PHYSICAL REVIEW C VOLUME 47, NUMBER 2 FEBRUARY 1993

(d,^{2}He) reactions at $E_d = 260$ MeV as a possible probe to nuclear spin-isospin excitation

H. Ohnuma,[1] K. Hatanaka,[2] S. I. Hayakawa,[3] M. Hosaka,[4] T. Ichihara,[5] S. Ishida,[6]
S. Kato,[7] T. Niizeki,[1] M. Ohura,[5] H. Okamura,[6] H. Orihara,[8] H. Sakai,[6] H. Shimizu,[7]
Y. Tajima,[1] H. Toyokawa,[9] H. Y. Yoshida,[1] and M. Yosoi[10]
[1]*Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo, Japan*
[2]*Research Center of Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan*
[3]*Ashikaga Institute of Technology, Ashikaga, Japan*
[4]*Department of Physics, Tohoku University, Sendai, Japan*
[5]*Institute for Physical and Chemical Research (RIKEN), Wako-shi, Saitama, Japan*
[6]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan*
[7]*Faculty of General Education, Yamagata University, Yamagata, Japan*
[8]*Cyclotron and Radioisotope Center, Tohoku University, Sendai, Japan*
[9]*Institute of Physics, University of Tsukuba, Ibaraki, Japan*
[10]*Department of Physics, Kyoto University, Kyoto, Japan*

(Received 23 April 1992)

The (d,^{2}He) reactions on light nuclei were studied at $E_d = 260$ MeV with a large solid-angle, wide momentum-acceptance spectrometer. The data indicated the direct one-step nature of the reaction at this energy. Observed excitation-energy spectra for $N = Z$ nuclei compared well with those from the (p,n) reactions at similar momentum transfer. The peaks corresponding to the $0^+ \rightarrow 1^+$ transitions showed angle dependence characteristic of $\Delta L = 0$. The 0° (d,^{2}He) cross sections were found to be proportional to the Gamow-Teller β-decay strengths.

PACS number(s): 25.45.Kk

I. INTRODUCTION

Spin-isospin excitation modes of nuclei, Gamow-Teller (GT) transitions in particular, have been studied extensively by (p,n) reactions. The observed GT strengths are consistently below the sum-rule limit [1]. This so-called "quenching" of the GT strengths has been the subject of many theoretical and experimental studies. It is currently thought [1,2] that there are two major origins of the quenching; random phase approximation correlations in nuclei and subnucleon degrees of freedom of constituent nucleons. The GT strengths measured in (p,n) reactions correspond to those decreasing the isospin z component by 1 unit, i.e., those for β^- decays. It is necessary to measure GT strengths in the β^+ counterparts to make a rigorous comparison with the sum rule [3]. Intermediate-energy (n,p) reactions are being studied [4–6] to obtain the latter information. Such studies are a natural extension of (p,n) studies, and the results can be directly compared with those from (p,n) reactions. However, since intermediate-energy neutron beams can be obtained only as reaction products of a primary nuclear reaction, the beam intensities are limited even with thick neutron production targets at a sacrifice of resolution. Furthermore, although spin-flip components are more strongly excited by intermediate-energy (n,p) reactions than non-spin-flip components, spin-flip probability measurements are required, in principle, to distinguish the two components. Heavy-ion charge-exchange reactions such as (^{12}C,^{12}N) are also expected to give us information on β^+ strengths. In heavy-ion charge-exchange reactions, however, successive transfer reactions dominate at lower incident energies [7]. Although the one-step mechanism dominates above ~50 MeV/nucleon, substantial $\Delta L = 2$ contributions were found [7] in expected GT-dominant transitions even at 70 MeV/nucleon incident energy. It seems that incident energies above 1 GeV, or more than 100 MeV/nucleon, are required to reduce uncertainties involved in such reactions.

