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0^- state at low excitation energy in ^{26}Al

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Measurements of T_{20} for the ^{28}Si($\vec{d}, \alpha$)^{26}Al reaction near 0°, for five beam energies, have been used to make a unique $J^\pi = 0^-$ assignment for a state in ^{26}Al at 4.48 MeV. Shell model calculations show the structure of this state to be dominated by excitation to the *fp* shell.

Nuclei in the middle of the *sd* shell have predominantly positive parity states at low excitation energies. Because such nuclei are far from closed shells, it is unlikely that the wave functions for lower excitation states will contain any significant terms which include orbits from the $1p$ or *fp* shells. A significant amount of energy is required to promote nucleons from the $1p$ shell to the *sd* shell or from the *sd* shell to the *fp* shell; so the negative parity states, which must include configurations from the $1p$ or *fp* shells, are expected to occur at significantly higher excitation energies than the positive parity states. ^{26}Al is a nucleus in the middle of the *sd* shell and in the simplest view it has a full $1p$ shell with ten nucleons in the $1d_{5/2}$ orbit, a $(1d_{5/2})^{-2}$ configuration with respect to ^{28}Si. An unnatural parity state at 4.48 MeV in ^{26}Al (Refs. 1 and 2) has previously been given a spin and parity assignment of $0^-(1^+, 2^-)$. Data from the ^{25}Mg(p, γ)^{26}Al reaction[1,3] showed the 4.48-MeV state to be strongly excited at a 1^-;1 resonance and weakly excited at a 2^-;0 resonance and to appear to decay only to the four lowest 1^+ states, indicating that it is likely to be a 0^- state; however, the 1^+ and 2^- possibilities could not be ruled out. The simplest configuration for a 0^- state in ^{26}Al would involve excitation of a nucleon from the $1p_{1/2}$ orbit into the $2s_{1/2}$ orbit to give a $(1d_{5/2})^{-2}$ $(1p_{1/2})^{-1}2s_{1/2}$ configuration with respect to ^{28}Si, which would not be expected to occur as low as 4.48 MeV. It was therefore important to establish whether the 4.48-MeV state is, in fact, a 0^- state or not.

Whether a state has a natural or unnatural parity or is 0^-, may be determined[4] by measuring the tensor analyzing power T_{20} for the ($\vec{d}, \alpha$) reaction on an even-even target near 0°. The yield is given by

$$\sigma = \sigma_u(1 + T_{20}t_{20}) \ , \tag{1}$$

where t_{20} is the beam polarization and σ_u is the yield which would result from an unpolarized beam. T_{20} takes the value $-\sqrt{2}$ for a 0^- state at 0°. If the deuteron spin substate m, relative to the beam direction, is selected, a pure $m = 1$ beam has $t_{20} = 1/\sqrt{2}$, and a pure $m = 0$ beam has $t_{20} = -\sqrt{2}$. It is clear from Eq. (1) that an $m = 1$ beam will give no yield $\sigma_1 = 0$ for a 0^- state, and an $m = 0$ beam will give a large yield $\sigma_0 = 3\sigma_u$, assuming ideal polarization. The tensor analyzing power may be calculated using the following expression:

$$T_{20} = \left[\frac{\sigma_1}{\sigma_0} - 1\right] \Bigg/ \left[\sqrt{2}\, P\frac{\sigma_1}{\sigma_0} + \frac{1}{2}\right] \ ,$$

where P is the fraction of the ideal beam polarization and is assumed to be equal for $m = 0$ and $m = 1$ beams.

The experiment was carried out using a deuteron beam from the Lamb-shift polarized ion source at McMaster University and accelerated by an FN tandem. A resistive-wire position-sensitive counter was placed in the focal plane of the Enge split-pole magnetic spectrograph to detect α particles from the ^{28}Si($\vec{d}, \alpha$)^{26}Al reaction at 4°, which is near enough to 0° that T_{20} will not be significantly different from its value at 0°. The target was in the form of silicon oxide on a carbon backing where the silicon was enriched to 96% in ^{28}Si. P was determined from the quench ratio Q (Ref. 5) according to the prescription

$$P = 0.95(1 - 1/Q) \ .$$

The empirically determined factor 0.95 arises from the characteristics of the beam quenching, whereby there is still some polarization of the quenched beam. For these measurements, values of P lay in the range 0.66–0.76, with an uncertainty of 0.03. The detected α particles were separated from deuterons by setting a window on a two-dimensional spectrum of position versus energy loss in the counter. Figure 1 shows typical α-particle spectra obtained using $m = 0$ and $m = 1$ beams. The yield for the 4.48-MeV state in ^{26}Al is seen to dramatically increase on switching from an $m = 1$ to an $m = 0$ beam. Measurements of T_{20} for the 4.48-MeV state, taken for five different beam energies, are given in Table I. The errors shown are purely statistical and the actual errors are expected to be slightly larger because of the uncertainty in defining the background subtracted beneath the peak. All five T_{20} values are observed to be close to $-\sqrt{2}$. An unnatural parity state, for which T_{20} can take any value, could have $T_{20} = -\sqrt{2}$. However, the probability of T_{20} remaining the same for five different beam energies separated by more than the coherence width is less than 0.1%. This has been discussed in detail by D. Petty *et al.*[6] The data thus show that the 4.48-MeV state in ^{26}Al can be assigned $J^\pi = 0^-$.

