Spectroscopy with the Singlet-Deuteron Reaction $^{12}C(\alpha,d_{S=0})^{14}N$ at 50 MeV

A. Sakaguchi
Department of Physics, Kyoto University, Kyoto 606, Japan

K. Nagatani[a] and M. Torikoshi
Institute for Nuclear Study, University of Tokyo, Tokyo 188, Japan

S. I. Hayakawa
Ashikaga Institute of Technology, Tochigi 326, Japan

T. Motobayashi
Department of Physics, Rikkyo University, Tokyo 171, Japan

O. Satoh and T. Yamaya
Department of Physics, Tohoku University, Sendai 980, Japan

and

M. Fujiwara, N. Matsuoka, and H. Sakai
Research Center for Nuclear Physics, Osaka University, Osaka 567, Japan
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The $(\alpha,d_{S=0})$ reaction was studied for the first time with a ^{12}C target at $E_\alpha = 50$ MeV. Three $T=1$ states in ^{14}N, 0^+ at 2.31 MeV, 3^- at 8.91 MeV, and a level at 12.6 MeV, were selectively excited. The experimental results were well described by exact finite-range distorted-wave calculations.

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In this Letter we wish to report an initial study of the $(\alpha,d_{S=0})$ reaction. The unbound singlet deuteron $(d_{S=0})$ can be treated as a particle with the quantum numbers $T=1$, $T_z=0$, and $S=0$.[1-4] These quantum numbers of the singlet deuteron are in contrast with the $T=0$, $T_z=0$, and $S=1$ of the ordinary deuteron. The selection rules of spin and isospin for the $(\alpha,d_{S=0})$ reaction are $\Delta S=0$, $\Delta T=1$, and $\Delta T_z=0$, while those for the (α,d) reaction are $\Delta S=1$, $\Delta T=0$, and $\Delta T_z=0$. Thus the $(\alpha,d_{S=0})$ reaction is complementary to the (α,d) reaction and can be used as a powerful spectroscopic tool for studying nuclear structure. To our knowledge, however, the $(\alpha,d_{S=0})$ reaction has never been studied.

We chose ^{12}C as the target because of the strong selectivity of this reaction for the excitation of states in self-conjugate nuclei. When the target is a self-conjugate nucleus with $T=0$ and $S=0$, the $(\alpha,d_{S=0})$ reaction excites only $T=1$ natural-parity states in the final nucleus, because of the selection rules mentioned above. Thus, in the reaction $^{12}C(\alpha,d_{S=0})^{14}N$ we expect to see only the isospin-triplet states with natural parity excited in ^{14}N, which are analogs to those in ^{14}C and ^{14}O. The target was a natural carbon foil with a thickness of 1.0 mg/cm^2. A 50-MeV alpha beam obtained from the azimuthally varying field cyclotron at the Research Center for Nuclear Physics, Osaka University, was used in the experiment.

In order to detect singlet deuterons, the geometrical arrangement of the detectors was made with the following consideration. The energies of the singlet deuterons expected from the reaction $^{12}C(\alpha,d_{S=0})^{14}N$ at $E_\alpha=50$ MeV are about 30 MeV. On the other hand, the most probable value of the relative energy between the proton and the neutron in the singlet deuteron is about 60 keV according to the Watson-Migdal formalism[5] of the final-state interaction. Therefore, most of the singlet deuterons are expected to be found among the pairs of neutrons and protons which are localized in a small geometrical cone with its apex on the target. A pair of proton and neutron counters was placed on a straight line from the target. Five such pairs of detector systems were used in the experiment. Silicon solid-state detectors and NE213 liquid-scintillation counters were used respectively for detecting the protons and the neutrons. The typical solid angles of the proton and neutron detectors were 21 and 8 msr, respectively. The proton detectors were placed at 10.5 cm from the target in the air. The neutron energies were determined by the time-of-flight method. A typical flight-path length from the target to the liquid scintillation detector was 2 m. The signals from the neutron and proton detectors were used as the start and stop signals, respectively, in the measurements. The overall timing resolution of the detecting system was 2.5 nsec, corresponding to an energy resolution of 2.0 MeV for a 15-MeV neutron.