Intermediate-energy (d,^{2}He) reactions could also be used to measure β^+ strengths. Compared with (n,p) reactions, use of the primary beam in (d,^{2}He) reactions would allow us measurements with higher counting rates and higher resolution. We can expect a simple one-step charge-exchange mechanism for (d^2He) reactions at incident energies above ~200 MeV, much lower than in heavy-ion charge-exchange reactions. Furthermore, the detection of ^{2}He, two protons in the relative singlet S state, ensures automatically that the reaction goes through spin-flip components [8]. A major disadvantage of (d,^{2}He) reactions lies in the difficulty of detecting ^{2}He with good efficiency, since coincidence measurements are required between two protons emitted in the same direction. In addition, it is important to measure (d,^{2}He) cross sections at small momentum transfer, preferably at 0°. This means such a measurement must be done under strong backgrounds of other charged particles. Another disadvantage is that the mechanism of (d,^{2}He) reactions is not well understood. This could be circumvented if one could establish an empirical relation between the small-angle (d,^{2}He) cross sections and the GT strengths known from β-decay studies. Such empirical relations are well established in the case of intermediate-energy

(p,n) and (n,p) reactions, where the reactions go through a simple one-step mechanism and the central $\sigma\cdot\tau$ force is the dominant part of the interaction. In the case of $(d,{}^2\mathrm{He})$ reactions at incident energies below 100 MeV, it has been argued that the reactions do not show angular distributions characterized by transferred angular momenta ΔL [9] or go primarily through multistep processes [10]. Silicon counter telescopes were used in these experiments to detect two protons, and small-angle data were not obtained. At much higher incident energies, at 650 MeV and 2 GeV, direct excitation of the spin-flip component has been indicated [11] in $(d,{}^2\mathrm{He})$ reactions, but it is difficult to separate low-lying individual levels at these energies. It is therefore important to see whether or not $(d,{}^2\mathrm{He})$ reactions can preferentially excite $\Delta S=1$, $\Delta T=1$ components at incident energies of 100–200 MeV/nucleon. It is also necessary to establish experimental techniques for efficient ${}^2\mathrm{He}$ detection at small angles with reasonable counting rates and reasonable resolution.

We have studied the $(d,{}^2\mathrm{He})$ reactions on ${}^6\mathrm{Li}$, ${}^{12,13}\mathrm{C}$, and ${}^{23}\mathrm{Na}$ at $E_d=260$ MeV using a large solid-angle magnetic spectrometer with wide momentum acceptance in order to explore the possibility of using intermediate-energy $(d,{}^2\mathrm{He})$ reactions as a probe to nuclear spin-isospin excitation. The ground states of all the residual nuclei in these reactions decay to the target ground state by GT β transition, and their $\log ft$ values are well known [12,13]. The measured cross sections at 0° are compared with the known B (GT) values.

II. EXPERIMENTAL PROCEDURE

Details of the detection system will be discussed in a separate paper, and only brief description is given below.

A 260-MeV deuteron beam, accelerated by the RIKEN ring cyclotron, was transported in an achromatic mode onto the target through a beam swinger and a beam twister [14]. The targets were 149 mg/cm^2 thick ${}^6\mathrm{Li}$ (enriched to 99%), 180 mg/cm^2 thick ${}^{\mathrm{nat}}\mathrm{C}$, 166 mg/cm^2 thick ${}^{13}\mathrm{C}$ (enriched to 98.8%), and 133 mg/cm^2 thick ${}^{\mathrm{nat}}\mathrm{Na}$ (100% in ${}^{23}\mathrm{Na}$), all in elemental form. The magnetic spectrometer [14] consists of three quadrupole magnets and two dipole magnets in the quadrupole-quadrupole-dipole-quadrupole-dipole (QQDQD) configuration. The first three components (QQD) were designed to work as a large-solid angle, wide momentum-acceptance spectrometer, and were used in the present experiment. Two protons emitted from the target into a defining aperture of 20 msr (horizontally 100 msr and vertically 200 msr) were detected in coincidence. Two sets of position counters after the first dipole, each consisting of four 84-cm-long and 42-cm-high multiwire drift chambers, were used to determine the trajectory of each proton. Three sets of plastic scintillator hodoscopes behind them provided main triggers and timing information. Zero-degree measurements are crucial in the comparison of the $(d,{}^2\mathrm{He})$ strength with the GT β-decay strength. This was realized by stopping the deuteron beam at an insulated carbon block inside the dipole magnet. The beam stopper was shielded by lead blocks to reduce backgrounds. Measurements were also made at a few angles other than 0° for ${}^6\mathrm{Li}$ and ${}^{12}\mathrm{C}$ to obtain a crude idea of angular distributions. Figures 1(a)–1(c) show ${}^2\mathrm{He}$ energy spectra from the ${}^{12}\mathrm{C}(d,{}^2\mathrm{He}){}^{12}\mathrm{B}$ reaction at three different angles. The 0° spectra for the other targets are shown in Figs. 1(d)–1(f). Each spectrum was taken in 1–5 h with the maximum beam current of 50 pA. The beam intensity was limited by the singles rate of breakup protons. The true-to-accidental ratio was usually between 4 and 5. The overall energy resolution was about 1 MeV, and was limited by the target thickness in all cases.

