.3, respectively, in the backbending process. It appears that the alignments all come from a strongly decoupled high-j orbit. In principle, this could be either the $h_{11/2}$ protons or the $h_{11/2}$ neutrons since both orbitals are near the Fermi surface in these nuclei. However, blocking measurements in ^{127}La and ^{129}La by Ward *et al.*,[5] in ^{129}Ce by Aryaeinejad *et al.*,[9] and in ^{131}Ce by Nolan *et al.*[2] have shown rather conclusively that the $h_{11/2}$ protons are responsible for the backbending in this region. Additional verification on this point is provided by cranked shell model calculations. We have carried out such calculations for ^{128}Ce, as did Nolan *et al.*[2] for ^{130}Ce, and in both cases the alignment gains and crossing frequencies are consistent with alignment by $h_{11/2}$ protons. (In these calculations the nucleus was assumed to be prolate, i.e., $\gamma = 0°$.) It should be pointed out, however, that in these light cerium nuclei, one must retain some reservation about the particles active in the alignment process. This is because it appears quite probable that neutrons play a role in ^{134}Ce backbending, based on the measured g-factor value of -0.30 for the 10^+ state by Zemel *et al.*[10] Todd *et al.*[4] interpreted the reduced frequency of the highest state they observed in ^{130}Ce (26^+) as an effect

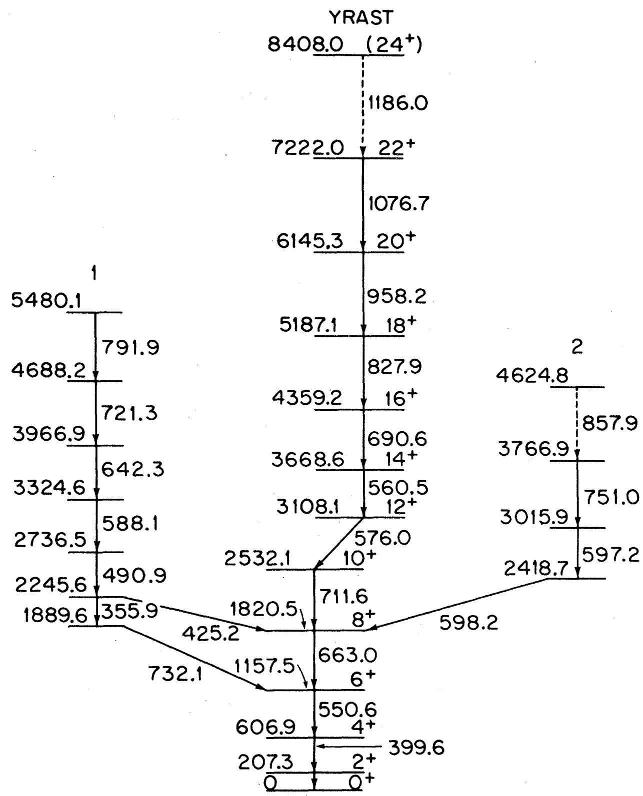

FIG. 2. Level scheme of ^{128}Ce deduced from the present coincidence measurements.

of the $h_{11/2}$ neutron alignment process, as predicted by cranked shell model calculations. Such a crossing has apparently not begun yet at $I = 24$ in ^{128}Ce, judging from the I_x vs $\hbar\omega$ curve shown in Fig. 3. It is possible that such a crossing will occur in ^{128}Ce at slightly higher frequencies.

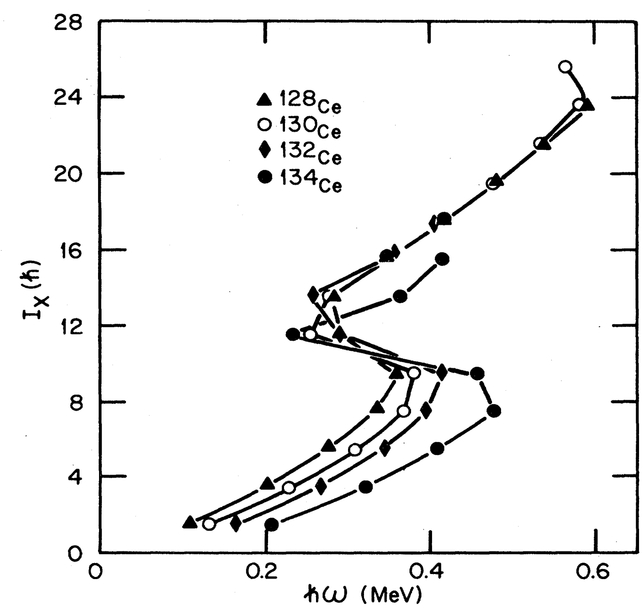

FIG. 3. Plots of aligned momentum along the rotation axis (I_x) vs rotational frequency ($\hbar\omega$) for ^{128,130,132,134}Ce.

The present study has provided increased understanding of the high spin states in ^{128}Ce and verified the presence of an increased moment of inertia which is indicative of increasing collectivity in this nucleus. In a separate recent study, we[11] measured lifetimes of yrast states in ^{128}Ce by the Doppler-shift recoil-distance method and showed clear evidence for enhanced collective behavior in the ground band. The $B(E2)$ values deduced for the 2^+ through 14^+ states indicated that in the ground band ^{128}Ce conforms much more closely to rigid-rotor behavior than do the heavier cerium isotopes. It is interesting that in the s bands, the moments of inertia of ^{128,130,132}Ce are very similar as evidenced by the I_x vs $\hbar\omega$ curves (Fig. 3) which practically coincide. This is in contrast to the markedly varying moments in the ground bands. Although it appears that the alignment of the $h_{1/2}$ protons affects these moments of inertia greatly, producing nearly identical values in the s bands of $^{128-132}$Ce, it must be stressed that there seems to be no general consensus on the underlying causes for this behavior.

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