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Spin and Parity of the 4.82-MeV Level of ^{27}Mg

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The spin and parity of the 4.82-MeV level of ^{27}Mg are assigned to be $1/2^+$ by the ^{26}Mg$(d,p)^{27}$Mg reaction, in contrast with the assignments by Cujec and Hinds *et al.* The reaction protons were analyzed with a broad-range magnetic spectrograph and the energy resolution of the whole system was less than 7 keV. This level is a very strong single-particle state and the isobaric-analog state of the 11.758-MeV level of ^{27}Al.

NUCLEAR REACTION ^{26}Mg(d,d), (d,p), $E=3.1$ MeV; measured $\sigma(E;\Theta)$; deduced optical-model parameters. ^{27}Mg levels deduced J, π, S, IAS. Enriched target, DWBA analysis, resolution 7 keV; $\Theta=15$–120°.

The levels of ^{27}Mg have been studied by many authors.[1–5] Spins and parities of the low-lying levels have been obtained by means of various reactions like(d,p), (t,p), etc. In particular, here we would like to take notice of the 4.82-MeV level of ^{27}Mg. The spin and parity of this level was assigned $(\frac{1}{2}^-, \frac{3}{2}^-)$ with $l_n=(1)$ in the ^{26}Mg$(d,p)^{27}$Mg reaction by Cujec[4] and by Hinds, Middleton, and Parry.[5]

If this note we have examined the spin and parity of the 4.82-MeV level with the ^{26}Mg$(d,p)^{27}$Mg reaction at 3.1-MeV bombarding energy using a broad-range spectrograph. We report the spin and parity as well as spectroscopic factor, of the level mentioned above. Our result is very different from theirs. We would like to show that this level has a special theoretical significance from the viewpoint of nuclear structure, namely from the viewpoint of the isobaric-analog state and a recent shell-model calculation performed by Wildenthal *et al.*[6]

The experimental procedure and results are as follows. The target was self-supporting and isotopically enriched of 20 μg/cm^2. The incident deuterons were accelerated to 3.1 MeV with the Van de Graaff accelerator at the Tokyo Institute of Technology. The reaction protons were ana-

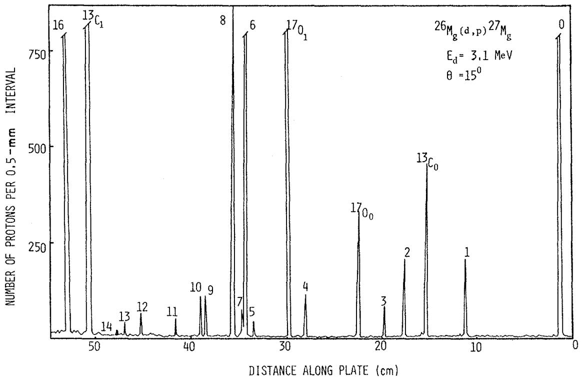

FIG. 1. Proton spectrum from the ^{26}Mg$(d,p)^{27}$Mg reaction, measured at $\Theta=15°$ in the spectrograph.

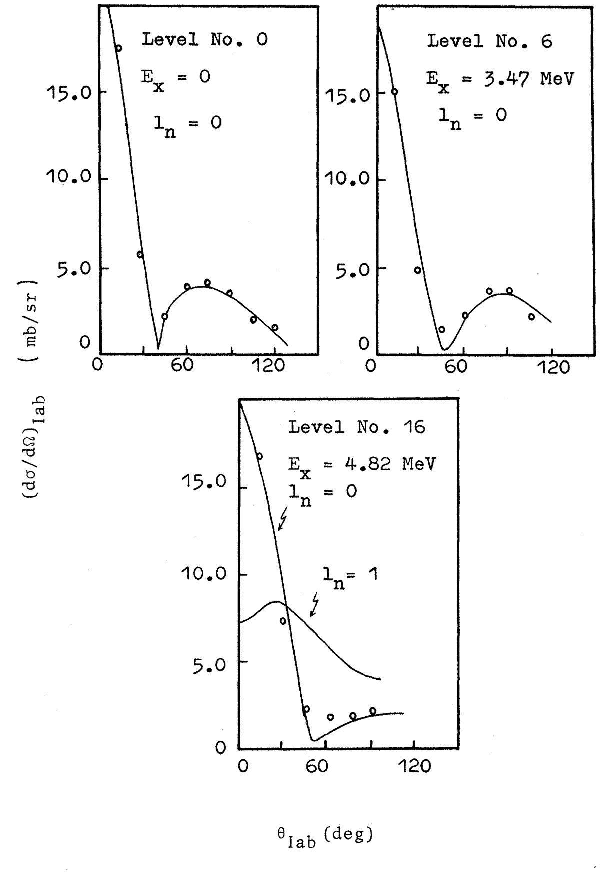

FIG. 2. Measured angular distribution for the proton groups corresponding to the 4.82-MeV level of ^{27}Mg is fitted by the DWBA calculation with $l_n=0$. For the 4.82-MeV level, the angular distribution calculated with $l_n=1$ is also shown. The ones for the ground state and 3.47-MeV level of ^{27}Mg are also shown for comparison.

lyzed with a broad-range magnetic spectrograph and detected on 100-μm SAKURA nuclear emulsion plates. The total exposure was measured by a Faraday cup to be 1000 μC. The energy resolution of the whole system in this experiment was about 7 keV. It is the main reason why we could have such a high resolution that the beam from the accelerator was able to be defined to an area of 0.1 mm×2.0 mm.

