along these lines are in progress.

In conclusion it can be said that the mechanism of the $p+d \to p+p+n$ reaction is fairly well understood by considering only QFS along with FSI processes.

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## Spins and Parities of Highly Excited States in $Mg^{24}$†

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

*A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*

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From a study of the reaction $C^{12}(O^{16},\alpha_1)Mg^{24}(\alpha_2)Ne^{20}$, spins and parities have been measured for states in $Mg^{24}$ at the following excitation energies (in MeV): 12.10 ($4^+$), 12.45 ($7^-$), 13.07 ($5^-$), 14.41 ($4^+$), 16.07 ($6^+$), and 16.59 ($6^+$). Branching ratios were measured for several states in $Mg^{24}$ with $13 \leq E_{exc} \leq 23$ MeV decaying to the following states in $Ne^{20}$: $0^+$ (ground state), $2^+$ (1.63 MeV), and $4^+$ (4.25 MeV). These results permit the elimination of several postulated structures for the states in question.

The recent observation[1] of several unexpected narrow-width states in $Mg^{24}$ at excitation energies near 16 MeV which are strongly populated in the reaction $O^{16}(C^{12},\alpha)Mg^{24}$ suggests a number of interesting and different possibilities for the structure of levels in this energy region. It is presently a matter of conjecture whether these are high-spin members of rotational bands, quasimolecular states,[2] $\alpha$ clusters,[3] or, possibly, structures of some other type. Spin and parity assignments are obviously of fundamental importance in the determination both of their nature and of the reaction mechanisms whereby they are populated. In this Letter we report new experimental information on the spins, parities, and branching ratios for a number of states in $Mg^{24}$ in the region of excitation $12 \leq E_{exc} \leq 23$ MeV, obtained from a study of the reaction $C^{12}(O^{16},\alpha_1)Mg^{24}(\alpha_2)Ne^{20}$ at $E_{O^{16}} = 48.0$, 48.8, and 58.3 MeV (lab).

States above 9.32 MeV in $Mg^{24}$ are unbound to $\alpha$ decay. A measurement of the angular correlation of their decays to the $0^+$ ground state of $Ne^{20}$ enables a straightforward determination of the spin and parity $J^\pi$ of the parent states in $Mg^{24}$. Since the ground-state spins and parities of $O^{16}$, $C^{12}$, and $He^4$ are all $0^+$, and since $\alpha_1$ is detected along the beam axis, only normal-parity states are observed[4] and the angular correlation of $\alpha_2$ leading to the $Ne^{20}$ ground state is proportional to $P_J^2$, where $P_J(\cos\theta)$ is the Legendre polynomial of order $J$. A 10-mm × 50-mm position-sensitive, solid-state detector (PSD) subtending laboratory angles from 25° to 90° recorded all particles with $E_{lab} \geq 2$ MeV which were in coincidence with $\alpha$ particles emerging in a $10^{-2}$-sr solid angle at 0°. Silver and nickel absorber foils sufficiently thick (~20 mg/cm$^2$ in total) to stop the incident $O^{16}$ beam were placed between the 20-μg/cm$^2$ carbon target and the $dE/dx$-$E$ solid-state counter telescope at 0°. For each coincident event, $E_{\alpha_1}$, $E_{\alpha_2}$, $P_{\alpha_2}$, and $T_{\alpha_1-\alpha_2}$ were recorded on magnetic tape, where $E$, $P$, and $T$ denote energy, position, and time. These data were analyzed and sorted on the basis of the reaction kinematics in a multiparameter space both on and off line with the laboratory's IBM 360/44 data acquisition system. The absolute position calibration of the PSD was obtained with a precision of ±1° in a separate measurement in which a grid was placed over the face of the detector. Figure 1 shows an example of a two-dimensional display of selected coincident events obtained at 48.0 MeV for the transition to the $Ne^{20}$