III. RESULTS AND DISCUSSION

Observed $(d,{}^2\mathrm{He})$ spectra for $N=Z$ target nuclei show a remarkable resemblance to those from intermediate-energy (p,n) work at similar momentum transfer. This indicates that $(d,{}^2\mathrm{He})$ reactions at this energy go through a direct one-step mechanism as expected. The resemblance between the $(d,{}^2\mathrm{He})$ and (p,n) spectra in turn confirms the dominance of the spin-flip excitations in intermediate-energy (p,n) reactions, since non-spin-flip components do not contribute to $(d,{}^2\mathrm{He})$ reactions.

The 0° spectrum from the ${}^{12}\mathrm{C}(d,{}^2\mathrm{He}){}^{12}\mathrm{B}$ reaction in Fig. 1(a) is almost identical to those from the ${}^{12}\mathrm{C}(p,n){}^{12}\mathrm{N}$ and ${}^{12}\mathrm{C}({}^3\mathrm{He},t){}^{12}\mathrm{N}$ reactions observed [15–17] at 100–200 MeV/nucleon. The 7° and 10° spectra in Figs. 1(b) and 1(c) are also very similar to those from the ${}^{12}\mathrm{C}(p,n)$ reaction at nearly the same momentum transfer [16]. The strongest peak in the 0° spectrum corresponds to the 1^+ ground state of ${}^{12}\mathrm{B}$. Dominance of the $\Delta L=0$ component in this transition, characterized by rapid falloff with increasing angles, is evident from the figures. Broadening of the highest-energy peak at 10° is partly due to the kinematic effect, and partly due to the contribution from the 2^+ state at 0.96 MeV. Two peaks around 4.4 and 7.7 MeV become relatively stronger at larger angles as seen in Fig. 1. Corresponding peaks observed in the ${}^{12}\mathrm{C}(p,n){}^{12}\mathrm{N}$ and ${}^{12}\mathrm{C}(n,p){}^{12}\mathrm{B}$ reactions [16,18] were assigned as the spin-dipole states and other negative-parity states. The present data are consistent with these previous interpretations.

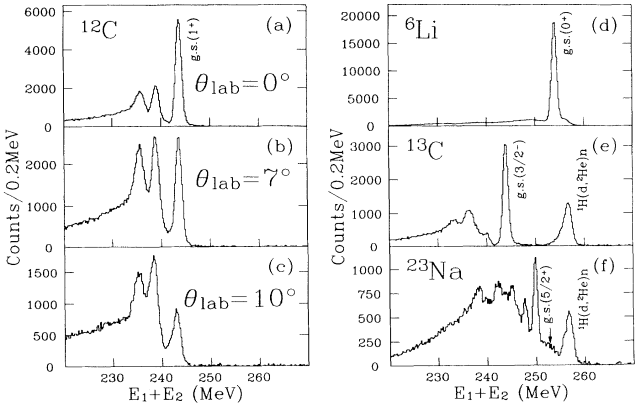

FIG. 1. Energy spectra of ${}^2\mathrm{He}$ from the ${}^{12}\mathrm{C}(d,{}^2\mathrm{He})$ reaction at three angles are shown in (a)–(c), and the 0° spectra from the other reactions are in (d)–(f).

