High-Spin States in ^{24}Mg†

D. P. Balamuth, James E. Holden, John W. Noé, and R. W. Zurmühle
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
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Angular correlation measurements involving the reaction $^{16}O(^{12}C, \alpha)^{24}Mg^* \rightarrow \alpha + {}^{20}Ne^*$, leaving ^{20}Ne in its first excited state, have been used to study several highly excited states in ^{24}Mg. The method was tested using the known 8^+ state at 14.14 MeV. The results indicate that the triplet of states at 16.30, 16.55, and 16.84 MeV all have high spin (probably 8, 9, or 10). In the analysis it was assumed that the decay proceeds by the lowest allowed L value.

The recent discovery[1] of states in ^{24}Mg unbound to α-particle decay by ~7 MeV yet having total widths $\lesssim$20 keV has been received with considerable interest. These states (E_{ex}= 16.30, 16.55, and 16.84), and the previously observed[2] state at 14.14 MeV, were found[1] to be very strongly excited in the reaction $^{16}O(^{12}C, \alpha)^{24}Mg$—at forward angles they dominate the spectrum, with differential cross sections in the center-of-mass system of ~5 mb/sr. Despite considerable effort, at present a spin and parity assignment ($J^{\Pi} = 8^+$) has been made[2-4] only for the 14.4-MeV level. The principal reason for the inclusive results obtained to date for the triplet of levels near 16.5 MeV is that these states do not have a sufficiently strong α-particle decay to the ground state of ^{20}Ne to permit the use of conventional angular correlation techniques. (These states decay mainly to the 1.63-MeV 2^+ and 4.25-MeV 4^+ states in ^{20}Ne.) Knowledge of the spins of these states is particularly important, however, since it is not clear whether their narrow width results from unusual structure or is simply due to high spin and consequent inhibition of the decay by the angular-momentum barrier.

The present work was undertaken to obtain information about the spins of the three states at 16.30, 16.55, and 16.84 MeV by measuring the angular correlation of decay α particles to the first excited 2^+ state in ^{20}Ne from aligned states in ^{24}Mg. This work was part of an intensive investigation of the structure of these states, involving both particle-particle and particle-γ angular correlation measurements. A complete account of those measurements will be published later.

Conservation of angular momentum and parity limit the orbital angular momentum transferred in an α decay from a natural-parity state of spin J to a 2^+ state to the values $L = J-2$, J, $J+2$. Clearly the angular momentum barrier favors the lowest allowed L value. In the absence of any detailed knowledge of the structure of the states in question it seems reasonable to assume that the decay proceeds via $L = J-2$. This assumption can be checked in the case of the known 8^+ state at 14.14 MeV, which also decays to the first excited state of ^{20}Ne. The theoretical form of the angular correlation, assuming that the decay occurs via the lowest allowed L value, is

$$W(\Theta_{c.m.}) = \sum_{M_f} \langle L, -M_f, J_f, M_f | J_i, 0 \rangle^2 \times | Y_L^{-M_f}(\Theta_{c.m.})|^2, \qquad (1)$$

where J_i is the spin of the decaying state in ^{24}Mg, L is the orbital angular momentum, and $J_f = 2$ is the spin of the first excited state in ^{20}Ne. The theoretical predictions for a number of spins are shown in Fig. 1. It can be seen that the sum over final magnetic substates washes out the oscilla-

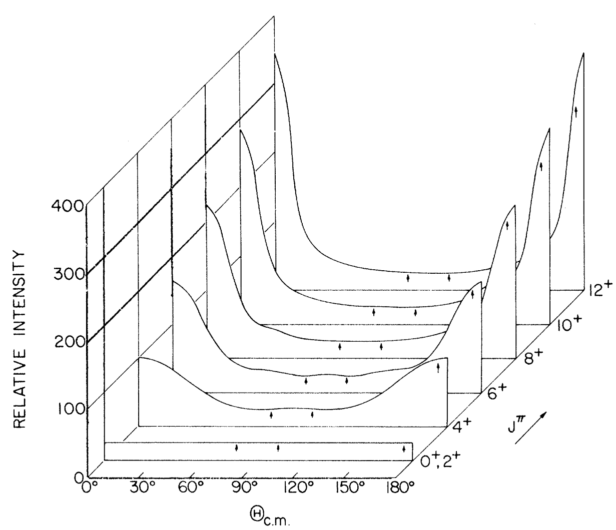

FIG. 1. Theoretical predictions for the angular correlation of α-particle decays from aligned natural-parity states of spin J to a 2^+ state via the lowest allowed L value. The predictions for odd spins, not shown here, are approximately intermediate between those of the adjacent even spins. The arrows indicate the angles of measurement in the present work.

tory pattern observed in transitions to spin-zero states at angles near 90° in the center-of-mass system, but there remains a forward and backward peaking which is a strong function of the spin. Thus, a measurement of the ratio of the number of α particles emitted near $\Theta_{c.m.}=90°$ to the number emitted at $\Theta_{c.m.}=175°$ can, in principle, determine the spin of the initial state.