A shell model calculation with a configuration space consisting of the $1p$ and *sd* shells was carried out to predict where the lowest 0^- state is expected to occur. Since a full calculation for 22 nucleons in the five orbits would have been too large, some restrictions were imposed on the occupancies of the various orbits. The same restrictions were used to calculate energy eigenstates for the 5^+ ground state and the lowest 0^- state. Not more than two holes were allowed in the $1p$ shell, and the number of nucleons in each of the $s_{1/2}$ and $d_{3/2}$ orbits was constrained to be not greater than two. The occupancy of the $d_{5/2}$ orbit was required to be eight nucleons or more. The interaction matrix elements of Millener and Kurath[7] were used for the calculation which was done with the code OXBASH.[8] The above shell model calculation predicts the lowest 0^- state to occur at 10.4-MeV excitation, much higher than the observed level at 4.48

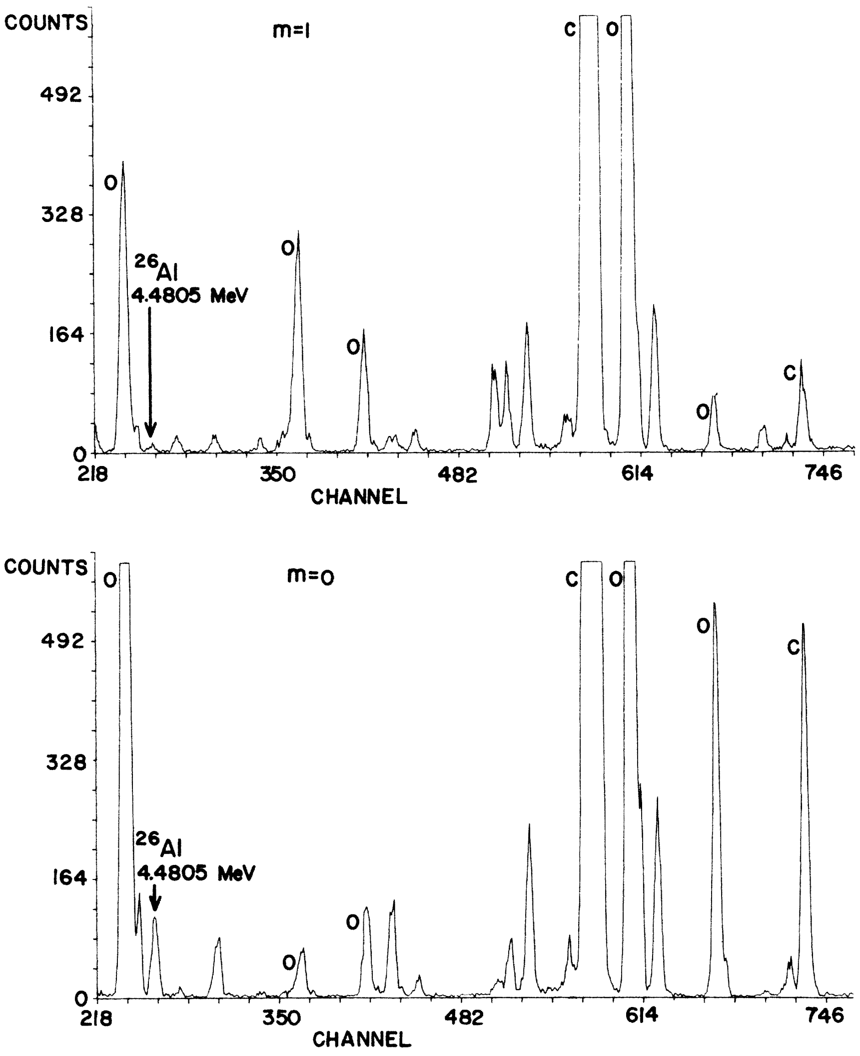

FIG. 1. Alpha particle spectra for the $^{28}\mathrm{Si}(\vec{d},\alpha)^{26}\mathrm{Al}$ reaction at 4° for 9 MeV $m=1$ and $m=0$ beams. (Peaks arising from carbon and oxygen in the target are labeled C and O, respectively.)