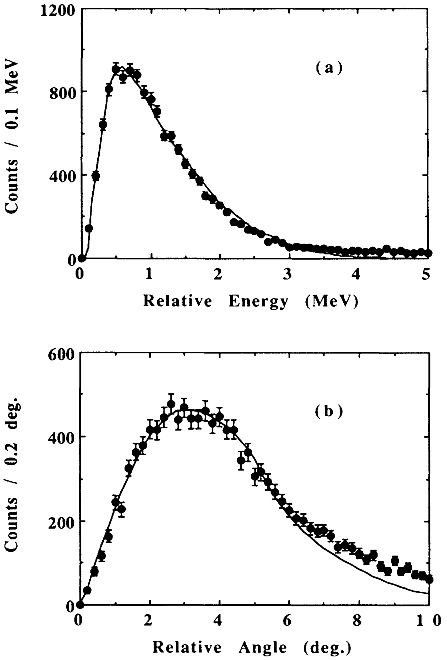

FIG. 2. (a) Proton relative-energy spectrum and (b) relative opening-angle spectrum in the reaction ^{12}C(d,^{2}He)^{12}B(g.s.) at 0°. The curves are the results of Monte Carlo calculations described in the text.

The ground state of ^{6}Li is $1^{+}, T=0$. Only the $0^{+}, T=1$ ground state is bound in ^{6}He. The 0° spectrum for the ^{6}Li(d,^{2}He) reaction shows a strong peak corresponding to the ground state, and a tail corresponding to continuum states. This agrees well with the result from the ^{6}Li(p,n)^{6}Be reaction at 200 MeV [19]. The yields of the continuum states become larger at larger angles, suggesting that higher multipoles are responsible for their excitation. Large enhancements of cross sections with $\Delta L=1$ character were reported [20] for the continuum in a ^{6}Li(n,p) study at $E_n=60$ MeV.

Only 0° spectra were taken for the odd-A target in the present experiment. The $\frac{3}{2}^{-}$ ground state of ^{13}B decays to the $\frac{1}{2}^{-}$ ground state of ^{13}C by a pure Gamow-Teller β transition with a logft value of 4.0 [12]. This state was strongly excited in the ^{13}C(d,^{2}He)^{13}B reaction at 0°. Additional broad peaks, somewhat similar to those observed in the ^{12}C(d,^{2}He) reaction, are seen at higher excitation. The $\frac{5}{2}^{+}$ ground state of ^{23}Ne was very weakly populated in the (d,^{2}He) reaction on ^{23}Na, whose ground state is $\frac{3}{2}^{+}$, in agreement with the logft value of 5.27 known [13] from the β decay. Only an upper limit of the yield was obtained for the ground state of ^{23}Ne. A state with large GT strength has been predicted around 2 MeV in ^{23}Ne by shell-model calculations [21]. A strong peak was observed in the ^{23}Na(d,^{2}He)^{23}Ne reaction whose energy agrees with the predicted position.

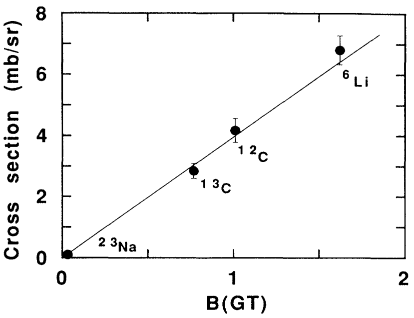

FIG. 3. A comparison of the 0° (d,^{2}He) cross sections with B(GT) values. The straight line shows a least-squares fit to the data.

A relative-energy spectrum of two coincident protons obtained for the ^{12}C(d,^{2}He)^{12}B(g.s.) reaction at 0° is shown in Fig. 2(a). Figure 2(b) shows a dependence of the yield on the relative opening angle of two protons for the same reaction. The lines in the figures were calculated with a Monte Carlo code using the Watson-Migdal approximation [22] for the final-state interaction in the relative S state of two protons. The spectrometer optics and counter geometries are also incorporated in the code. Both spectra are reproduced by the calculation very well. Slight enhancement at large opening angles may be due to multiple scattering in the wire chambers. The effective solid angles of the detection system, typically 5–7 msr depending on the reaction Q values, were obtained by integrating the calculated curves with and without cuts, and used to calculate cross sections.

