215 K). We may therefore conclude that the magnetostriction is mainly responsible for the $\Delta_1$ gap but the pair excitation mechanism proposed here is responsible for the $\Delta_2$ gap.

It may be worth pointing out that, if our interpretation of the MA and TO mode mixing is correct, the phenomenon is the first experimental confirmation that the electron bands of heavy rare earths are strongly influenced by the spin-orbit coupling.

A part of this work was done at the Danish Atomic Research Establishment at Risø. The author would like to thank Professor H. Højgaard Jensen at the Ørsted Institute and Professor A. R. Mackintosh at Risø for their hospitality. He is also indebted to Professor L. M. Falicov and Professor Mackintosh for numerous helpful discussions, and to Professor Falicov for a critical reading of the manuscript.

*On sabbatical from Iowa State University, Ames, Iowa 50010.

[1]J. Jensen, Int. J. Magn. 1, 271 (1971).
[2]H. B. Møller, J. C. G. Houmann, M. Nielsen, J. Jensen, and A. R. Mackintosh, private communication.
[3]R. M. Nicklow and N. Wakabayashi, in Proceedings of Fifth International Atomic Energy Agency Symposium on Neutron Inelastic Scattering, Grenoble, France, 6–10 March 1972 (to be published).
[4]B. D. Rainford, J. G. Houmann, and H. J. Guggenheim, in Proceedings of Fifth International Atomic Energy Agency Symposium on Neutron Inelastic Scattering, Grenoble, France, 6–10 March 1972 (to be published).
[5]C. Herring, Phys. Rev. 52, 361 (1937), and J. Franklin Inst. 233, 525 (1942).
[6]R. J. Elliott, Phys. Rev. 96, 280 (1954).
[7]M. H. Cohen and L. M. Falicov, Phys. Rev. Lett. 5, 544 (1960).
[8]J. O. Dimmock and A. J. Freeman, Phys. Rev. Lett. 13, 750 (1954).
[9]S. C. Keeton and T. L. Loucks, Phys. Rev. 168, 672 (1968).
[10]H. B. Møller, J. C. G. Houmann, and A. R. Mackintosh, Phys. Rev. Lett. 19, 312 (1967).

# Spin Assignments to Highly Excited States in $^{24}$Mg from Triple-Correlation Measurements*

R. W. Zurmühle, D. P. Balamuth, L. K. Fifield, and J. W. Noé
*Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104*
(Received 24 July 1972)

Triple correlation measurements using the reaction $^{16}O(^{12}C,\alpha_1)^{24}Mg^* \to \alpha_2 + {}^{20}Ne(2^+) \to \gamma + {}^{20}Ne(g.s.)$ have been made to determine spins and parities of several highly excited states in $^{24}$Mg. Our results allow unambiguous assignments of spin and parity $8^+$ to the states at 16.30 and 16.84 MeV. The group at 16.55 MeV is a doublet with one member having spin and parity $8^+$, while the other member is most likely a $9^-$ state.

The observation[1] of three narrow states at energies 16.30, 16.55, and 16.84 MeV in $^{24}$Mg, which are strongly populated in the reaction $^{16}O(^{12}C,\alpha)^{24}Mg$, has generated considerable speculation about their structure.[2] In particular, it has been suggested that one of these states might be the $10^+$ member of the ground-state rotational band, predicted[3] to lie near 17 MeV. Initial attempts[4,5] to determine the spins of these three states were unsuccessful, principally because these states decay predominantly by $\alpha$-particle emission to excited states of $^{20}$Ne with nonzero spin. The theoretical angular correlation of the two $\alpha$ particles thus contains a sum over the unobserved spin projections in the residual state in $^{29}$Ne; this summation washes out the pronounced structure of the individual transitions to the various magnetic substates which can be observed, for example, in transitions leading to spin-0 states. More recently the measurements of the $\alpha$-$\alpha$ angular correlations were extended to extreme backward angles,[6] where the theoretical correlation still displays some sensitivity to the spin. This measurement showed that the three states all possess high spin. Subject to the assumption that the $\alpha$ decay proceeds via the lowest allowed $L$ value consistent with the conservation of angular momentum and parity, the spins were suggested to be 8, 9, or 10. However, these results are sensitive to small admixtures of higher $L$ values in the $\alpha$ decay.

