ANGULAR CORRELATION AND COINCIDENCE STUDIES OF EXCITED 0^+ AND OTHER LEVELS IN THE TRANSITIONAL Ce NUCLIDES ^{142}Ce, ^{144}Ce, ^{146}Ce and ^{148}Ce

W. B. Walters and C. Chung

University of Maryland
College Park, MD 20742 USA

D. S. Brenner

Clark University
Worcester, MA 01610 USA

R. Gill, M. Shmid, R. Chrien, H.-I. Liou, G. Gowdy, M. Stelts*) and Y. Y. Chu

Brookhaven National Laboratory
Upton, NY 11973 USA

F. K. Wohn, K. Sistemich**) and H. Yamamato

Iowa State University
Ames, IA 50011 USA

R. Petry

University of Oklahoma
Norman, OK 73019 USA

Abstract

The decays of the neutron-rich nuclides ^{142}La, ^{144}La, ^{146}La and ^{148}La to the levels of the transitional nuclides ^{142}Ce, ^{144}Ce, ^{146}Ce and ^{148}Ce, respectively, have been studied using mass-separated sources. Angular correlation studies have been employed to identify new excited 0^+ levels in ^{146}Ce and support spin and parity assignments for 1^-, 3^-, 2^+, 3^+, 4^+ and 6^+ levels in ^{144}Ce and ^{146}Ce. An excited 0^+ level in ^{148}Ce is indicated by coincidence ratios and electron studies, while no clear evidence can be found for the location an excited 0^+ level below 2 MeV in ^{144}Ce. The resulting isotonic and isotopic systematics are discussed in terms of the transition from the closed shells at N=82 and Z=50 to the region of deformed nuclides.

1. Introduction

As no single, unified description of nuclear structure exists that offers reliable results for all nuclides, much interest is focussed on nuclides at the edges of regions where good theoretical fits are found. The great success of the rotational description of nuclides[1,2] with N>90 has stimulated extensive experimental and theoretical study of the nuclides with $82<N<90$ in various attempts to both observe rotational features below N=90 and to gain an understanding of the nature of the transition from the closed shell at N=82 to the deformed region at N>90. Until recently, the lightest nuclides studies in detail in this region were the Z=60 Nd nuclides and Z=61 Pm nuclides whose structures were consistent with a transition to deformed structures for N=90. These nuclides have 10 or more protons beyond the closed shell at Z=50 and show few, if any, effects related to that shell closure. The measurement[3] of a $3/2^+$ ground state for the N=88 nuclide ^{143}Cs has stimulated considerable study of the nuclides with $54<Z<60$ and $82\leq N\leq 90$ to further investigate this transition. In particular Scott et al.[4] have reported studies of the decay of odd-odd Cs nuclides to even-even Ba nuclides and found evidence to support the extension of the deformed region to N=88.

2. Experimental Procedures

We have studied the decays of the neutron-rich La nuclides, 92.5-min ^{142}La, 40-sec ^{144}La, 6-sec ^{146}La and 1.2-sec ^{148}La to levels of ^{142}Ce, ^{144}Ce, ^{146}Ce and ^{148}Ce, respectively, using sources produced at the on-line mass separator TRISTAN located at the High Flux Beam Reactor at Brookhaven National Laboratory. Both the general layout of the facility[5] and the data collection system[6] are described in detail elsewhere. For these experiments several specific experimental arrangements were used. The most complete angular correlation studies were performed on ^{142}Ce and ^{146}Ce where data were collected in separate experiments at 90°, 130° and 180° using a 15% n-type Ge detector and a 20% Ge(Li) detector, each at 5 cm from the source. Approximately 2×10^6 three parameter $\gamma\gamma t$ events were collected at each angle. The characteristic 0^+-2^+-0^+ function (considerably attenuated by the small source-to-detector distance, especially at 130°) was observed for the decay of the 2030-keV level in ^{142}Ce and for the 1656- and 1043-keV levels in ^{146}Ce. The 2030-keV assignment[7] in ^{142}Ce had been

---

*)Now at Los Alamos National Laboratory, Los Alamos, NM 87545 USA
**)On leave of absence from KFA Julich, West Germany

suggested earlier using a NaI(Tℓ)-Ge(Li) setup. In a similar experiment on ^{144}Ce γ rays no cascade with the 0^+-2^+-0^+ shape was observed.

