First 8^+ state in ^{28}Si and level systematics of *sd* shell nuclei

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Differential cross sections for the $^{25}Mg(^{12}C,^{9}Be)$ reaction were measured at $\theta_L = 10, 15, 20°$ for bombarding energies near 100 and 120 MeV. These data are consistent with direct ^3He transfer to highly excited, high-spin states in ^{28}Si. The energy spectra, angular distributions, level systematics of *sd*-shell nuclei, and shell-model calculations strongly suggest that a state observed at 15.8 MeV is the previously unidentified 8^+ member of the ground-state rotational band of ^{28}Si.

NUCLEAR REACTIONS $^{25}Mg(^{12}C, ^{9}Be)$, $E_{^{12}C} \simeq 100$, 120 MeV; measured σ for $\theta_{lab}=10$, 15, 20°; deduced ^{28}Si levels. Comparison with shell-model calculations, suggested 8^+ levels.

The location of high-spin states in *sd* shell nuclei and their grouping into various rotational band structures bear on a number of questions of current concern in nuclear physics. These nuclei have served as a testing ground for a variety of nuclear models, including the shell, cluster, and rotational models. In particular, comparison of measurements for *sd* shell nuclei with the results of the large shell-model codes[1-4] recently developed for this mass region provides not only a stringent test of this model, but, at the same time, furnishes the experimentalist with a valuable tool for the interpretation of his data.

The determination of the yrast line in *sd* shell nuclei also has consequences regarding the nature and location of quasimolecular states or resonances.[5,6] Furthermore, determination of the yrast line is needed in order to understand the angular momentum limitations imposed on the fusion cross sections of light nuclei.[7,8]

Three-nucleon transfer reactions, such as $(^{10}B, ^{7}Li)$ and $(^{12}C, ^{9}Be)$ preferentially excite high-spin states at high excitation energies for target nuclei such as ^{12}C, ^{15}N, and ^{16}O.[9-11] As is typical for heavy-ion reactions, momentum matching conditions[12] for these reactions strongly favor the excitation of high-spin states.

Despite extensive work on the level structure of ^{28}Si (Ref. 13) and the great interest in quasimolecular states populated in the $^{12}C + ^{16}O$ system,[14] the ground-state rotational band of ^{28}Si remains one of the most poorly identified in the *sd* shell nuclei, as it is known only through the 6^+ member. Consequently, we have used the $^{25}Mg(^{12}C, ^{9}Be)$ reaction to investigate the level structure of ^{28}Si and to search for the first 8^+ state.

A 140-$\mu g/cm^2$ target (enriched to 99.21% in ^{25}Mg) was bombarded with ~100- and 120-MeV ^{12}C ions accelerated in the Oak Ridge isochronous cyclotron (ORIC). The reaction products were detected in a 60-cm-long, position sensitive double proportional counter system located at the focal plane of a broad-range magnetic spectrograph. The energy resolution, approximately 200 keV for the detected ^9Be ions, was limited by the target thickness. Figure 1 displays the ^9Be spectrum observed at a laboratory angle of 10° and a bombarding energy of 99.9 MeV. The known 2^+, 4^+, and 6^+ members of the ground-state rotational band are identified by their excitation energies as listed in Ref. 13. The remaining excitation energies shown in the figure were determined in the present experiment. The selectivity of the reaction can be noted from the fact that only about 18 levels are strongly populated of the approximately 140 states that have been previously identified be-

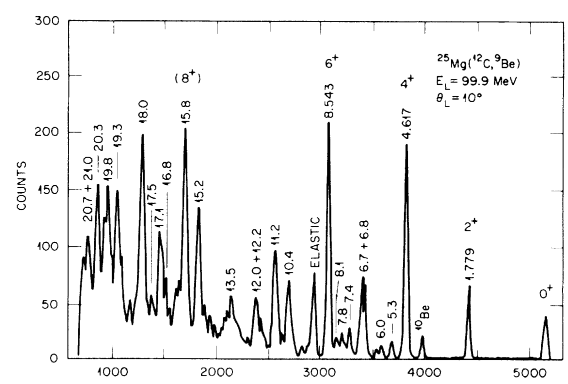

FIG. 1. The $^{25}Mg(^{12}C, ^{9}Be)$ spectrum measured at an incident energy of 99.9 MeV and a laboratory angle of 10°. The energies for the known 2^+, 4^+, and 6^+ states at 1.779, 4.617, and 8.543 MeV, respectively, are taken from Ref. 13, while those for the other peaks were determined from the present measurements.

low an excitation energy of 15.3 MeV.[13] The levels strongly excited near 15.8 and 18.0 MeV appear likely candidates for 8^+ levels, and the energy of the lower peak agrees well with that expected (~15.2 MeV) from a linear extrapolation of the ground-state rotational band on a $J(J+1)$ plot. The peaks labeled ^{10}Be and elastic in Fig. 1 result from strong lines in the ^{10}Be and ^{12}C groups tailing into the ^{9}Be spectrum, but the weak peaks near 5.3 and 6.0 MeV, which did not appear at all energies and angles, do not appear to correspond to ^{28}Si. The optimum Q value for this reaction is about −21 MeV, as calculated from the expressions of Brink.[12] Since the ground state Q value is −3.098 MeV, states with about 17 to 18 MeV of excitation energy should be preferentially populated.