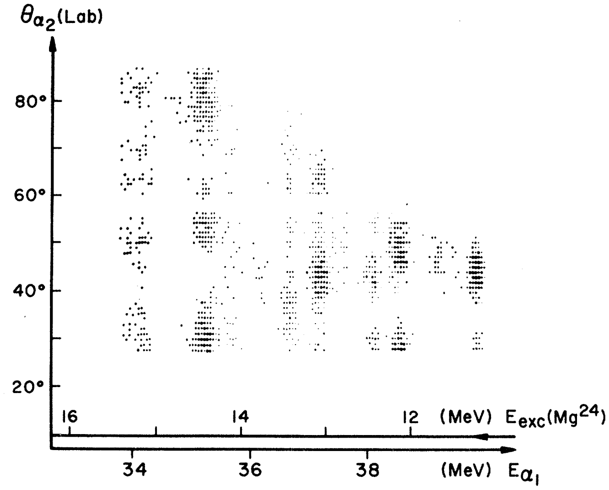


FIG. 1. Photograph taken directly from the on-line data acquisition display: Those events for which the ground state of $Ne^{20}$ was populated are shown in a two-dimensional display as a function of the energy of $\alpha_1$ and the angle of $\alpha_2$. Thus, a vertical slice selects all events corresponding to the decay of a particular state in $Mg^{24}$, and the projection of the events in this slice onto the $\theta_{1ab}$ axis yields the $\alpha_1$-$\alpha_2$ angular correlation. Note that the maxima and minima corresponding to different $P_J^2$ (and hence the $J^\pi$ assignments of the states in $Mg^{24}$) are readily discernable in several cases directly from the on-line computer display. A threshold on the display has suppressed most of the background, and the sharp minimum at $\theta_{1ab} = 58°$ arises from the 1-mm-wide strip masking the center of the detector.

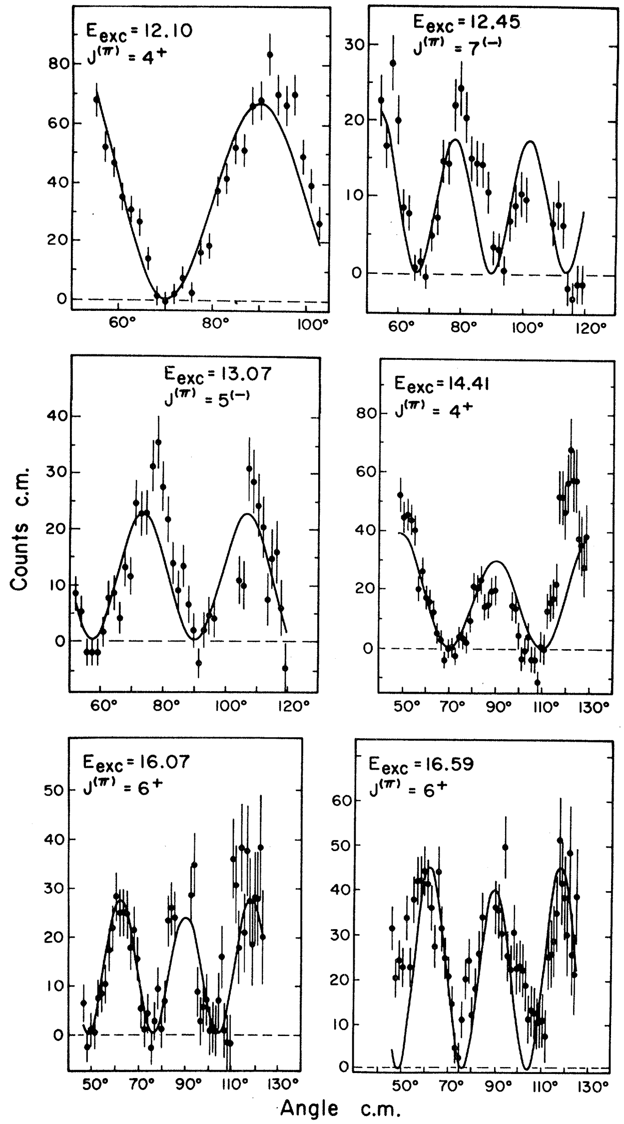


FIG. 2. Angular correlations for the reaction $C^{12}(O^{16}, \alpha_1)Mg^{24}(\alpha_2)Ne^{20}$ (ground state) obtained at bombarding energies of 48.0 and 48.8 MeV. After subtraction of a constant background in the laboratory system, the number of coincidence events is converted to the center-of-mass system and plotted versus c.m. angle. The full drawn curves represent fits to the data of the form $CP_J^2(\cos\theta)$, where the normalization constant $C$ is adjusted for a minimum value of $\chi^2$. The parities are given by $(-1)^J$. Data for the levels at $E_{exc} = 12.1$, 14.41, and 16.07 MeV and at 12.45, 13.07, and 16.59 MeV were obtained at bombarding energies of 48.0 and 48.0 MeV, respectively.

ground state. After the subtraction of a constant background in the laboratory system and transformation to the center-of-mass system, the correlations displayed in Fig. 2 were obtained. The main limitation in the deduction of a spin for a given level arose from the background; thus only the six cases shown in Fig. 2 allowed a unique spin assignment and, for example, the state at 13.44 MeV, although probably of negative parity, remains unassigned. An angular correlation obtained for a state at 14.14 MeV confirmed the $8^+$ spin assignment previously reported.[5]