In a second experiment on ^{144}La decay to ^{144}Ce levels, 2×10^7 events were collected on tape at 90° and 3×10^7 events were collected on tape at 180°. During the 90° experiment at third 18% Ge detector was positioned at 130° relative to the 15% detector and used with a single channel analyzer to accumulate a spectrum in coincidence with the 397-keV 2^+ to 0^+ γ ray.

The data at 90° and 180° have been used separately to determine 180°/90° anisotropies for the stronger cascades and have been summed to search for weak γ-ray coincidences. The levels established in ^{144}Ce below 2 MeV are shown in Fig. 1. The largest 180°/90° anisotropy of ~1.6 was observed for the 1422-keV γ ray. The data at 130° were of limited usefulness for many of the weaker γ rays as there was no provision for Compton background subtraction. The characteristic dip at 130° was not observed for the 1422-keV γ ray and a $2^+(1,2)2^+(2)0^+$ cascade indicated with $-0.1<\delta<1.7$ for the 2^+ to 2^+ transition. The difficulty encountered in observing excited 0^+ states in ^{144}Ce arises directly from the 3^- spin and parity of ^{144}La as contrasted with 2^- for the other odd-odd La nuclides. As allowed β decay will populate only 2^-, 3^- and 4^- levels, direct cascades from 2^- to 0^+ states by M2 transitions are quite unlikely. Thus, excited 0^+ states in ^{144}Ce can be fed directly only from 2^+ states following forbidden beta decay or by two-γ cascades following allowed β decay.

The measured anisotropy values did, however, give strong support for the other spins and parities shown for the levels below 2 MeV in Fig. 1. In particular, the peak ratios for the γ rays de-exciting the three 4^+ levels were identical at both angles, whereas the 1294-keV γ ray showed a large negative 180°/90° anisotropy of 0.5 that is characteristic[8] of a $3^+(1,2)2^+(2)0^+$ cascade. Such a large negative value is not possible for a $2^+(1,2)2^+(2)0^+$ cascade and indicates a δ value of $-0.5>\delta>-4.0$ for the 3^+ to 2^+ transition. The γ rays from the 1^- and 3^- levels at 1346.1 and 1242.3 keV, respectively, showed 180°/90° anisotropies fully consistent with $1^-(1)2^+(2)0^+$ and $3^-(1)2^+(2)0^+$ cascades. Similar cascades in ^{146}Ce from the 924- and 960-keV levels were observed. The identification of the 0^+ level in ^{148}Ce is described in detail by Gill et al.[8] elsewhere in these proceedings.