MeV. The dominant term in the ground state wave function is $(1d_{5/2})^{-2}$ with respect to ^{28}Si. This term amounts to 76% of the ground state wave function. The 0^- wave function comprises many terms, the largest of which is 49% $(1d_{5/2})^{-2}(p_{1/2})^{-1}s_{1/2}$, indicating a nucleon promoted from the $p_{1/2}$ orbit to the $s_{1/2}$ orbit with respect to the ground state. Overall, 87% of the wave function involves terms with a $p_{1/2}$ hole and 13% involves terms with a $p_{3/2}$ hole.

TABLE I. T_{20} measurements for the $^{28}\mathrm{Si}(\vec{d},\alpha)^{26}\mathrm{Al}$ reaction to the 4.48-MeV state at 4°.

Beam energy (MeV)	T_{20}	Statistical error
8.0	−1.25	0.14
8.5	−1.27	0.09
9.0	−1.51	0.08
9.5	−1.35	0.09
12.0	−1.36	0.09

Following the inability of the above calculation to account for a 0^- level at 4.48 MeV, another shell model calculation was carried out using a configuration space consisting of the *sd* and *fp* shells and the SDPFMK interaction of OXBASH. Only one nucleon was allowed in the *fp* shell, and the nucleons in the *sd* shell were restricted such that a minimum of seven nucleons was required in the $d_{5/2}$ orbit and a maximum of three nucleons were allowed in each of the $d_{3/2}$ and $s_{1/2}$ orbits. This calculation gave several 0^- states at low excitation energies. Three 0^- states were predicted below 5 MeV, the lowest at 2.4 MeV and the other two at 3.7 and 4.9 MeV. The wave functions for these states comprise many configurations, the dominant two being $(d_{5/2})^8 d_{3/2} f_{7/2}$ and $(d_{5/2})^7 (d_{3/2})^2 f_{7/2}$. For the lowest two states, 88% of the wave function includes terms with the *fp* shell nucleon in the $f_{7/2}$ orbit. For the 4.9-MeV state, this figure is reduced to 64% with a 29% contribution from terms with the nucleon in the $f_{5/2}$ orbit.

It is well established that nuclei in the *sd* shell are deformed. ^{25}Mg and ^{25}Al are well described by the Nilsson model as prolate nuclei.[9,10] The lowest negative parity state in each of these nuclei is a $3/2^-$ state near 3 MeV. If a 0^- state in ^{26}Al were considered to be one nucleon added in a $d_{3/2}$ orbit to a $3/2^-$ state in a mass 25 nucleus, an energy of 4.48 MeV for the 0^- state would not seem unreasonable. Rotational bands have been identified in ^{26}Al (Refs. 11 and 12), indicating it has deformation. If deformed nuclei are to be well described by the shell model, a large configuration space is required. The shell model calculations show that the structure of the 0^- state at 4.48 MeV is likely to be described as many small terms, involving configurations in the *sd* and *pf* shells and not in terms of configurations involving the 1*p* and *sd* shells.

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[1] P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978); and (private communication).

[2] D. Boerma, Eidgenossische Technische Hochschule Zürich, Jahresbericht, 1978.

[3] J. Keinonen, B. Nyako, A. Luukkainen, and A. Anttila, Nucl. Phys. **A403**, 45 (1983).

[4] J. A. Kuehner, P. W. Green, G. D. Jones, and D. T. Petty, Phys. Rev. Lett. **35**, 423 (1975).

[5] G. G. Ohlsen, G. P. Lawrence, P. W. Keaton, Jr., J. L. McKibben, and D. D. Armstrong, Los Alamos Scientific Laboratory Report No. LA-4465-MS, 1970.

[6] D. T. Petty, J. A. Kuehner, J. Szücs, P. W. Green, and G. D. Jones, Phys. Rev. C **14**, 12 (1976).

[7] D. J. Millener and D. Kurath, Nucl. Phys. **A255**, 315 (1975).

[8] B. A. Brown, A. Etchegoyen, W. D. M. Rae, and N. S. Godwin, OXBASH, the Oxford–Buenos Aires Shell Model Code, Cyclotron Laboratory, Michigan State University, Internal Report, 1984.

[9] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).

[10] M. Lambert, P. Midy, and P. Desgrolard, Phys. Rev. C **8**, 1728 (1973).

[11] J. F. Sharpey-Schafer, D. C. Bailey, P. E. Carr, A. N. James, P. J. Nolan, and D. A. Viggars, Phys. Rev. Lett. **27**, 1463 (1971).

[12] H. G. Price, A. N. James, P. J. Nolan, J. F. Sharpey-Shafer, P. J. Twin, and D. A. Viggars, Phys. Rev. C **6**, 494 (1972).