Thin self-supported films of SiO_2 about 30 μg/cm^2 thick were bombarded with a beam of 36-MeV $^{12}C^{5+}$ ions from the University of Pennsylvania tandem accelerator. α particles leading to states in ^{24}Mg were detected at 0° with respect to the beam by a position-sensitive detector placed at the focus of a magnetic spectrometer.[5] (This geometry ensures that only natural-parity states are populated.[6]) The resolution, limited primarily by target thickness, was 120 keV full width at half-maximum. α particles from the decay of the aligned states thus produced were detected in time coincidence by an array of four surface-barrier detectors. These were placed at laboratory angles of 55°, 75°, 170° and −170°. Two detectors were employed at ±170° principally to check the position of the beam spot, since the theoretical angular correlations are a rapid function of angle near 180°. In all cases the numbers of counts in the 170° detectors were equal within statistical errors.

For each event the position of the α particle at 0°, the energy of the decay α particle, and their time difference were recorded on magnetic tape using a PDP9/ND3300 computer-analyzer system.[5] The subsequent data reduction and extraction of the experimental angular correlations were performed off line using the same computer.

Angular correlations for decay α particles leading to the 2^+ state in ^{20}Ne were obtained for each state in ^{24}Mg observed in the 0° spectrum. Apart from statistical uncertainties in the number of counts, an additional experimental error arises from the contribution of the background. This background consists of both broad states and relatively narrow discrete states which are not separated by the experimental energy resolution at 0°. In this second category is a 6^+ state at 16.59 MeV which is strongly excited at forward angles in the reaction $^{12}C(^{16}O,\alpha)^{24}Mg$. In the reaction used in the present work the cross section at 0° for this state is known[1] to be ≈20% of that of the 16.55-MeV state. There is also a state at 16.48 MeV which is evident in the spectrum of Ref. 1 and which is unresolved from the 16.55-

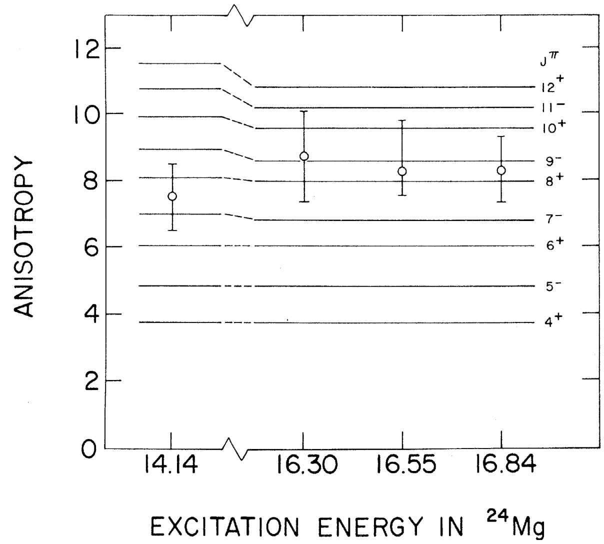

FIG. 2. Experimental anisotropies for the 14.14-, 16.30-, 16.55-, and 16.84-MeV states in ^{24}Mg. Also shown are the theoretical predictions for spins 4-12.

MeV state in our 0° spectrum. We have attempted to evaluate the contribution of the background both by varying the energy width of the window set on the 0° spectrum during data reduction and by obtaining experimental anisotropies for relatively flat portions of the 0° spectrum. The experimental errors (which are not necessarily symmetric about the best value) include the uncertainty in background subtraction.

The experimental results are presented in Fig. 2 as the most probable value of the experimental anisotropy and an estimate of the error. The anisotropy is defined as the ratio of the average number of counts observed at $\Theta_{lab}=\pm170°$ to the average of the numbers of counts observed at $\Theta_{lab}=55°$ and 75°, corrected to the center-of-mass system. For each state, the observed yields at the two forward angles were found to be equal within statistical errors, in agreement with the theoretical predictions shown in Fig. 1. The theoretical predictions for the anisotropy seen in Fig. 2 were obtained by evaluating Eq. (1) at the center-of-mass angles corresponding to the angles of measurement (hence the slightly different prediction for the 14.14-MeV state). No correction has been made for the population of magnetic substates with $M\neq0$ due to the finite solid angle of the 0° detector. This effect cannot be calculated explicitly without knowledge of the mechanism of the reaction leading to states in ^{24}Mg. However, similar experiments[7] involving the reaction $^{12}C(^{12}C,2\alpha)^{16}O$ in which the population of the $M=\pm1$ substates was treated as a free parameter indicate that the population of these substates is only a few percent of that of the $M=0$ substate. This would result in a negligible depression of the predicted anisotropy.

