can then be ascribed to the breakdown of the mirror relationship between the outgoing pair of nuclei.

Considering this breakdown further, one can distinguish theoretically between two effects which combine to produce the fore-and-aft asymmetry. One might be called the "static" departure from the situation where the two nuclei are related to each other by a rotation in isospace. Thus, for instance, the two like nucleons in He^3 and H^3 may be spatially correlated in a different manner,[1,2] leading to the breakdown of an exact mirror relationship. Note that this effect varies linearly with the amplitude parameter expressing the deviation from exact isobaric analogy between C and C'. The second effect is the "analyzing power" of a particular nuclear reaction, i.e., its ability to distinguish such differences in the angular distribution. It is conceivable that even though two states, C and C', are not exact analogs in isospace, a particular reaction might be relatively insensitive to the difference, treating the states, in effect, as components of a multiplet, and hence leading to fore-and-aft symmetry. A trivial example of this situation is given in point (3) above. A measured asymmetry attributed to a breakdown of isobaric analogy between C and C' must be analyzed as a result of these two factors, the former depending linearly upon static differences between C and C', the latter varying from reaction to reaction.

To sum up, then, we point out the possibility of some incisive tests of isospin analogy, based on simple geometric properties of reaction cross sections, and applying equally well to ground states and excited states of nuclei, from the lightest mirror pairs to the heaviest isobaric analogs. Recent technological advances place the necessary reactions well within the realm of present-day capabilities.

We are grateful to Professor B. F. Bayman for enlightening discussions.

Note added in proof.—It has just come to our attention that recent experimental data exist on Case I of Table I [B. Kuehn and B. Schlenk, Nucl. Phys. 48, 353 (1963)]. The angular distributions exhibit striking symmetry about 90° at all four measured energies, with a slight but significant degree of fore-and-aft asymmetry (~10%), whereas other reaction channels at the same energies show no symmetry at all.

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*Work supported in part by the National Science Foundation.

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OBSERVATION OF THE JAHN-TELLER SPLITTING OF THREE-VALENT d^7 IONS VIA ORBACH RELAXATION*

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In this Letter an investigation on the line broadening of octahedrally coordinated d^7 ions with t^6e configuration is reported. This broadening is due to an Orbach resonance relaxation. For Pt^{3+} in Al_2O_3 and for Ni^{3+} in $SrTiO_3$ the obtained energy separation Δ between the lowest two levels is shown to be the Jahn-Teller (J-T) splitting of the ^2E ground state.

Relaxation between the two states of a Kramers doublet by the Orbach process takes place when there is a third energy level lying within the phonon spectrum.[1] The relaxation time T_1 for this process obeys the relation

$$T_1 = A \exp(\Delta/kT),$$

where Δ is the separation of the first excited level from the ground doublet and A is the lifetime of the excited state.

In transition metal ions this type of relaxation was first observed by Zverev and Petelina[2] for

Co^{2+} in Al_2O_3. For the O_h group the ground state of this ion is $^4\Gamma_4$ belonging to a weak field configuration t^5e^2. The ground state is split by the trigonal field into six Kramers doublets, and the predicted distance Δ between the lowest two levels has been verified. Geschwind and Remeika[3] have shown that the Ni^{3+} and the Pt^{3+} in Al_2O_3 belong to the strong-field t^6e configuration. The orbitally degenerate octahedral ground state $^2\Gamma_3$ is not split either in trigonal Al_2O_3 or in cubic $SrTiO_3$ by the crystalline field, but the degeneracy is removed by the J-T effect. From the isotropic paramagnetic resonance lines this effect is shown to be dynamic above 77°K in both crystals.[3,4] The lines broaden with increasing temperature and it was thought that this broadening could be due to resonance relaxation. The linewidths were then measured in the temperature range of 77° to 500°K using a conventional superheterodyne spectrometer at 3.2 cm. In order to obtain the relaxation times the relation $T_1 = h/(\pi g\beta\Delta H_{sl})$ was used, where $\Delta H_{sl}(T) = \Delta H(T) - \Delta H_0$, and ΔH_0 is the residual linewidth measured at low temperature. In the graph of Fig. 1 $\ln T_1$ is plotted against T^{-1}. The straight line obtained indicates the presence of resonance relaxation. The other relaxation mechanisms such as the T^{-7} and T^{-9} Raman effect and the direct process have been shown to be negligible. The results for A and Δ, including those for Ni^{3+} in $SrTiO_3$,[5] are given in Table I.

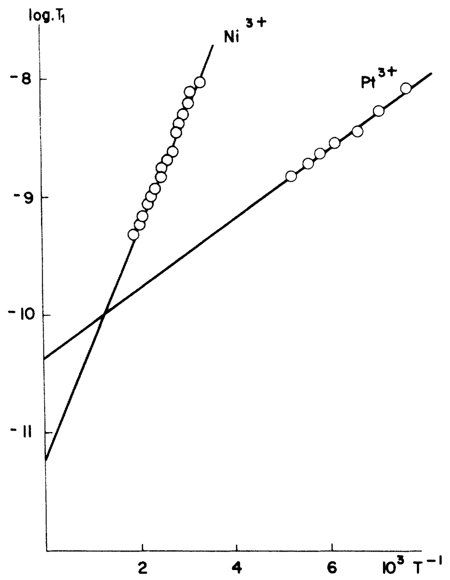

FIG. 1. A graph of the spin-lattice relaxation time T_1 of Ni^{3+} and Pt^{3+} in Al_2O_3 plotted on a logarithmic scale against inverse temperature.