In the present Letter we report definite assignments of $8^+$ to both the 16.30- and 16.84-MeV states. The 16.55-MeV group appears to be a doublet with one of the states being $8^+$ and the other one probably being $9^-$. The experiment consisted of a measurement of triple coincidences involving two $\alpha$ particles and one $\gamma$ ray from the reaction

$$^{16}O + {}^{12}C \to {}^{24}Mg^* + \alpha_1$$
$$\quad \hookrightarrow {}^{20}Ne(2^+, 1.63\ \text{MeV}) + \alpha_2$$
$$\quad\quad \hookrightarrow {}^{20}Ne(\text{g.s.}) + \gamma.$$

The first emitted $\alpha$ particle was detected at 0°, and therefore only natural-parity states in $^{24}Mg$ were observed. Restricting the decay $\gamma$ ray to a fixed angle introduces pronounced structure into the theoretical correlations of the two $\alpha$ particles that strongly depends on the spin of the state in $^{24}Mg$. The theoretical form for the angular correlation is given by

$$W(\theta_{\alpha_1}=0;\theta_{\alpha_2},\theta_\gamma,\varphi) = \sum_{LL'M_BM_B'kq} (L\,-M_B J_B M_B|\,J_A 0)(L'\,-M_B' J_B M_B'|\,J_A 0)\langle\| L\|\rangle\langle\| L'\|\rangle^* \times (J_B M_B J_B\,-M_B'|kq)(-1)^{J_B-M_B'}\left(\frac{4\pi}{2k+1}\right)^{1/2} Y_L^{-M_B}(\theta_{\alpha_2},0)Y_{L'}^{-M_B'*}(\theta_{\alpha_2},0) \times R_k(L_\gamma L_\gamma J_B J_F)Q_k Y_k^q(\theta_\gamma,\varphi), \quad (1)$$

where $\varphi$ is the relative azimuthal angle of the $\gamma$ detector and the $\alpha_2$ detector. The spins of the state in $^{24}Mg$ and of the $2^+$ and $0^+$ states in $^{20}Ne$ are denoted by $J_A$, $J_B$, and $J_F$, respectively; $L$ and $L'$ are the orbital angular momenta of the second $\alpha$ particle and $L_\gamma$ is the $\gamma$-ray multipolarity. The quantity $\langle\| L\|\rangle$ is the reduced matrix element for the decay $^{24}Mg^* \to {}^{20}Ne^* + \alpha$ with the $\alpha$ particle carrying orbital angular momentum $L$. The attenuation factors $Q_k$ take the finite solid angle of the $\gamma$ detector into account. The $R_k$ are angular distribution coefficients as defined by Rose and Brink.[7]

In the present work $L, L' = J_A - 2$ was assumed. However, admixtures of the next higher allowed $L$ value, with the ratio $\langle\| J_A\|\rangle/\langle\| J_A-2\|\rangle$ of the order of 0.5, do not noticeably affect the calculated correlations. A large admixture of the next higher allowed $L$ value in the decay of these states is not expected because of the much higher angular momentum barrier. Also, this $L$ value would allow the decay to the ground state of $^{20}Ne$ which is energetically favored. However, the ground-state decays from all three peaks are known to be weak (Ref. 6 and see below); as the ground state and first excited state of $^{20}Ne$ are members of a rotational band, and are therefore expected to have similar structures, this strongly suggests that there is little admixture.