Figure 1 shows two-dimensional coincidence energy spectra of the protons and neutrons. In the figure there are several loci which correspond to the levels in ^{14}N. Excitation of these levels in ^{14}N can be seen better when the data are plotted as a function of the summed energy spectrum. The summed energy spectra of the protons and neutrons, which correspond to the two-dimensional spectrum shown in Fig. 1(a), are shown in Fig. 2(a). As shown in the figure, two known $T=1$ states were strongly excited, but in addition several $T=0$ states were also observed in the summed energy spectrum. However, clear identification of the singlet deuterons was made by examination of the shape of the proton energy spectrum for each state in ^{14}N. Two proton energy spectra, which correspond to the $T=1$, $J^{\pi}=3^-$ state at 8.91 MeV of excitation in ^{14}N and the ground state ($T=0$, $J^{\pi}=1^+$) of ^{14}N, are shown in Fig. 2(b). Each proton energy spectrum in this figure is the same as that of each locus shown in Fig. 1(a). Since the relative energy of the proton and neutron from a singlet deuteron is very small, the proton energy spectrum from singlet deuterons is expected to show a clear bump at around $E_p=E_n$, which corresponds to the minimum relative energy. The arrows in Fig. 2(b) indicate the proton energies which correspond to the minimum relative energy. The proton spectrum for the $T=1$ state in ^{14}N shows the characteristics of the protons from singlet deuterons. On the other hand, the proton spectrum for the $T=0$ ground state of ^{14}N shows no such strong correlation between the proton and neutron energies. This feature is expected, because the $T=0$ states can be excited only through sequential processes such as ^{12}C$(\alpha,p)^{15}$N$^* \rightarrow {}^{14}$N$+n$ and ^{12}C$(\alpha,n)^{15}$O$^* \rightarrow {}^{14}$N$+p$, or through the reaction ^{12}C$(\alpha,d^*)^{14}$N with d^* being the excited triplet deuteron, where the proton energy spectrum is expected to show a broad bump. Some sharp peaks in the broad yield for the $T=0$ state were found to be the protons from the reaction ^{12}C$(\alpha,p)^{15}$N*, leading to some discrete states in ^{15}N, followed by a neutron emission decaying to the ground state of ^{14}N. Figure 1(b) shows coincidence spectrum of the protons and the neutrons detected at 60° apart. Few singlet deuterons were identified from the analysis of this spectrum. This result provides us with additional experimental evidence of the strong spatial correlation between the proton and neutron of a singlet deuteron.

In Fig. 2(b), the solid curve for the $T=1$ state is a

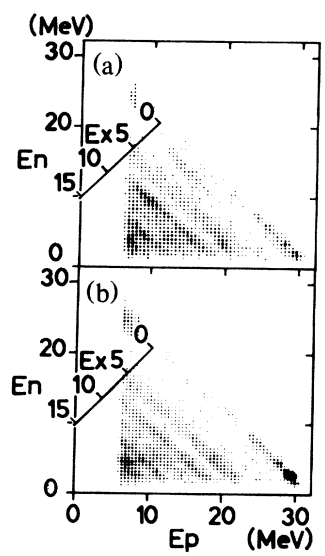

FIG. 1. Two-dimensional energy spectrum of protons and neutrons in coincidence obtained from the alpha-induced reactions on ^{12}C target at $E_{\alpha}=50$ MeV. The spectra were measured at (a) $\theta_p=\theta_n=35°$ and (b) $\theta_p=35°$, $\theta_n=-25°$. The scale of E_x inserted in the figure corresponds to the excitation energy in ^{14}N expected from the reaction ^{12}C$(\alpha,d_{S=0})^{14}$N. Several strong loci observed correspond to the states in ^{14}N. Strong yields at around $E_p=E_n$ which are a signature for the $d_{S=0}$ were observed in (a) but not in (b). See the text.