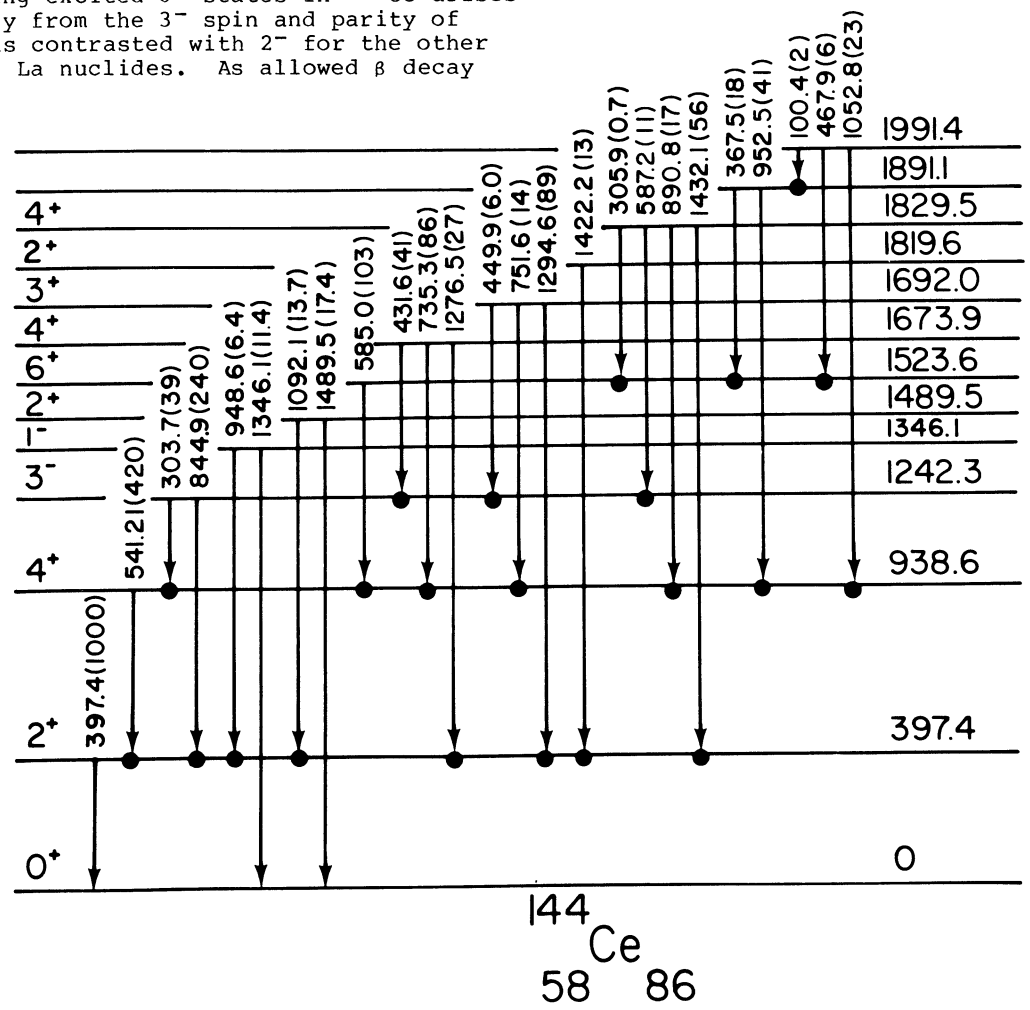

Fig. 1 The low-lying levels of ^{144}Ce populated in the β decay of ^{144}La.

3. Discussion

The systematic movement of the low-lying levels in the Ce nuclides as N increases beyond 82 is shown in Fig. 2. The levels of ^{150}Ce from the fission product studies of Chefitz[9] are also shown. The first 2^+ state is seen to drop by a factor of ~0.625 with the addition of each successive pair of neutrons. The 4_1^+ and 6_1^+ states drop more slowly by factors of ~0.75 shifting the E_4^+/E_2^+ ratio from near the vibrational limit of 2 to near the rotational limit of 3.33. The higher-lying states compress somewhat less smoothly but many also drop by ratios of between 0.75 and 0.85 with the addition of each neutron pair. These trends serve to suggest the presence of an underlying behavior dependent strongly on neutron number.

A very different picture of these nuclides is shown in Fig. 3 where the partial level structures of the N=84, 86, 88 and 90 isotones are shown that include only the ground band ($0^+,2^+,4^+$) octupole band (1^- and 3^-), β-band head (0^+) and γ-band head (2^+). The most obvious difference lies in the upward trend in the level structures of the ground band as proton pairs are added to the nucleus for N=84, 86 and 88 versus the downward trend for N>90 (and for neutron pair addition). A similar shift is observed for the γ-band head which trends upward in N=84 and downward on N=88 and lies nearly flat in N=86. The octupole band undergoes the opposite shift, trending down in N=84 (and also in N=82 as noted by Kleinheinz *et al.*[11]) and N=86 and upward in N=88 and N=90. The β band exhibits yet a third type of behavior, peaking in Ce or Nd for N=84, 86 and N=88, and then bottoming in Nd for N=90.