In order to assign the level at the energy Δ above the ground state we consider a Tanabe-Sugano[6] type diagram. In Fig. 2 the position of the levels for Ni^{3+} and Pt^{3+} are indicated for the typical values of the crystal-field parameter Dq and the Racah parameters $B = 4.5C$. Those were taken to be $Dq = 1700$ and $2500\ cm^{-1}$, and $B = 660$ and $330\ cm^{-1}$, respectively.[7] For Pt^{3+} the lowest lying level $^4\Gamma_4$ occurs at $18\,000\ cm^{-1}$ above the $^2\Gamma_3$ level. Thus, the observed Δ value can only be due to the Jahn-Teller splitting of the $^2\Gamma_3$ level. This assignment has been tentatively pro-

Table I. Resonance relaxation results of d^7 ions and highest reported allowed and forbidden lattice vibration bands of their trigonal (Al_2O_3) and cubic ($SrTiO_3$) hosts.

		Resonance relaxation data		Highest reported lattice modes	
d^7 ion	Host crystal	Lifetime $A \times 10^{11}$ (sec)	Splitting Δ (cm^{-1})	of host (cm^{-1})	References
Ni^{3+}	Al_2O_3	0.6 ± 0.3	1530 ± 150	630; 806	a, b, and this paper
Ni^{3+}	$SrTiO_3$	20 ± 5	665 ± 50	550; 750	c, d, e, and f
Pt^{3+}	Al_2O_3	4 ± 1	470 ± 40	630; 806	a and this paper

[a] A. S. Barker, Phys. Rev. 132, 1474 (1963).

[b] U. Höchli, O. S. Leifson, and K. A. Müller, Helv. Phys. Acta 36, 484 (1963). In this communication the residual width has not been taken into account.

[c] A. S. Barker and M. Tinkham, Phys. Rev. 125, 1527 (1962).

[d] W. G. Spitzer, R. C. Miller, D. A. Kleinman, and L. E. Howarth, Phys. Rev. 126, 1710 (1962).

[e] K. A. Müller and R. S. Rubins, to be published.

[f] Weak band, probably two-phonon combination band [see Fig. 3 of reference c, and R. C. Miller and W. G. Spitzer, Phys. Rev. 129, 94 (1963)].

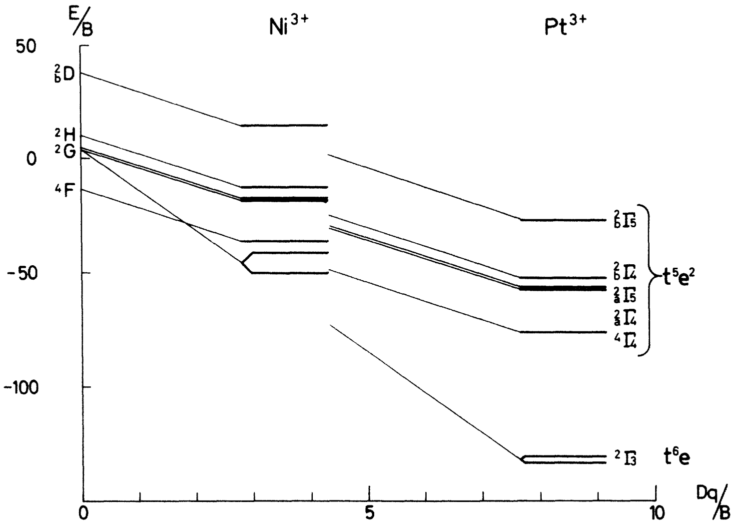

FIG. 2. The energy level diagram of d^7 ions is an octahedral field computed according to Tanabe and Sugano.[6] The observed splittings Δ are included and magnified by a factor 5 for better clarity.

posed for Ni^{3+} in $SrTiO_3$, where the Δ value of 665 cm^{-1} is considerably lower than the estimated distance of the $^4\Gamma_4$ from the $^2\Gamma_3$ level of 3000 to 7000 cm^{-1}.[5] The assignment for Ni^{3+} in Al_2O_3 cannot be made since the large observed Δ is estimated to be nearly the same as the distance of $^2\Gamma_3$ from the lowest level of the split $^4\Gamma_4$ state. The observed splittings of 400 cm^{-1} to 1500 cm^{-1} are in the range of the J-T splittings originally estimated by Van Vleck[8] for transition metal ions. Relatively little is known about these splittings. It seems to be difficult to observe them by optical spectroscopy because of the presence of the phonons which in turn favor the detection by resonance relaxation.