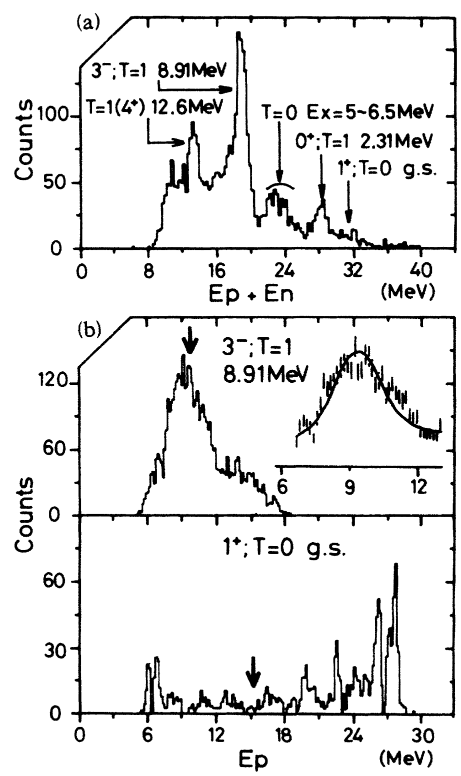

FIG. 2. (a) The summed energy spectrum of protons and neutrons detected at $\theta_p=\theta_n=35°$. (b) The proton energy spectra at $\theta_{lab}=15°$ which correspond to the ground state of ^{14}N (1^+,$T=0$) and the 3^-, $T=1$ state at 8.91 MeV in ^{14}N. The solid line for the 3^- state is a fit obtained from a Monte Carlo simulation calculation. See the text for details.

fit to the data, in order to obtain the experimental differential cross section. The fit was obtained from Monte Carlo simulation calculations. In the calculations, the probability distribution of the relative energy between the proton and the neutron in a singlet deuteron was required as an input, together with the detector efficiency of the neutron detector, and the geometrical solid angles of the proton and neutron detectors. This probability distribution was calculated by use of the Watson-Migdal formalism.[5] Possible background contributions, from the neighboring $T=0$ states excited through the sequential processes and reaction $^{12}C(\alpha,d^*)^{14}N$, were estimated. A weak correlated structure was expected in the proton and neutron energy spectra for the unbound triplet deuterons, from the reactions $^{12}C(\alpha,d^*)^{14}N$. Indeed the calculated shape of the proton energy spectrum from this reaction was almost flat. Therefore, a constant background was assumed in minimizing the χ^2 fit to the data. The fit to the data confirms that the proton spectrum in the figure is indeed due to the protons produced by the breakup of the singlet deuterons.

We extended the analysis to the other levels which were observed as peaks in the summed energy spectra [cf. Fig. 2(a)], and found that two other levels were excited by the $(\alpha,d_{S=0})$ reactions. One is the 0^+ state at 2.31 MeV and the other is a level at 12.6 ± 0.3 MeV of excitation in ^{14}N. The differential cross section was obtained from the fit to the proton yields. The angular distributions of the singlet deuterons thus obtained are shown in Fig. 3. For the 12.6-MeV state, the differential cross sections were obtained only at two angles, because of the proton energy cutoff of 5 MeV which was set in the experiment. The error bars of the data points in the figure indicate the errors which are the statistical errors in most cases, but which in some cases include the errors due to the uncertainty caused by the proton energy cutoff.

In the theoretical analysis we treated the unbound singlet deuteron as a particle, and performed distorted-wave Born-approximation calculations of the reaction $^{12}C(\alpha,d_{S=0})^{14}N$.

