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Mixed symmetry in the vibrational nucleus ^{142}Ce

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Low-lying levels of the nucleus ^{142}Ce have been studied by Coulomb excitation with ^{4}He, ^{12}C, and ^{16}O projectiles to determine various $B(E\lambda)$ values and the static quadrupole moment $Q(2_1^+)$. Excellent agreement is found between the observed properties and predictions made using the U(5) limit of the proton-neutron interacting boson model. The results strongly support the contention that the 2_3^+, 2.004-MeV level has mixed proton-neutron symmetry. Combining the present measurement for $B(E2;0_1^+ \rightarrow 2_3^+)$ of 0.070 ± 0.011 e^2b^2 with known branching and mixing ratios gives a substantial $M1$ strength of $(0.26 \pm 0.05)\mu_N^2$ for the $2_3^+ \rightarrow 2_1^+$ transition.

In their review of the interacting boson model (IBM), Arima and Iachello[1] suggested that "the location of collective states of mixed proton-neutron symmetry is one of the most interesting open experimental problems in the study of collective features of nuclei." Such states are expected in the version of the IBM known as IBM-2, which explicitly contains neutron and proton degrees of freedom, but not in IBM-1, which does not differentiate between neutron and proton bosons. Subsequently, there has been experimental evidence[2–5] for mixed-symmetry states in strongly deformed nuclei ranging from ^{46}Ti to ^{238}U, mainly from electron and photon scattering. Most of the work has concentrated on 1^+ states, which have very large $M1$ transition strengths to the ground state; these states have been picturesquely described in a geometric framework as a type of "scissors" mode, involving small-amplitude oscillations of the angle between the symmetry axes of the deformed proton and neutron distributions. Iachello[6] has pointed out that these 1^+ levels are not the only type of mixed-symmetry states expected but are merely one of an entirely new class of collective modes. In spherical nuclei a collective 2^+ mode is expected at 2-3-MeV excitation energy with $B(E2;0_1^+ \rightarrow 2^+) \approx 3$ W.u. and a large $M1$ strength to the lowest fully symmetric 2^+ state. In a geometrical picture, this mode would be described as a quadrupole vibration with the protons and neutrons oscillating out of phase. Despite considerable interest[7] unambiguous experimental evidence for these states has been very elusive.

In the case of the nucleus ^{142}Ce Hamilton, Irbäck, and Elliott[8] have suggested that the 2_3^+ level at 2.004 MeV is a mixed-symmetry state. They carried out calculations using the vibrational U(5) limit of IBM-2 and were able to obtain good agreement with experimental branching ratios and $M1/E2$ mixing ratios for the decays of the 2_3^+ level. However, it should be stressed that absolute transition strengths for the 2_3^+ level are not known and without these the comparison with theory is inconclusive. Indeed, no absolute strengths are known in ^{142}Ce with the exception of the $2_1^+ \rightarrow 0_1^+$ transition. In the present work, we have used Coulomb excitation to determine various $B(E2)$ values, including $B(E2;0_1^+ \rightarrow 2_3^+)$ from which it is possible to use the known branching ratios and mixing ratios[9] to obtain the absolute $E2$ and $M1$ strengths for the $2_3^+ \rightarrow 2_1^+$ transition. We have also carried out an improved determination of the quadrupole moment of the 2_1^+ level since this is a quantity used by Hamilton *et al.* as an important test of their model parameters.

Only essential details of the experimental procedure and analysis will be described here. The experimental and analytical procedures are similar to those of Ref. 10 and a more detailed account of the present work will be presented elsewhere. Beams of ^{4}He, ^{12}C, and ^{16}O at energies of 10–12, 31–38, and 44–50 MeV, respectively, were obtained from the ANU 14UD accelerator and used to bombard targets consisting of CeF_3 evaporated onto thin carbon foils. The isotopic material was enriched to 93.4% in ^{142}Ce. Backscattered particals were detected at a mean laboratory angle of 170.6° using an annular silicon surface-barrier detector. A typical spectrum is shown in Fig. 1. Spectra were analyzed to extract excitation probabilities for the various states populated. Excitation probabilities obtained at bombarding energies which were found