Figure 3 presents $\alpha$ spectra obtained in direct and coincidence measurements at $E_{1ab} = 48.0$ MeV with the counter telescope at $\theta_{1ab} = 0°$. The resolution (full width at half-maximum) for $\alpha$ groups of ~20 MeV was about 250 keV. Absolute cross sections were determined in a separate measurement, independent of beam-current integration. The state at $E_{exc} = 16.59$ MeV has a differential cross section at 0° of $7.5 \pm 1.5$ mb/sr (center of mass). The branches to the $0^+$, $2^+$, and $4^+$ states of $Ne^{20}$ shown in Fig. 3 represent a sum of coincident events over the entire length of the PSD. The branching ratios extracted from these spectra and from similar measurements at $E_{1ab} = 48.8$ and 58.3 MeV are presented in Table I. We note that a number of these ratios (e.g., those for the

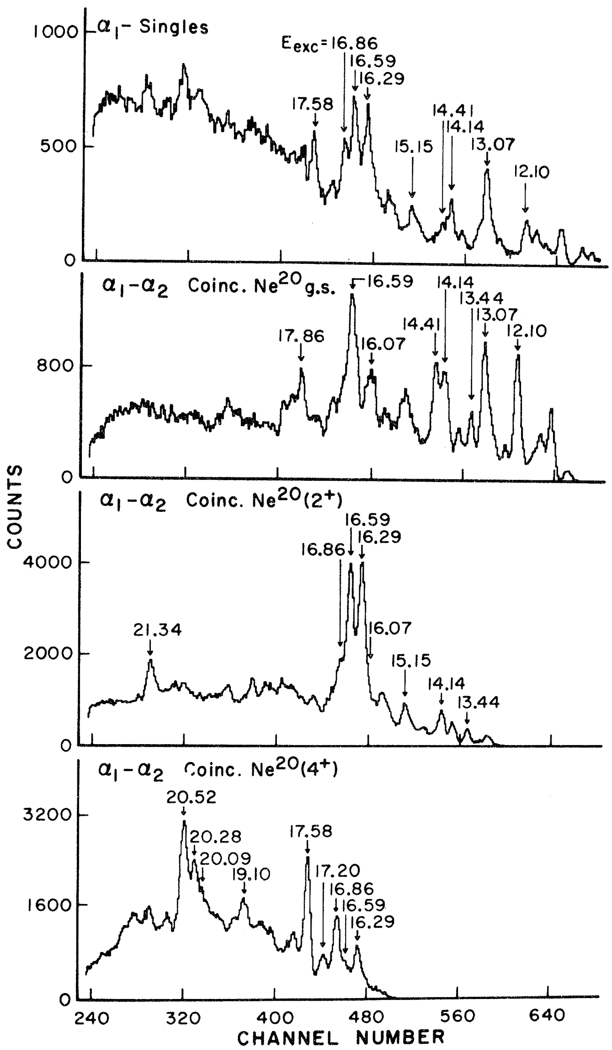


FIG. 3. $\alpha$-particle spectra obtained at 0° in direct singles and in coincidence with $\alpha_2$ particles to the lowest $0^+$, $2^+$, and $4^+$ states of $Ne^{20}$. The bombarding energy was 48.0 MeV. The portion below 10-MeV excitation in $Mg^{24}$ has been omitted in the direct spectrum. The PSD had an effective threshold of ~2 MeV for detection of $\alpha$ particles which, together with the kinematic variation of energy $E_{\alpha_2}$, accounts for the observed terminations of the coincidence $\alpha$ spectra at $E_{exc} \approx 10.5$, 12.5, and 16 MeV for transitions to the $0^+$, $2^+$, and $4^+$ states of $Ne^{20}$, respectively.

states at 19.31 and 21.34 MeV) are quite surprising since they indicate a decay which goes strongly to the $2^+$ state of $Ne^{20}$ but only weakly or not at all to the $0^+$ and $4^+$ states. Although the errors, arising from the uncertainty due to the background under the peaks and to the restricted angular range of observation, are rather large, these branching ratios should nevertheless provide essential information on the structure of the parent state.