A typical proton spectrum in this experiment is shown in Fig. 1. The angular distribution of the reaction proton groups corresponding to the 4.82-MeV level is shown in Fig. 2, in which those for the ground state and the 3.47-MeV level of ^{27}Mg are also shown for comparison.

The angular distributions were analyzed in terms of the zero-range distorted-wave Born approximation (DWBA) using the program Y3/TC/AA03 developed by Kawai, Kubo, and Yamaura.[7] The optical potential used here for the deuteron is as follows

$$U(r) = -V(1+e^{x})^{-1} + 4iW\left(\frac{d}{dx}\right)(1+e^{x'})^{-1} + V_C(r) ,$$

where V and W are real constants, x and x' are defined by $x = (r - r_{0s}A^{1/3})/a_s$ and $x' = (r - r_{0I}A^{1/3})/a_I$, respectively. The Coulomb potential $V_C(r)$ is obtained by assuming that charges are uniformly distributed inside the sphere of radius $R_c = r_0A^{1/3}$. A spin-orbit term of the form

$$\left(\frac{\hbar}{m_\pi c}\right)^2 V_{so}\vec{L}\cdot\vec{\sigma}r^{-1}\left(\frac{d}{dr}\right)(1+e^{x})^{-1}$$

must be added to the above potential for the reaction proton. The values of the parameters that we take are listed in Table I. The values of the parameters for the optical potential are taken from a study by Perey.[8] These potentials were extracted from 9-MeV proton elastic scattering data on ^{27}Al. By fitting at $\Theta = 15°$, the measured and calculated angular distribution for the 4.82-MeV level is in good agreement with $l_n = 0$ as is seen in Fig. 2, where l_n is the orbital angular momentum of the captured neutron. Since Hinds, Middleton, and Parry,[5] have suggested $l_n = (1)$ for the 4.82-MeV level, we have also shown the angular distribution calculated with $l_n = 1$ in Fig. 2, however, we would never be able to fit the calculated angular distribution with $l_n = 1$ to the measured one. Therefore, we recognize that the conclusion of $l_n = 0$ for the 4.82-MeV level is definite. Since the spin of the ground state of ^{26}Mg is zero, the spin and parity of the 4.82-MeV level of ^{27}Mg is now assigned to be $\frac{1}{2}^+$, in this note.

TABLE I. Optical-model parameters in the DWBA calculation. The deuteron parameters are obtained from the analysis of elastic scattering. The proton parameters are the ones obtained by Perey (Ref. 8).

Particle	V (MeV)	W (MeV)	r_{0s} (fm)	a_s (fm)	r_0 (fm)	a (fm)	r_c (fm)	V_{so} (MeV)
Deuteron	75.0	15.0	1.15	0.81	1.34	0.68	1.15	
Proton	51.0	6.2	1.27	0.66	1.25	0.65	1.27	7.5

TABLE II. Spectroscopic factors and strength functions. The S_n factor and strength function are calculated not only for the 4.82-MeV level but also for the ground state and the 3.47-MeV level. The ones for the ground state, 3.47-, and 4.82-MeV levels are more or less of the same order.

Level No.	E_x (MeV)	l_n	$(2J_f+1)S_n$	J^π	S_n
0	0	0	0.9	$\frac{1}{2}^+$	0.45
6	3.47	0	0.44	$\frac{1}{2}^+$	0.22
16	4.82	0	0.72	$\frac{1}{2}^+$	0.36

The spectroscopic factor for the present reaction on a zero-spin target is defined by

$$S_n = \frac{(d\sigma/d\Omega)_{\text{exp}}}{1.53(2J_f+1)(d\sigma/d\Omega)_{\text{DWBA}}} ,$$

where J_f is the spin of a final nuclear state and $(d\sigma/d\Omega)_{\text{exp}}/(d\sigma/d\Omega)_{\text{DWBA}}$ is the radio of the experimentally measured angular distribution to the theoretically calculated one. The spectroscopic factor S_n and the strength function $(2J_f+1)S_n$ for the 4.82-MeV level of ^{27}Mg are calculated at $\Theta = 15°$ and tabulated in Table II, in which the ones for the other $\frac{1}{2}^+$ states (ground state and the 3.47-MeV level of ^{27}Mg) are also shown for comparison. As is seen in Table II, both S_n factors for the ground state and the 3.47-MeV level are of the same order with the values obtained by Silverstein *et al.*[3] Furthermore, the S_n factor for the 4.82-MeV level is of the same order with

TABLE III. Percentage in intensity of wave functions for the 0^+ states of ^{26}Mg. The wave functions are constructed by placing 10 nucleons in the orbitals $1d_{5/2}$ and $2s_{1/2}$, and inert core of ^{16}O being assumed. The wave functions having zero, one, two, three, and four particles in the $2s_{1/2}$ orbit are denoted by, respectively, d^{10}, d^9s^1, d^8s^2, d^7s^3, and d^6s^4.