The exact finite-range form factors were used in the distorted-wave calculations. In the form-factor calculations, the angular momentum between each of the transferred nucleons and the outgoing singlet deuteron was assumed to be zero. The nucleon wave functions in the alpha particle were assumed to be Gaussian wave functions in relative coordinates. Consequently, the wave function of the singlet deuteron in the alpha particle was also Gaussian, and its range parameter was chosen to be 2.77 fm which corresponds to the root mean square radius of 1.47 fm for the alpha particle. The scattering wave function of the singlet deuteron in the final state was obtained from a rectangular-well potential, which reproduces the p-n scattering length of -23.8 fm and the effective range parameter of 2.49 fm. The interactions between each of the transferred nucleons and the singlet deuteron were derived from the foldings of the nucleon-nucleon Gaussian-shape interactions[6] with the wave function of the singlet deuteron. The nucleon-nucleon interactions used in the present calculations reproduce very well the S-wave phase shifts of the nucleon-nucleon scatterings at low energies. The optical-potential parameters used in the calculations[7] are $V=199.1$ MeV, $r=1.262$ fm, $a=0.65$ fm, $W=42.17$ MeV, $r_W=1.262$ fm, and $a_W=0.65$ fm for the $\alpha+{}^{12}C$ channel. For the $d_{S=0}+{}^{14}N$ channel, the optical potential parameters used are $V=95.6$ MeV, $r=1.05$ fm, $a=0.85$ fm, $W=6.5$ MeV, $r_W=1.76$ fm, and $a_W=0.50$ fm. The computer codes TWOFNR and TWONUC written by Igarashi[8] were used for the calculations.

Let us now examine the results for each of the three $T=1$ states. In the case of the 0^+ state at 2.31 MeV, the Cohen-Kurath[9] shell-model wave function for the state was used in a distorted-wave Born-approximation (DWBA) calculation. The calculation reproduces reasonably well not only the shape of the experimental $d_{S=0}$ angular distributions, but also the magnitude of the yields. The normalization factor needed to fit the data was $N=0.67$, where N was defined by $(d\sigma/$

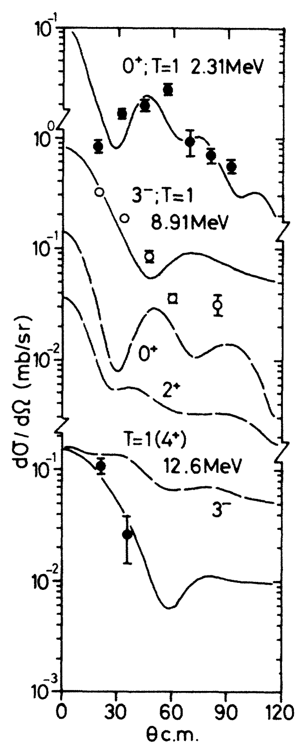

FIG. 3. Angular distributions of the differential cross sections for the reaction $^{12}C(\alpha,d_{S=0})^{14}N$ leading to $T=1$ states in ^{14}N. The lines in the figure are theoretical predictions obtained from the finite-range distorted-wave calculations.

$d\Omega)_{\text{expt.}} = N(d\sigma/d\Omega)_{\text{DWBA}}$. The result is shown in Fig. 3.

Care has to be taken in the case of the 3^- state at 8.91 MeV, because there are a couple of $T=1$ natural-parity states near the 3^- state. One is a 0^+ state at 8.61 MeV, and the other is a 2^+ state at 9.17 MeV. The 0^+ state is known to have a dominant configuration of $s_{1/2}^2$, and the 2^+ state is essentially a particle-hole state of $p_{3/2}^{-1}p_{1/2}$ configuration. Experimentally, it was not possible to resolve these states from the 3^- state. However, the comparisons between the experimental data and the distorted-wave predictions are quite revealing. In Fig. 3, the distorted-wave calculation for the 3^- state is shown together with those for the 0^+ and 2^+ states (broken lines labeled 0^+ and 2^+, respectively). The predicted shapes of the singlet-deuteron angular distributions are distinct for each of the states, with different J values in ^{14}N. In the calculation for the 2^+ state, the shell-model wave function of the state obtained by Cohen and Kurath[9] was used. In the case of the 0^+ state, a simple configuration of $s_{1/2}^2$ was assumed for clarity of comparison. In regards to the magnitude of the yields, the calculations are somewhat dependent on the configuration; however, the 0^+ yields are smaller than the yields for other J values in the forward angles, regardless of the configurations (p and s,d shells) considered. This feature is consistent with our experimental finding that the yield for the 0^+ state at 2.31 MeV was much smaller than that for the 3^- state at 8.91 MeV. The predicted low yield for the 2^+ is mainly due to the small amplitude of the $p_{3/2}^{-2}$ configuration in the ground-state wave function of ^{12}C. Thus, the contribution from the neighboring $T=1$ states to the 3^- state was estimated to be less than 20% of the experimental yields. The fit to the data was calculated with the 3^- wave function obtained by Lie.[10] The normalization factor $N=1.82$ was needed in the fit which is shown in Fig. 3.