A beam of 36-MeV $^{12}C$ ions from the University of Pennsylvania tandem accelerator was used to bombard a $SiO_2$ target about 35 $\mu g/cm^2$ thick. The first emitted $\alpha$ particle ($\alpha_1$) from the reaction $^{16}O(^{12}C, \alpha_1\alpha_2\gamma)^{20}Ne$ was detected at 0° with respect to the beam direction using a position-sensitive detector at the focus of a magnetic spectrometer. $\alpha$ particles resulting from the decay of the states in $^{24}Mg$ were detected at sixteen angles simultaneously from 30° to 90° in the laboratory system by using a slice detector consisting of sixteen surface-barrier detectors on a single silicon wafer. This device was constructed by dividing the gold contact of the front electrode into sixteen slices $\frac{1}{8}$ in. wide and $\frac{1}{2}$ in. high, which were connected by a resistor chain. One end of this chain was grounded, while the other was connected to a charge-sensitive preamplifier. The total charge of every pulse was collected at the back contact. The pulse height from the back contact corresponded to the particle energy, while the ratio of the two pulse heights identified the slice that recorded the event. A strong magnet was placed in front of the detector to protect it from electron bombardment, and a thin Ni foil was used to stop slow heavy ions. In addition, both particle detectors were cooled to approximately −30°C to suppress the otherwise steadily increasing leakage current from radiation damage. $\gamma$ rays were detected using two 3 in.×4 in. NaI(Tl) crystals placed at $(\theta_\gamma, \varphi) = (47°, 180°)$ and $(133°, 0°)$. These two $\gamma$ angles are, of course, equivalent and the second detector only served to augment the counting rate. Triple coincidences and double coincidences involving an $\alpha$ particle at 0° were recorded. The appropriate linear signals from the detectors were digitized and stored on magnetic tape along with logic signals to identify the type of coincidence. The parameters digitized for each triple coincidence were the position signal of the 0° detector, the pulse from the $\gamma$-ray detector, and both signals from the multidetector array observing $\alpha_2$. The data were acquired using a PDP-9 computer. The experimental arrangement will be described in detail in a future publication.

The data were analyzed using an off-line sorting procedure which yielded the angular correla-

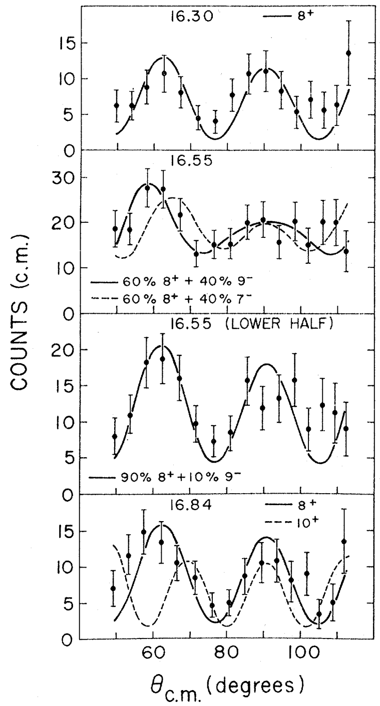


FIG. 1. Results of triple correlation measurement. Angular distributions of the second emitted $\alpha$ particle in coincidence with both the first $\alpha$ particle and the decay $\gamma$ ray are shown versus $\theta_{\alpha_2}$ for several states in $^{24}Mg$. The curves are the best fits for the spins shown.