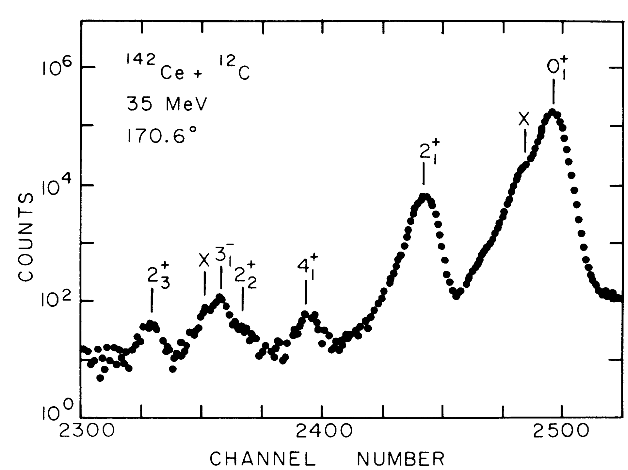

FIG. 1. Spectrum obtained with an annular silicon surface-barrier detector for ^{12}C projectiles scattering from a ^{142}Ce target. States of ^{142}Ce are indicated by their spin and parity. The expected positions of peaks from a 6.6% isotopic impurity of ^{140}Ce are indicated by the symbol ×.

experimentally[11] to be free from nuclear interference were fitted using theoretical excitation probabilities calculated with the de Boer-Winther semiclassical Coulomb excitation code. Five excited states were included in the analysis: 2_1^+ (0.641 MeV), 4_1^+ (1.219 MeV), 2_2^+ (1.536 MeV), 3_1^- (1.653 MeV), and 2_3^+ (2.004 MeV). The usual small corrections[10] were applied for electron screening, vacuum polarization, nuclear polarization, target thickness, and $E1$ interference from the giant dipole resonance. The results obtained are summarized in Table I.

The result for $Q(2_1^+)$, the static quadrupole moment of the 2_1^+ level, is very sensitive to the sign assumed for the interference term from the 2_3^+ level. We obtain $Q(2_1^+) = -0.16 \pm 0.05$ eb for destructive interference from the 2_3^+ level, i.e., $P_4 > 0$, where P_4 is defined by

$$P_4 = \langle 0_1^+ || M(E2) || 2_1^+ \rangle \langle 2_1^+ || M(E2) || 2_3^+ \rangle \times \langle 0_1^+ || M(E2) || 2_3^+ \rangle \langle 2_1^+ || M(E2) || 2_1^+ \rangle . \quad (1)$$

For constructive interference ($P_4 < 0$) the result for $Q(2_1^+)$ is -0.37 ± 0.05 eb. The only previous measurement of $Q(2_1^+)$ is -0.12 ± 0.09 eb obtained by Engler.[12] The present work is superior both because of an order of magnitude improvement in statistical accuracy of the data and a far better knowledge of the higher-state matrix elements and various small corrections. Engler took into account only the 2_2^+ level when considering the effects of higher states and used a value for $\langle 2_1^+ || M(E2) || 2_2^+ \rangle$ which differs substantially from the value which we have measured.

Table I shows the transition strengths and $Q(2_1^+)$ predicted by the IBM-2 calculations of Hamilton, Irbäck, and Elliott.[8] The predicted sign of P_4 is positive and the calculated quadrupole moment is -0.11 eb. This is consistent with the experimental result of -0.16 ± 0.05 eb for $P_4 > 0$. An unusual feature of the parameter set used in Ref. 8 was the use of a larger effective charge for neutron bosons ($e_\nu = 0.24$ eb) than for proton bosons ($e_\pi = 0.12$ eb). If instead e_π were to be larger than e_ν, the predicted sign for P_4 would be negative and it would be necessary to compare the prediction for the quadrupole moment with an experimental value of -0.37 ± 0.05 eb. It would be very difficult, if not impossible, to reproduce such a large magnitude for the quadrupole moment with any reasonable set of parameters. Another consequence of having $e_\pi > e_\nu$ is that the predicted sign of the $M1/E2$ mixing ratio $\delta(2_3^+ \rightarrow 2_1^+)$ would be negative[8] in conflict with experiment.[9]

Puddu, Scholten, and Otsuka[13] studied Xe, Ba, and Ce isotopes with neutron number $N < 82$ and found a good fit was obtained with $e_\pi = e_\nu = 0.12$ eb. Likewise, Robinson *et al.*[14] fitted $N = 84$ isotones with $e_\pi = e_\nu = 0.12$ eb and suggested that this gave a better fit than the values of Hamilton *et al.* However, equal neutron and proton effective charges for ^{142}Ce would require $B(E2;0_1^+ \rightarrow 2_3^+) = 0$ since[8]

$$B(E2;0_1^+ \rightarrow 2_3^+) = \frac{5N_\pi N_\nu}{N_\pi + N_\nu}(e_\pi - e_\nu)^2 , \quad (2)$$

where N_π and N_ν are the number of proton and neutron bosons. There is an ambiguity in the value of N_π due to the possible $Z = 64$ shell closure; for the present purposes we use the values[8] $N_\pi = 4$ and $N_\nu = 1$. Our value for $B(E2;0_1^+ \rightarrow 2_3^+)$ of 0.070 ± 0.011 e^2b^2 is quite large (3.2 ± 0.5 W.u.) and implies $|e_\nu - e_\pi| = 0.132 \pm 0.010$ eb. This is in excellent agreement with $e_\nu - e_\pi = 0.12$ eb obtained by Hamilton *et al.* from an analysis of $B(E2;0_1^+ \rightarrow 2_1^+)$ values for vibrational Ba, Ce, and Nd isotopes.