The nature of the $T=1$ state at 12.6 MeV is not clear. In this region of high excitation energy, many $T=1$ levels are expected. However, this state could be the analog of the 4^+ state at 10.72 MeV in ^{14}C, which was reported by Jahn *et al.* in their study of the reaction $^{12}\mathrm{C}(\alpha,{}^2\mathrm{He})^{14}\mathrm{C}$.[11] In the distorted-wave calculation, $J^\pi = 4^+$ was assumed, and the wave function proposed by Lie[10] was used. The solid curve in the figure is the fit with $N=1.11$.

We have shown that there is a good agreement between the experiment and the finite-range distorted-wave calculations for the 0^+ and the 3^- states. This agreement is particularly gratifying, because discrepancy between experiments and zero-range distorted-wave predictions is a well-known fact in ordinary two-nucleon-transfer reactions, such as (α,d) or (p,t) reactions, and the zero-range calculation usually underestimates the reaction yield by an order of magnitude or more in some cases.[12] Perhaps we should point out that result of our zero-range analysis of the reaction $^{12}\mathrm{C}(\alpha,d)^{14}\mathrm{N}$ at $E_\alpha = 50$ MeV, which we studied, was also no exception. The predicted shape of the deuteron angular distributions from the zero-range calculations were so different from the experimental ones that it was difficult to deduce a meaning for experimental value of D_0^2 from the analysis.[13] The finite-range effects are essential in understanding $(\alpha,d_{S=0})$ and (α,d) reactions at low incident energies. The equivalent zero-range parameters of the folded interactions used in our finite-range analysis were estimated to be 25.4×10^4 MeV^2 fm^3 for the $(\alpha,d_{S=0})$ reaction and 23.2×10^4 MeV^2 fm^3 for the (α,d) reactions, which can be compared with the theoretical value of $D_0^2\,\hat{\Omega}_d^2 = 16.4\times10^4$ MeV^2 fm^3 estimated by use of the direct method prescribed by Lim[14] for the (α,d) reaction.

To summarize, we studied the reaction $^{12}\mathrm{C}(\alpha,d_{S=0})^{14}\mathrm{N}$ at $E_\alpha=50$ MeV. Three $T=1$ states were selectively excited in this reaction. They are the 0^+ state at 2.31 MeV, the 3^- state at 8.91 MeV, and a state at 12.6 MeV. The experimental singlet-deuteron angular distributions for the 0^+ and 3^- states were well described by our exact finite-range distorted-wave calculations. The spin and parity of 4^+ was suggested for the 12.6-MeV state.

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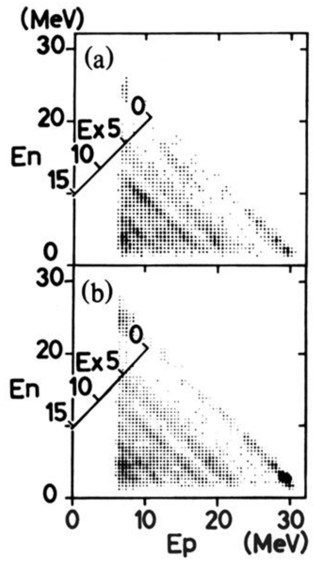

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