The erratic behavior shown in Fig. 3 by these isotones as protons are added beyond the closed shell at Z=50 stands in sharp contrast to the very smooth behavior shown for the Ce nuclides in Fig. 2. The

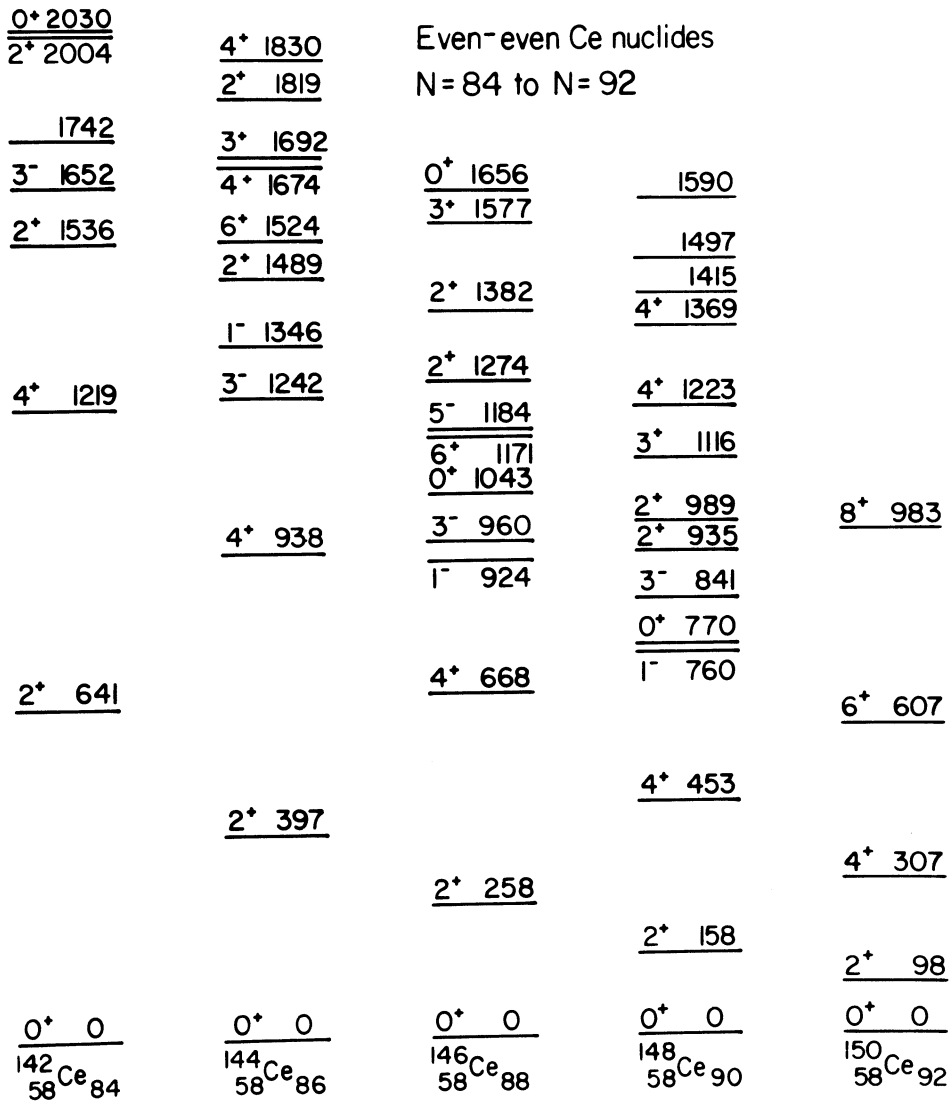

Fig. 2 The low-lying levels of the even-even Ce nuclides with 84<N<92.