Table I. Spin assignments and branching ratios[a] for $\alpha$ decay to the $0^+$ (ground state), $2^+$ (1.63-MeV), and $4^+$ (4.25-MeV) states in $Ne^{20}$.

| Level Energy (MeV) | $J^\pi$ | $2^+/0^+$ | $4^+/2^+$ |
|---|---|---|---|
| 12.10 | $4^+$ | | |
| 12.45 | $7^-$ | | |
| 13.07 | $5^-$ | | |
| 13.44 | | 0.92 ± 0.22 | |
| 14.14 | $8^+$ | 0.97 ± 0.16 | |
| 14.41 | $4^+$ | 0.15 ± 0.08 | |
| 15.15 | | 9.7 ± 1.7 | |
| 16.07 | $6^+$ | < 0.35 | |
| 16.29 | | 11.4 ± 4.8 | 0.16 ± 0.05 |
| 16.59 | $6^+$ | 2.4 ± 0.7 | 0.07 ± 0.05 |
| 16.86 | | 2.5 ± 1.0 | 0.95 ± 0.32 |
| 17.20 | | | > 9.4 |
| 17.58 | | > 1.4 | 5.9 ± 2.3 |
| 19.10* | | > 15.0 | 1.33 ± 0.16 |
| 19.31* | | >15. | < 0.09 |
| 20.3* | | > 2.2 | 5.7 ± 2.3 |
| 20.52* | | > 4.9 | 5.0 ± 0.9 |
| 21.34 | | > 5.9 | |

[a]The branching ratios have been corrected for the finite angle of observation and the errors include an estimated contribution from this correction.

The direct and coincidence spectra obtained at the three different bombarding energies exhibited quite different structure. The states labeled with asterisks in Table I, for example, were observed predominantly at $E_{O^{16}} = 58.3$ MeV. The choice of bombarding energies was made on the basis of previously measured excitation functions, in which it was found that the differential cross sections varied strongly with bombarding energy (suggesting contributions from a compound-reaction mechanism). Several of the states observed in this measurement using at 48.0-MeV $O^{16}$ beam (e.g., at $E_{exc} = 14.41$, 16.59, and 17.59 MeV) are not evident in the spectra of Ref. 1, where a 36-MeV $C^{12}$ beam was used, even though the center-of-mass energy was the same in both cases; it should be noted, however, that the experimental arrangements correspond to the observation in the center-or-mass system of the $\alpha$ particle at 0° and at 180° with respect to the incident $O^{16}$ ion. A comparison of the spectrum of $\alpha_1$-$\alpha_2$ coincidence transitions leading to the $Ne^{20}$ ground state (Fig. 3) and the analogous spectrum observed with reversed target and projectiles[6] shows that the ratio of the forward to the backward cross sections [$\sigma(0°)$ to $\sigma(180°)$] is $\geqslant 5$ for the state at 16.59 MeV. Considering that the angular distributions for the population of these states are smooth,[1] the observed asymmetry at the extreme scattering angles becomes suggestive of a direct-reaction mechanism. If the reaction does proceed in part via a direct process, we note that an important role is thereby implied for the transfer of complex clusters in the mechanism populating certain of these states. These clusters consist of two $\alpha$ particles ($Be^8$) in the case of the $C^{12}$ incident projectiles and of three $\alpha$ particles ($C^{12}$) in the case of $O^{16}$ incident projectiles. Certainly, further experimental work is needed to determine the extent of direct and compound contributions to the reaction mechanism, and theoretical treatments must reconcile the smooth, asymmetric angular distributions with the observed energy dependence of the cross sections.

One very interesting possibility for the structure of some of these states initially arose from the suggestive spacing of the states at 14.14, 15.14, and at 16.29, 16.59, and 16.85 MeV, and from their proximity to the $C^{12}+C^{12}$ threshold at 13.9 MeV. These states could have formed the 0-, 1-, and 2-phonon members of a quasimolecular vibrational sequence. This possibility, however, is apparently ruled out on the basis of the measured and inferred (on the basis of branching ratios) high spins of the states populated by this reaction in this region of excitation, leaving completely open, however, the possible rotational quasimolecular character of these states. Another possible and very attractive alternative is the $\alpha$-cluster or quartet states predicted by Arima, Gillet, and Ginocchio[3]. It is improbable that any of the states observed here are the calculated $0^+$ members, but an identification of the higher spin states (preferentially populated in this reaction) with a rotational structure built upon such an intrinsic $\alpha$ cluster is certainly a possibility.

The $10^+$ member of the $K=0$ ground-state rotational band has been predicted by Akiyama, Arima, and Sebe[7] to lie in the vicinity of 17 MeV. There are several candidates for this particular level, namely those states observed at 16.85, 17.20, and 17.58 MeV, which are strongly populated and which undergo $\alpha$ decay predominantly to $Ne^{20}$ $(4^+)$. Investigations of the $\gamma$-ray decay of these states should prove definitive in making an assignment, and are in progress in this laboratory[8].

It is already clear, however, that these heavy-ion reactions open up a new dimension of nuclear spectroscopy of very highly excited configurations and hold promise of providing insight into new aspects of nuclear structure.

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*NATO Fellow. Permanent address: Universita di Firenze, Istituto di Fisica "Antonio Garbasso," 50125 Firenze, Largo Enrico Fermi 2 (Arcetri), Italy.

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