Cross sections measured at laboratory angles of 10°, 15°, and 20° for the known 4^+ and proposed 8^+ members of the ground-state band are shown in Fig. 2. All the angular distributions display the rapid decline with angle seen in the figure. The 120-MeV angular distributions are similar in magnitude and shape. Measurements at more forward angles were obscured by increased background due to elastic scattering and slit scattering. Solid lines in the figure represent distorted-wave Born approximation (DWBA) calculations, using a heavy-ion version of DWUCK, arbitrarily normalized to the data. The calculations assumed that a ^{3}He ion was transferred as a cluster. Different values are possible for the transferred angular momentum, but the curves shown are those calculated for $L=5$, the value expected for the most favored angular momentum transfer. If the spectroscopic factors for the two states are equal, then the calculated ratio for the magnitude of the 4^+ to the 8^+ state at 10°, 1 : 0.94, is of the same order of magnitude as the observed ratio of 1 : 0.65. The significant point is that the curves in Fig. 2 reproduce the sharp dropoff of the data and, therefore, give strong support to the hypothesis of direct three-nucleon transfer as the dominant reaction process for this reaction.

The observed spectra and angular distributions are consistent with the excitation of high-spin states at high excitation energies by a direct process, but they do not establish that this is indeed the reaction mechanism. Angular momentum considerations imply that the observed strongly excited states are likely to be high-spin states regardless of the mechanism by which they were populated. For example, compound nucleus reactions also tend to selectively populate high-spin states above the ground-state region (see for example, Refs. 15–17). It would be difficult, however, to account for the observed ^{9}Be yield by a statistical compound nucleus reaction. At an incident energy of 100 MeV, the compound nucleus, ^{37}Ar, is produced with an excitation energy of 85 MeV and the decay then strongly favors very highly excited residual nuclei, and there is an insignificant population of states below 20 MeV. Hauser-Feshbach calculations, using standard level density and optical model parameters, underestimate the yields for the rotational band members (including the proposed 8^+ state) by factors of about 10^5. In addition, the measured angular distributions drop more rapidly with angle than the calculated Hauser-Feshbach curves (see Fig. 2).

Shell-model calculations provide a further means of locating candidates for high-spin states in nuclei. In Fig. 3, the level positions of the ground-state rotational band of ^{28}Si are shown, including the proposed 8^+ level at 15.8 MeV, by solid lines, together with shell-model predictions[18] (dotted lines). Such comparisons are meaningful, as demonstrated by information currently available concerning the ground-state rotational bands of various *sd* shell nuclei summarized in Fig. 3. If

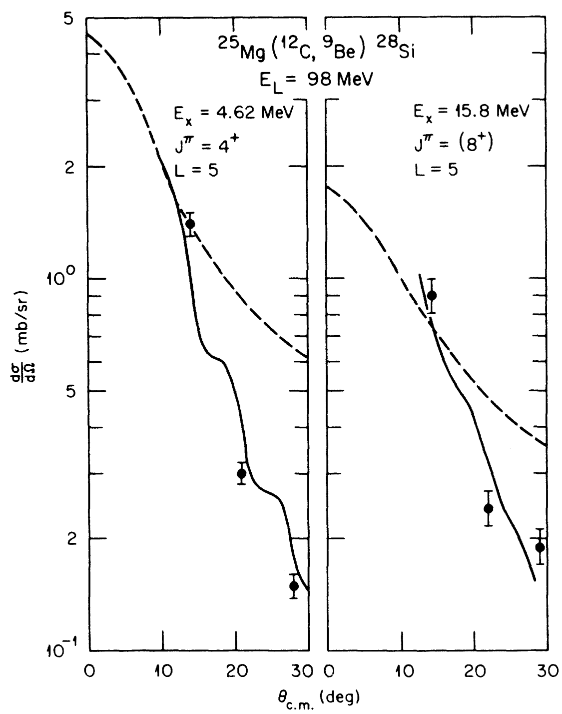

FIG. 2. Cross sections measured for the 4.62 MeV, 4^+ and 15.8 MeV, 8^+ levels at laboratory angles of 10°, 15°, and 20°. The solid curves result from the DWBA calculations described in the text for the case of $L=5$ transfer. The Hauser-Feshbach results (dashed curves) have been arbitrarily normalized to the data although the calculations underestimate the cross sections by a factor of ~10^5.