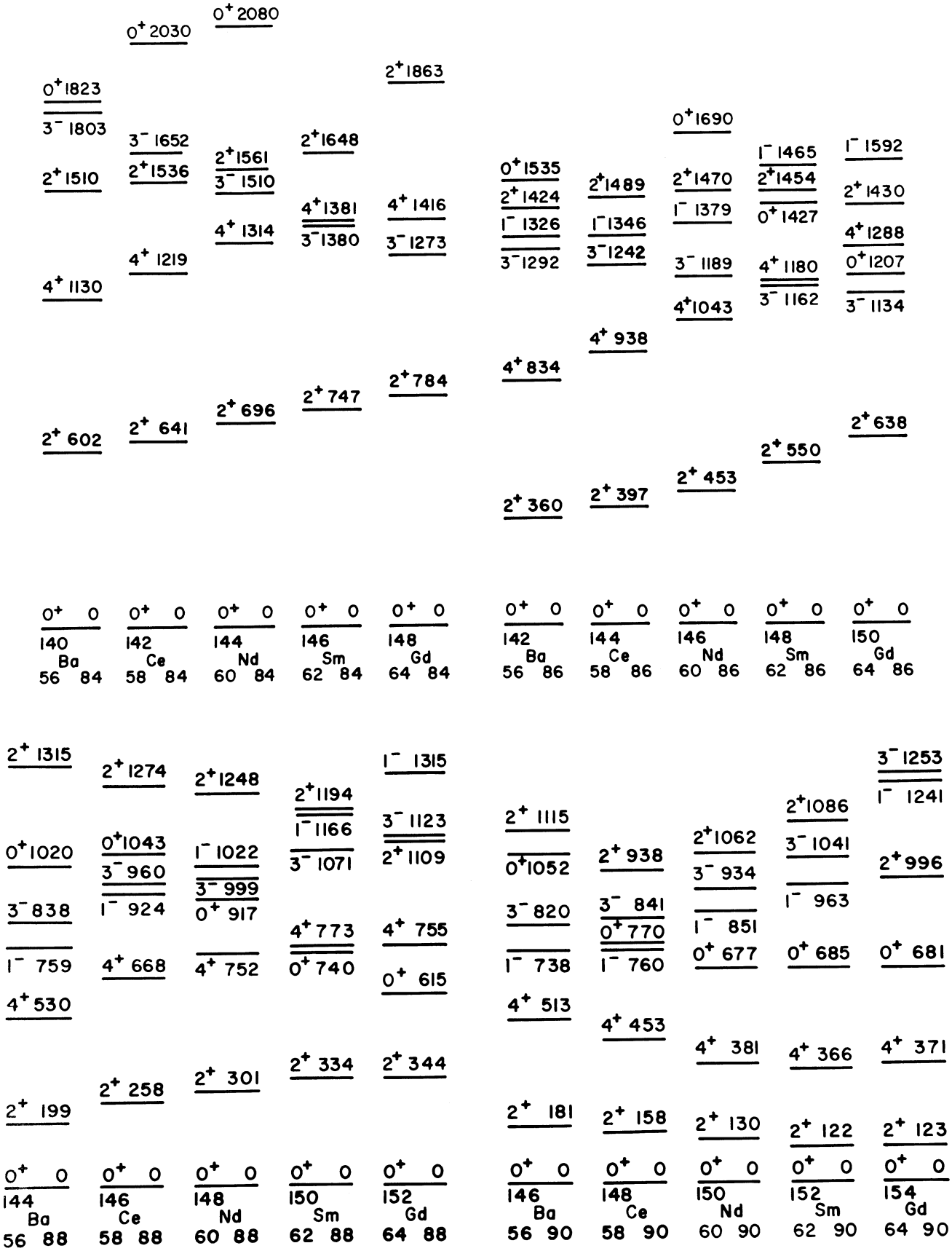

Fig. 3 Selected members of the ground band ($0^+, 2^+4^+$) octupole band ($1^-, 3^-$), β band (0^+) and γ band (2^+) for the N=84, 86, 88 and 90 isotones with $56 \leq Z \leq 64$.

upward trend for the ground band also stands in sharp contrast to the isotonic behavior observed for the N=80 two-hole nuclides, the N=78 four-hole nuclides and the N=76 six-hole nuclides, etc.