A g-value calculation has been made using strong-field, single-electron wave functions. The static J-T effect for Pt^{3+} yielded $g_\perp > g_\parallel$[3]; this enables us to assign the levels of the split ground state. The group-theoretically allowed wave functions (including spin) of the configuration $t^6e = \overline{e}^3$ transform according to $^2\Gamma_3$ and are explicitly given by[9]

$$U^{\pm} = Y_2^{0\pm}\tfrac{1}{2}(Y_2^{2} + Y_2^{-2})^{-}(Y_2^{2} + Y_2^{-2})^{+} f(r),$$
$$V^{\pm} = 2^{-1/2}(Y_2^{2} + Y_2^{-2})^{\pm} Y_2^{0+}\overline{Y}_2^{0} f(r).$$

The higher lying levels which interact with the ground state via the spin-orbit coupling belong to the configuration $t^5e^2 = \overline{e}^2\overline{t}^1$. Their wave functions transform according to $^2\Gamma_5 \times {}^2\Gamma_3 \times {}^2\Gamma_3 = {}^4\Gamma_4 + 2\,{}^2\Gamma_4 + 2\,{}^2\Gamma_5$. Our calculation yields[9] $g_\perp > g_\parallel$ for V which, therefore, must be the lower lying level. Due to the lowering of the symmetry by the J-T effect, U and V couple and V is not pure but dominant.[9] For the weak-field case U and V are replaced by E_θ and E_ϵ.[5]

The results for Ni^{3+} in Al_2O_3 and $SrTiO_3$ show that line broadening due to resonance relaxation can occur even above room temperature. Although we are not able to assign an excited level to the observed Δ value for Ni^{3+} in Al_2O_3, this result is interesting in another respect. The observation of resonance relaxation between levels that are separated by 1500 cm^{-1} requires the presence of phonons of this energy with sufficient density.

Barker[10] in a recent study analyzed carefully the infrared spectrum of Al_2O_3. The highest of the group-theoretically allowed modes lies at 635 cm^{-1}. He further lists a series of weak forbidden modes extending up to 806 cm^{-1}. Weak forbidden modes may exist up to 1500 cm^{-1} causing the relaxation, or combination bands of the allowed modes of small oscillator strength may be present due to anharmonicity. This, however, would require a combination of three phonons. An alternative explanation which appears just as attractive to us is suggested in connection with a recent theoretical study of Slonczewski[11] on the dynamic Jahn-Teller effect. By analyzing the motion of the J-T ion and that of its surrounding ions he finds that an elastically and a centrifugally stabilized mode should occur. The latter may be well above the maximum lattice vibration frequency.

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DECAY OF O^{16} GIANT DIPOLE STATES TO EXCITED STATES OF O^{15}†

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Theoretical predictions of the properties of the 1^-, $T=1$ levels of O^{16} which are strongly excited in photon absorption have so far been made almost entirely in terms of single-particle, single-hole configurations.[1-3] While the energies calculated for these states agree fairly well with observations, other features are not so well predicted. For example, it is predicted that nearly all of the integrated cross section given by the dipole sum rule resides in the two states near 22 and 25 MeV, whereas it is found experimentally that at least half the sum rule is elsewhere, mostly spread over a wide range of higher energies.[4] This result agrees with recent calculations of Barker[5] and Abgrall,[6] which take account of two-particle, two-hole configurations in the ground state, but do not include them in the dipole states.

One of the clearest predictions of the strict one-particle, one-hole form of the theory is that decays of the major 1^- states by neutron or proton emission will leave the residual nucleus (O^{15} or N^{15}) in a p-hole state, i.e., a $\frac{1}{2}^-$ or $\frac{3}{2}^-$ state. In each of these nuclides the ground state is $\frac{1}{2}^-$ and the third excited state at about 6.2 MeV is $\frac{3}{2}^-$. There is, however, in each case at about 5.2 MeV a close doublet of positive-parity states ($\frac{1}{2}^+$ and $\frac{5}{2}^+$) which have the character of two p holes plus an s or d particle,[7] so that it is feasible to ascertain whether or not the O^{16} giant dipole states can decay into other than simple p-hole states. Thus one can learn about the strength of the two-particle, two-hole configurations in these giant dipole states. Figure 1 shows the pertinent energy levels of O^{16} and O^{15}. (The energies shown for O^{16} are those we measure, and are in generally good agreement with previously accepted values.[8,9]

The only previous evidence bearing on this point has been contradictory. Johansson and Forkman[10] reported that decays to the positive-parity doublet of N^{15} did not take place, while Milone et al.[11] reported that they did see such decays. A reanalysis of these data by Fuller and Hayward[12] led them to the conclusion that the decays probably take place, but that the data were too sparse to be interpreted unambiguously.

We have measured the 90° photoneutron spectrum of O^{16} irradiated with bremsstrahlung of about 34-MeV end-point energy from the Rensselaer electron linac.[13] The spectrometer consists of a 1024-channel time-to-pulse-height analysis system with 8-nsec channel widths, driven by signals from a 5-in. thick by 20-in. diameter liquid scintillation neutron detector located at the end of a 100-meter evacuated flight path. The one-ampere electron-beam pulse was 10 nsec long, and the over-all time resolution was 16 nsec, giving energy resolutions of 8.5 keV