Combining the present value for $B(E2;0_1^+ \rightarrow 2_3^+)$ with the mixing and branching ratios of Ref. 9 gives $B(E2;2_3^+ \rightarrow 2_1^+) = 0.033 \pm 0.011$ e^2b^2 and $B(M1;2_3^+ \rightarrow 2_1^+) = (0.26 \pm 0.05)\mu_N^2$. Both are in good agreement with IBM-2 predictions (Table I). The $M1$ strength here is not as large as in the case of the strongly deformed rare-earth nuclei ($\sim 1\mu_N^2$) because in the U(5) limit of IBM-2 there is no boson enhancement factor as for the SU(3) case. However, the $M1$ strength (0.15 ± 0.03 W.u.) is still considerably larger than the typical strength for nuclei in this mass region.[15]

It is evident that there is very good overall agreement between experiment and the calculations of Hamilton *et al.* using the U(5) limit of the IBM-2. The more detailed calculations of Robinson *et al.*[14] suggest that the properties of a mixed symmetry state would be shared between the experimental 2_2^+ and 2_3^+ levels. This is not consistent with the observed properties of these levels, such as the low limit on $B(E2;0_1^+ \rightarrow 2_2^+)$ of < 0.008 e^2b^2. The properties of the 2_2^+ level are consistent with those expected for a pure $2d$ boson symmetric state and the 2_3^+ state appears to be well described as a $1d$ boson mixed-symmetry state. This contrasts strongly with two other cases of suggested mixed-symmetry states in nuclei outside the well-deformed regions of the periodic table, i.e., the light nucleus ^{56}Fe (Ref. 16) and the O(6) nucleus ^{134}Ba.[17] In both these cases, the properties of a theoretical mixed-symmetry state would have to be shared between two or more experimental levels.

To conclude, the experimental evidence strongly sup-

TABLE I. Transition strengths and $Q(2_1^+)$ for levels in ^{142}Ce.

	Experiment (present work)	Theory[a] (IBM-2)
$B(E2;0_1^+ \rightarrow 2_1^+)$ (e^2b^2)	0.479 ± 0.004 [b]	0.52
$Q(2_1^+)$ (eb)	-0.16 ± 0.05 [b]	-0.11
$B(E2;4_1^+ \rightarrow 2_1^+)$ (e^2b^2)	0.117 ± 0.010	0.17
$B(E2;2_2^+ \rightarrow 2_1^+)$ (e^2b^2)	0.162 ± 0.037	0.17
$B(E2;0_1^+ \rightarrow 2_2^+)$ (e^2b^2)	<0.008	0
$B(E2;0_1^+ \rightarrow 2_3^+)$ (e^2b^2)	0.070 ± 0.011	0.058
$B(E2;2_3^+ \rightarrow 2_1^+)$ (e^2b^2)	0.033 ± 0.011 [c]	0.016
$B(M1;2_3^+ \rightarrow 2_1^+)$ (μ_N^2)	0.26 ± 0.05 [c]	0.23
$B(E3;0_1^+ \rightarrow 3_1^-)$ (e^2b^3)	0.202 ± 0.013	
$B(E4;0_1^+ \rightarrow 4_1^+)$ (e^2b^4)	<0.036	

[a] Reference 8.
[b] Results for destructive interference ($P_4 > 0$) from the 2_3^+ level. For constructive interference the results are $B(E2;0_1^+ \rightarrow 2_1^+) = 0.482 \pm 0.004$ e^2b^2 and $Q(2_1^+) = -0.37 \pm 0.05$ eb.
[c] Calculated using measured value of $B(E2;0_1^+ \rightarrow 2_3^+)$ and the branching and mixing ratios of Ref. 9.

ports the proposition that the 2_3^+ level of ^{142}Ce is a new type of collective excitation with mixed proton-neutron symmetry. There is a large $M1$ strength for the $2_3^+ \rightarrow 2_1^+$ transition and the $E2$ strength for the $0_1^+ \rightarrow 2_3^+$ transition of 3.2 ± 0.5 W.u. agrees with the order of magnitude estimate of ≈ 3 W.u. given by Iachello.[6] This relatively large $E2$ strength implies that the effective charges for protons and neutrons are substantially different. A detailed comparison of our results with the calculations of Hamilton *et al.*,[8] using the U(5) limit of the IBM-2, reveals a very close agreement and tends to support the parameter set which they use, including their controversial use of a larger effective charge for neutron bosons than for proton bosons.

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