Because of the apparent strong, smooth dependence of the Ce level structures on neutron number, the Interacting Boson Approximation (IBA) should prove particularly appropriate as a unified basis for describing these nuclides.[12] In view of the very different trends observed for the isotopes and isotones, we have made calculations for these structures using the IBA-2 code, NPBOS, that treats neutron and proton bosons separately. The parameters have been taken from the thesis of Scholten[13] who made a strong effort to fit the levels of Nd, Sm and Gd in the region $84<N<94$. Using a proton coupling constant for Z=58 taken from below the N=82 closed shell and neutron coupling constants from the Nd, Sm and Gd isotones, and deriving other parameters by smooth extrapolation from the respective Nd, Sm and Gd isotones, qualitative fits for the trends observed in the Ce nuclides can be obtained. For ^{146}Ce where the ground band is rather closely fit, we observe two 0^+ states and two 2^+ states. The calculated 0^+ and 2^+ states are further apart than the observed states, both the centroid is relatively close. Because the proton coupling constant was derived from below the shell and in view of the very different isotonic trends above and below the shell, we found a better fit for the two 0^+ states could be obtained by lowering the proton coupling constant to a value (-0.4) that followed more closely the trend found by Scholten for the neutron coupling constants. There remains a number of experimental features to be fully resolved and much calculational work to determine if a unified fit can be found for these nuclides with $Z>50$ and $N>82$.

4. Acknowledgements

This work has been supported by the U.S. Department of Energy and the guest authors have enjoyed the hospitable and productive atmosphere in the Physics Department at Brookhaven National Laboratory.

References

1. J. O. Rasmussen in Nuclear Reactions and Spectroscopy, edited by J. Cerny, Acad. Press, New York 1975, p. 97.

2. G. Scharff-Goldhaber, C. B. Dover and A. L. Goodman, Ann. Rev. Nucl. Sci. 26, 239 (1976).

3. C. K. Ekstrom, S. Ingelman, G. Wannberg and M. Skarestad, Phys. Ser. 19, 516 (1979).

4. S. M. Scott, D. D. Warner, W. D. Hamilton, G. Jung, K. D. Wunech and B. Pfeiffer, J. Phys. G: Nucl. Phys. 6, 1291 (1980).

5. R. E. Chrien, M. L. Stelts, V. Manzella, R. L. Gill, F. K. Wohn and J. C. Hill, Inst. Phys. Conf. Ser. 51, 44 (1980).

6. R. L. Gill, M. L. Stelts, R. E. Chrien, V. Manzella, H. Liou and S. Shostak, Proc. 10th EMIS Meeting, Nucl. Inst. and Meth. (in press, 1981).

7. G. Basinger, W. Schick, Jr., and W. L. Talbert, Jr., Phys. Rev. C11, 1755 (1975).

8. H. W. Taylor, B. Singh, F. S. Prato and R. McPherson, Nucl. Data Tables 9, 1 (1971).

9. R. Gill et al., paper in this volume.

10. E. Cheifetz, H. A. Selic, A. Wolf, R. Chechik and J. B. Wilhelmy, Inst. Phys. Conf. Ser. 51, 193 (1980).

11. P. Kleinheinz, R. Broda, P. J. Daly, S. Lunardi, M. Ogawa and J. Blomquist, Z. Physik A290, 274 (1979).

12. F. Iachello in Interacting Bosons in Nuclear Physics, Plenum Press, New York 1979, p. 1.

13. O. Scholten, Ph.D. Thesis, "The Interacting Boson Model and Applications," University of Groningen, The Netherlands, 1980 (unpublished).

DISCUSSION

W.D. Hamilton: I wish to point out some differences between your spin assignments and those obtained at OSTIS. In ^{142}Ce we find that the 1219 keV state is 2^+ rather than 4^+ with a possible 4^+ state lying a little ($\sim$ 10 keV) above. We find that the 0^+ state in ^{144}Ce occurs at 1819 keV. These points are mentioned in our contribution to this meeting. We also show the behaviour of the negative parity state and this closely follows the behaviour of the 1^- and 3^- levels found in the barium isotopes.

A. Gelberg: Successful calculations for Ba and Ce have been carried out on the neutron deficient side. It is probably the first time that IBA has been applied to an isotopic chain on both sides of the magic number.

D.S. Brenner: Yes. As far as we know this is the first time that IBA-2 calculations have been done in this region and it was very gratifying to find that the systematic trends predicted by the calculations were found experimentally.