J^π	E_x (MeV)	d^{10}	d^9s^1	d^8s^2	d^7s^3	d^6s^4
0^+	0	43	8	37	6	6
0^+	3.58	10	6	58	18	8
0^+	4.97	28	1	43	13	15

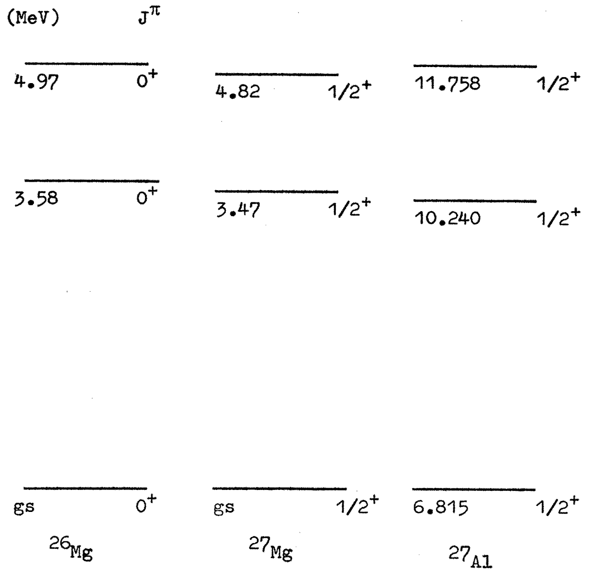

FIG. 3. Level schemes of ^{26}Mg, ^{27}Mg, and ^{27}Al. The 0^+ states of ^{26}Mg correspond to the $\frac{1}{2}^+$ states of ^{27}Mg. The $\frac{1}{2}^+$ states of ^{27}Mg have the isobaric-analog states of ^{27}Al.

the ones of the ground state and the 3.47-MeV level.

In order to see the theoretical significance of the 4.82-MeV level of ^{27}Mg, first of all we have to discuss the features of ^{26}Mg that is the target in the ^{26}Mg$(d,p)^{27}$Mg reaction. It is well known that the features of ^{26}Mg cannot be explained by a simple shell model. Let us discuss the features of ^{26}Mg on the basis of the calculation performed by Wildenthal *et al.*[6] According to Wildenthal *et al.*, the $T=1$ state in mass-26 nuclei were described by wave functions constructed by placing 10 nucleons in the orbitals $1d_{5/2}$ and $2s_{1/2}$, an inert core of ^{16}O being assumed. As an example, let us tabulate in Table III the percentage in intensity of each wave function, for the 0^+ state of ^{26}Mg, which comes from having zero particles in the $2s_{1/2}$ orbit (denoted by d^{10}), one particle in the $2s_{1/2}$ orbit (d^9s^1) etc. Now let us discuss the 4.82-MeV level of ^{27}Mg. This level might be understood on the basis of the calculation of Wildenthal *et al.* In order to see it, let us show in Fig. 3 that the 0^+ states of ^{26}Mg correspond to the $\frac{1}{2}^+$ states of ^{27}Mg; namely the ground state, the 3.58-, and 4.97-MeV levels of ^{26}Mg correspond to the ground state, the 3.47-, and 4.82-MeV levels of ^{27}Mg, respectively. The $\frac{1}{2}^+$ states of ^{27}Mg are assigned by the ^{26}Mg$(d,p)^{27}$Mg reaction which corresponds to a single-nucleon transfer that couples directly a neutron in the $2s_{1/2}$ orbit to the ground state of ^{26}Mg. Comparing the wave functions for the 0^+ states of ^{26}Mg, which are obtained by Wildenthal *et al.*[6] and shown in Table III, the correspondence in energies between the 0^+ states of ^{26}Mg and the $\frac{1}{2}^+$ states of ^{27}Mg must be consistently understood as well as the spins and parities of the ground state, the 3.47-, and 4.82-MeV levels of ^{27}Mg. In this connection, it would be expected that the spin and parity of the 4.82-MeV level of ^{27}Mg might be $\frac{1}{2}^+$.

Finally, let us see the isobaric-analog states of the $\frac{1}{2}^+$ states of ^{27}Mg. It had been recognized that the ground state and the 3.47-MeV level of ^{27}Mg are, respectively, isobaric-analog states of the 6.815- and the 10.240-MeV levels of ^{27}Al, by other authors.[9,10] We would like to point out that the 4.82-MeV level of ^{27}Mg is an isobaric-analog state of the 11.758-MeV level of ^{27}Al. The spin and parity of the 11.758-MeV level of ^{27}Al are now assigned $\frac{1}{2}^+$ with the ^{26}Mg$(p,\gamma)^{27}$Al and ^{26}Mg$(p,p)^{26}$Mg reactions by our group.[11] These isobaric-analog states are shown in Fig. 3. Moreover, the fact that the S_n factor for the 4.82-MeV level of ^{27}Mg is very large is again consistent with the fact the total width of the 11.758-MeV level of ^{27}Al is very large.

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