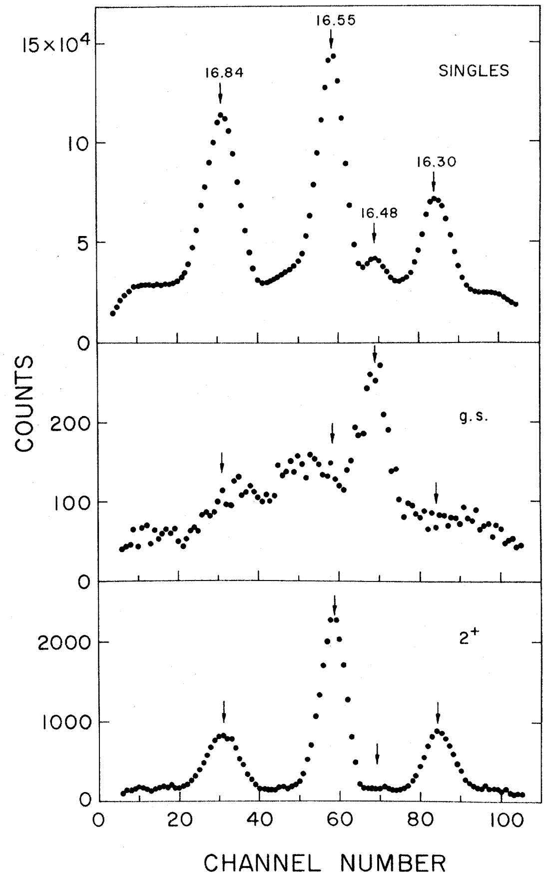


FIG. 2. Spectra of $\alpha$ particles observed at 0° in singles and in coincidence with decay $\alpha$ particles detected at $\theta_{lab}$ between 30° and 90° leading to the ground state and first excited state of $^{20}Ne$, respectively. The arrows mark the positions of the states at 16.30-, 16.48-, 16.55-, and 16.84-MeV excitation in $^{24}Mg$. Each of the spectra is derived from the data for the entire run, and therefore branching ratios can be deduced from this figure.

tion of the decay $\alpha$ particle ($\alpha_2$). No correction for random coincidences was made; however, the number of random triple coincidences was estimated by considering the various spectral distributions of random events that result if the three types of true double coincidences randomly coincide with a pulse in the third detector. The number of random coincidences estimated in this way was negligible.

The triple correlations obtained in the present work were fitted with Eq. (1) integrated numerically over the finite solid angle of the $\alpha_2$ detector (which is not cylindrically symmetric). No background was assumed. Spins $J_A = 4-11$ were tried. Only spin 8 gave an acceptable fit for the 16.30- and 16.84-MeV states. These fits are shown in Fig. 1; for the 16.84-MeV state, the fit for spin 10 is also shown for comparison. Because these states must all have natural parity, they can both be assigned $J^\pi = 8^+$. The analysis of the peak corresponding to an excitation energy of 16.55 MeV in $^{24}Mg$ was somewhat more complicated. It was already known that a doublet exists with a $J^\pi = 6^+$ member[5] at 16.59 MeV and a state of higher spin ($8^+$, $9^-$, or $10^+$) at 16.55 MeV.[6] For that reason we fitted the portion of the peak towards lower excitation energies in $^{24}Mg$ separately. We obtained a good fit for spin 8 only. Then we fitted the entire peak with a combination of spin 8 and spins between 4 and 11. A very good fit was obtained with a combination of 60% spin 8 and 40% spin 9. Admixing spin 7 instead of 9 also improved the fit, but resulted in a much higher value of $\chi^2$. Admixing either spin 6 or spin 10 to spin 8 did not give an acceptable fit. We therefore conclude that the decay of the group at 16.55 MeV to the $2^+$ state in $^{20}Ne$ comes from a doublet with one member having $J^\pi = 8^+$ and the other one having probably $J^\pi = 9^-$. The $6^+$ state at 16.59 MeV does not appear to be excited significantly at our bombarding energy and $\alpha_1$ angle. This is also evident from the spectrum of $\alpha$ particles at 0° that correspond to direct decays to the $^{20}$Ne ground state (Fig. 2). According to Ref. 5 the $6^+$ state at 16.59 MeV has a significant decay branch to the ground state, but only a weak particle group is visible in our spectrum at this energy.

Data from preliminary runs with two different angles of the $\gamma$-ray detector were also analyzed and gave results in good agreement with these spin assignments. Again, only spin and parity $8^+$ gave acceptable fits for the 16.30- and 16.84-MeV states, and $8^+$ also fitted the one half of the 16.55-MeV peak. A combination of $8^+$ and $9^-$ gave a very good fit to the entire 16.55-MeV peak; a combination of $8^+$ and $7^-$ gave a poorer but still acceptable fit.