For the state at 14.14 MeV, which is known[2-4] to have $J^{\Pi}=8^+$, the results of the present work, shown in Fig. 2, are in very good agreement with the predicted value for spin 8. This indicates that the assumption of the lowest allowed L value dominating the α decay is justified, at least for this state.

The results for the triplet of states near 16.5 MeV are also shown in Fig. 2. All three states clearly have high spin. Since these states must have natural parity,[6] the results for the triplet are consistent with $J^{\Pi}=8^+$, 9^-, or 10^+, although $J^{\Pi}=7^-$ and 11^- are not definitely ruled out. The somewhat larger error bars on the 16.30-MeV state reflect both poorer statistics and a larger contribution from the background. In addition, for the 16.30-MeV state the α particles emitted at $\Theta_{lab}=75°$ are partially obscured by a proton group from the decay of $^{24}Mg^*$ to the first excited state of ^{23}Na. Its contribution (about 25%) was estimated from correlation spectra at neighboring angles measured previously.[3]

For the 16.84-MeV state it was also possible to obtain a lower limit on the experimental anisotropy of the angular correlation for α decay to the 4^+ state in ^{20}Ne. The results are consistent with the spins suggested above.

Since the angular correlations for α decays from high spin states to the 0^+, 2^+, and 4^+ states in ^{20}Ne all peak at 180°, examination of the 0° spectra in coincidence with decay α particles observed at $\Theta_{lab}=170°$ provides an effective way of suppressing background in order to measure branching ratios. The spectra observed at 0° in singles and in coincidence with transitions detected at 170° to the ^{20}Ne ground, 1.63-MeV (2^+), and 4.25-MeV (4^+) states are shown in Fig. 3. All members of the triplet clearly show branches to the 2^+ and 4^+ states in ^{20}Ne. Inspection of the spectrum in coincidence with ground state decays shows that only the 16.55-MeV state possesses any detectable ground-state branch, although at least some of the counts in the peak can be attributed to the 16.59-MeV state. While there is structure in other regions of the spectrum *near* 16.30- and 16.84-MeV excitation, there are no identifiable peaks corresponding to these groups. An upper limit for a ground-state branch from these states was obtained by assuming that the counts observed at the expected position of the relevant peak formed the top of a peak with the same line shape as the peak in the singles spectrum. In order to correct for angular correlation effects (since the observations are only at one angle) it is necessary to know the spin. The limits given were calculated for spin 10. For the 16.84-MeV state, we find that the ratio of 2^+ to 0^+ decays in the center of mass is ≥ 7.0. This is in disagreement with the value of 2.5 ± 1.0 reported for this quantity in Ref. 4. For the 16.30-MeV state the ratio of 2^+ to 0^+ decays is ≥ 4.5. This is not inconsistent with the value of 11.4 ± 4.8 reported in Ref. 4.

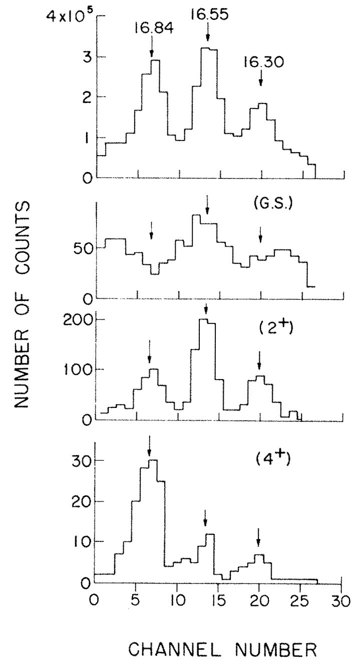

FIG. 3. Spectra of α particles observed at 0° in singles and in coincidence with decay α's detected at $\Theta_{lab}=170°$ leading to the ground state and first and second excited states of ^{20}Ne, respectively. The arrows mark the positions of the three states at 16.30-, 16.55-, and 16.84-MeV excitation in ^{24}Mg.