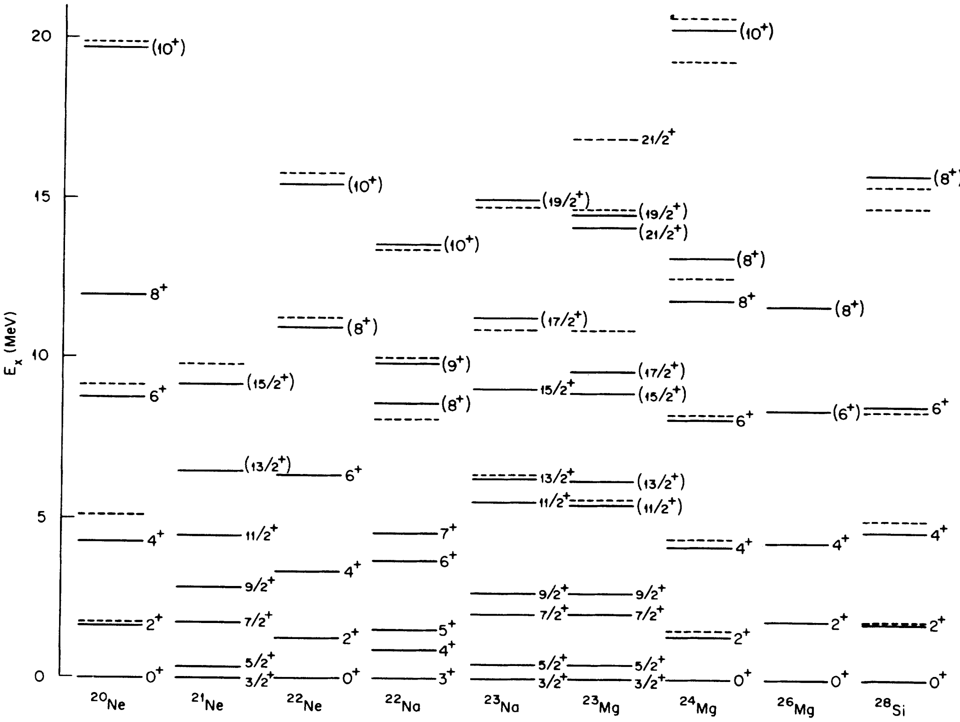

FIG. 3. Known and proposed members of the ground-state rotational band for various *sd* shell nuclei are indicated by solid lines. The dashed lines are shell-model predictions when such predictions differ from the experimental levels by ≲150 keV (calculations are not available for ^{26}Mg). See text for the experimental and theoretical references from which these level schemes were taken.

the difference between the experimental and calculated values are less than about 150 keV, then only a solid line is shown (calculations were not available for ^{26}Mg). The proposed 10^+ state at 19.7 MeV in ^{20}Ne was observed in the ^{16}O(^{14}N, ^{10}B) reaction by Nagatani *et al.*[19] They assigned this level to an excited $K^\pi = 0^+$ band, but the shell-model predictions of McGrory and Wildenthal[1] locate the 10^+ member of the ground-state band near this energy. High-spin states shown in parentheses for ^{21,22}Ne, ^{22,23}Na, and ^{23,24,26}Mg were suggested from studies of the compound nuclear reactions: ^{12}C(^{13}C, α)^{21}Ne,[20] ^{11}B(^{13}C, d)^{22}Ne,[21] ^{10}B(^{16}O, α)^{22}Na,[15] ^{12}C(^{15}N, α)^{23}Na,[22] ^{12}C(^{12}C, n)^{23}Mg,[23] ^{12}C(^{16}O, α)-^{24}Mg,[16,24-26] ^{10}B(^{16}O, d)^{24}Mg,[17] and ^{12}C(^{18}O, α)^{26}Mg.[27] The shell-model results indicated for ^{21,22}Ne, ^{22,23}Na, and ^{23,24}Mg are those of Refs. 4, 28, 1, 3, 4, and 2, respectively. Additional 8^+ and 10^+ states in ^{24}Mg have been suggested.[17,26] Also, the state at 11.86 MeV in ^{24}Mg does not appear to be the 8^+ member of the ground-state rotational band,[24,29] which is located instead at 13.21 MeV.[30] Spin values obtained from correlation measurements (see, for example, Refs. 24-26, 29, and 30) are in general agreement with those suggested by Hauser-Feshbach analyses.

The shell-model calculations and experimental level schemes shown in Fig. 3 are in excellent agreement. The ^{28}Si shell-model states, therefore, provide further confidence in the choice of the 15.8-MeV level observed in the present experiment as the 8^+ ground-state band member of ^{28}Si. The peak observed at 18 MeV, which has an angular distribution similar in magnitude and shape to that of the 15.8-MeV level, is also likely to be due to an 8^+ level, since two such states are predicted.[18] In conclusion then, the energy spectra, angular distribution data, level systematics, and shell-model predictions support the choice of 8^+ for the spins of these levels populated in the ^{25}Mg(^{12}C, ^{9}Be)^{28}Si reaction.

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