Summarizing, spin and parity $8^+$ have been definitely assigned to the 16.30- and 16.84-MeV states in $^{24}$Mg. The group at 16.55 MeV appears to be a doublet with one member having $J^\pi = 8^+$ and the other member most likely having $J^\pi = 9^-$. However, $J^\pi = 7^-$ for the second member cannot be excluded with certainty. These results imply that the $10^+$ member of the ground-state rotational band is probably located at an excitation energy greater than 17 MeV. Plans to investigate the spins of other levels in $^{24}$Mg with the present method are underway in this laboratory.

We wish to thank Mr. F. Peiffer for his assistance during the experimental phase of this project. The expertise and cooperation of Mr. L. Csihas in the production of the slice detector and the target is gratefully acknowledged.

*Work supported by the National Science Foundation.

[1]R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. Lett. 24, 1436 (1970).

[2]See, for example, J. Phys. (Paris), Suppl. 32, Nos. 11–12 (1971).

[3]Y. Akiyama, A. Arima, and T. Sebe, Nucl. Phys. A138, 273 (1969).

[4]R. W. Zurmühle, D. P. Balamuth, D. A. Blumenthal, J. E. Holden, R. Middleton, and J. W. Noé, Bull. Amer. Phys. Soc. 15, 1678 (1970).

[5]A. Gobbi, P. R. Maurenzig, R. G. Stokstad, and R. Wieland, Bull Amer. Phys. Soc. 15, 1677 (1970); A. Gobbi, P. R. Maurenzig, L. Chua, R. Hadsell, P. D. Parker, M. W. Sachs, D. Shapira, R. Stokstad, R. Wieland, and D. A. Bromley, Phys. Rev. Lett. 26, 396 (1971).

[6]D. P. Balamuth, J. E. Holden, J. W. Noé, and R. W. Zurmühle, Phys. Rev. Lett. 26, 1271 (1971).

[7]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

# Odd-Parity Three-Particle, One-Hole Structure in $^{18}$F via the Reaction $^{15}$N($^6$Li, $t$)$^{18}$F

R. A. Lindgren, H. H. Gutbrod,* H. W. Fulbright, and R. G. Markham
*Nuclear Structure Research Laboratory,† University of Rochester, Rochester, New York 14627*
(Received 26 June 1972)

Strong preferential excitation of the odd-parity levels in $^{18}$F and sharply forward-peaked angular distributions have been observed in the reaction $^{15}$N($^6$Li,$t$)$^{18}$F. These results imply that the reaction mechanism contains a direct component and that the odd-parity levels have large $(p)^{-1}(sd)^3$ configurations.

Recent weak-coupling-model calculations[1,2] have predicted that the particle-hole structure of many odd-parity levels of $^{18}$F is predominantly 3p-1h (three particle, one hole). Poletti[3] suggested that the low-lying $J^\pi = 0^-$ and $1^-$ states at 1.08 and 3.13 MeV in $^{18}$F are based on a 3p-1h configuration formed by coupling a $p_{1/2}$ hole to the $^{19}$F core in the $J^\pi = \frac{1}{2}^+$ ground state. Similarly, the $J^\pi = 2^-$ and $3^-$ states at 2.10 and 3.79 MeV may be formed by coupling a $p_{1/2}$ hole to the $J^\pi = \frac{5}{2}^+$ excited state of $^{19}$F. The spectroscopic strength[4-6] to the $J^\pi = 1^-$ and $0^-$ states deduced from neutron pickup on $^{19}$F is large, consistent with this interpretation. Since the $J^\pi = 2^-$ and $3^-$ states are based on an excited $^{19}$F core, it is not surprising that they were found to be weakly excited in the neutron pickup reactions. The supposition that these two states have a $(p)^{-1}(sd)^3$ structure has not been established by experiment, nor have higher-lying states of this type been identified. Since the ground states of available target nuclei do not have the appropriate particle-hole structure, these levels cannot be formed directly in the usual single or double nucleon transfer reaction.

In principle, however, such levels could be excited via the three-nucleon transfer reaction on $^{15}$N. Here the ground-state wave function is of