The results of the present work show that the states strongly populated at forward angles in the reaction $^{16}O(^{12}C,\alpha)^{24}Mg$ in the region of excitation $14\leq E_{ex}\leq 17$ MeV in ^{24}Mg have $J\geq 8$. It is interesting to note that this was the motivation of the original work[1]—to search for high-spin states as strong narrow peaks superimposed on a background of low-spin states. One member of the triplet at 16.30, 16.55, and 16.84 MeV is probably the 10^+ member of the ground-state rotational band, predicted to be at about 17 MeV.[8]

In conclusion, the results of the present study demonstrate that particle-particle angular correlations are a useful spectroscopic tool even in cases where the decay is to a state of nonzero spin. Plans to extend measurements of this kind to other highly excited states produced in heavy-ion–induced reactions are under way.

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

[2] D. Branford, N. Gardner, and I. F. Wright, in *Proceedings of the International Conference on Properties of Nuclear States, Montréal, Canada, 1969,* edited by M. Harvey *et al.* (Presses de l'Université de Montréal, Canada, 1969), Contribution No. 4.25.

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

[4] A. Gobbi, P. R. Maurenzig, L. Chua, R. Hudsell, P. D. Parker, M. W. Sachs, D. Shapira, R. Stokstad, R. Wieland, and D. A. Bromley, Phys. Rev. Lett. 26, 396 (1971).

[5] R. W. Zurmühle, P. F. Hinrichsen, C. M. Fou, C. R. Gould, and G. P. Anastassiou, Nucl. Instrum. Methods 71, 311 (1969).

[6] A. E. Litherland, Can. J. Phys. 39, 1245 (1961).

[7] J. A. Kuehner, Phys. Rev. 125, 1650 (1962).

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

New Model for the Interaction Between a Moving Charged Particle and a Dielectric, and the Cherenkov Effect*

Éamon Lalor† and Emil Wolf
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 8 April)

A new model is described for the interaction between a moving charged particle executing any two-dimensional motion and an infinite, homogeneous, linear dielectric. The model is based on the exact solution of the self-consistent integro-differential equation of molecular optics. The main results are illustrated by application to the Cherenkov effect.

Consider first a particle of charge e that moves on a trajectory $\vec{r}=\vec{r}_e(t)$ in the plane $z=0$ *in vacuo.* The Fourier frequency transforms [with kernel $(1/2\pi)\exp(i\omega t)$] of the electric and the magnetic fields that are generated by the particle may readily be derived by the use of the retarded potentials. It was shown by Asby and Wolf[1] that in each half-space $z\gtrless 0$ the fields have the following angular spectrum representation:

$$\vec{E}^{(v)}(\vec{r},\omega)=\iint_{-\infty}^{+\infty}\vec{e}^{(v)}(p,q;\omega;\gtrless)\exp[ik(px+qy\pm mz)]dpdq, \tag{1}$$

$$\vec{H}^{(v)}(\vec{r},\omega)=\iint_{-\infty}^{+\infty}\vec{h}^{(v)}(p,q;\omega;\gtrless)\exp[ik(px+qy\pm mz)]dpdq. \tag{2}$$

Here

$$k=\omega/c, \tag{3}$$

$$m=\begin{cases}+(1-p^2-q^2)^{1/2} \text{ if } p^2+q^2\leqslant 1, & \text{(4a)}\\ +i(p^2+q^2-1)^{1/2} \text{ if } p^2+q^2\geqslant 1; & \text{(4b)}\end{cases}$$

and the complex spectral vector amplitudes are given by

$$\vec{e}^{(v)}(p,q;\omega;\gtrless)=\hat{s}^{(\pm)}\times[\hat{s}^{(\pm)}\times\vec{f}(p,q;\omega)], \tag{5}$$

$$\vec{h}^{(v)}(p,q;\omega;\gtrless)=-\hat{s}^{(\pm)}\times\vec{f}(p,q;\omega), \tag{6}$$

with

$$\vec{f}(p,q;\omega)=(e/cm)(k/2\pi)^2\int_{-\infty}^{+\infty}\vec{V}(t')\exp\{i[\omega t'-k(px_e'+qy_e')]\}dt'. \tag{7}$$

In Eq. (7) x_e', y_e' are the coordinates and $\vec{V}(t')$ the velocity of the charged particle at time t'; c is the speed of light *in vacuo.* In (5) and (6), $\hat{s}^{(\pm)}$ are the unit vectors $(p,q,\pm m)$; the positive or negative sign on $\hat{s}^{(\pm)}$ and in $\pm m$ in (1) and (2), and the symbol $>$ or $<$ in the arguments of $\vec{e}^{(v)}$ and $\vec{h}^{(v)}$, are taken according as the field point $\vec{r}$ is in the half-space $z>0$ or $z<0$, respectively.