The 0° (d,^{2}He) cross sections obtained for the ground states are compared with the β-decay strengths B(GT) in Table I and Fig. 3. A linear relation between the two quantities shows that intermediate-energy (d,^{2}He) cross sections at 0° could be a good measure of GT strengths of the transition. Quoted errors in cross sections are relative errors only, which include statistical errors, errors due to background subtraction, beam integration and beam monitoring, uncertainties and nonuniformity of the target thickness, and estimated errors due to the multiwire chamber efficiencies and ray-tracking efficiencies. The last two errors and errors in the effective solid angles mostly affect cross section scales, but they also mildly

TABLE I. Summary of the results.

Target (J^{π})	Residual (J^{π})	B(GT)	Q(d,^{2}He) (MeV)	q(0°) (MeV/c)	$d\sigma/d\Omega$ (mb/sr)	Relative error (mb/sr)
^{6}Li (1^{+})	^{6}He (0^{+})	1.62	-4.44	10	6.80	0.47
^{12}C (0^{+})	^{12}B (1^{+})	1.01	-14.30	30	4.17	0.39
^{13}C ($\frac{1}{2}^{-}$)	^{13}B ($\frac{3}{2}^{-}$)	0.77	-14.37	31	2.78	0.25
^{23}Na($\frac{3}{2}^{+}$)	^{23}Ne ($\frac{5}{2}^{+}$)	0.032	-5.30	12	<0.2	

affect relative cross sections through the counting-rate dependence and the Q-value dependence. Chamber efficiencies and tracking efficiencies estimated from analyses with various different cuts were used to correct the ^{2}He yields. Nevertheless, small errors in these efficiencies can result in considerable change of the cross-section scale, since two protons have to pass through a total of 16 multiwire planes. Uncertainties in the effective solid angles, which depend on the assumptions of the S-wave breakup and the Watson-Migdal approximation, are hard to estimate and not included. All in all, the cross-section scale may have uncertainties as large as 50% or more at present.

In summary, we have measured 0° (d,^{2}He) spectra on light nuclei at $E_d=260$ MeV using a large solid-angle, wide momentum-acceptance spectrometer. Such a spectrometer was found very useful for the efficient detection of ^{2}He and possibly other quasibound particles. Observed excitation-energy spectra compare well with (p,n) spectra at similar momentum transfer. Angular dependence of the peaks corresponding to GT β transitions shows a forward rise, as expected for $\Delta L=0$ transfer. A good correlation is seen between the 0° (d,^{2}He) cross sections and the known GT β-decay strengths. Present data indicate the direct one-step nature and selective excitation of the spin-flip components of the intermediate-energy (d,^{2}He) reactions. These features, together with easy and efficient ^{2}He detection techniques, will provide us with a powerful tool in the study of spin-isospin excitation modes in nuclei.

---

[1] C. Gaarde *et al.*, Nucl. Phys. **A369**, 258 (1981); C. Gaarde in *Proceedings of the Niels Bohr Centennial Conference on Nuclear Structure,* edited by B. Broglia *et al.* (North-Holland, Amsterdam, 1985), p. 449c; F. Osterfeld, Rev. Mod. Phys. **64**, 491 (1992), and references therein.

[2] H. Toki and B. Castel, Phys. Lett. B **219**, 181 (1989); C. D. Goodman, J. Rapaport, and S. D. Bloom, Phys. Rev. C **42**, 1150 (1990).

[3] K. Ikeda, Prog. Theor. Phys. **31**, 434 (1964).

[4] M. C. Vetterli *et al.*, Phys. Rev. Lett. **59**, 439 (1987); Phys. Rev. C **40**, 559 (1989).

[5] F. P. Brady *et al.*, Phys. Rev. Lett. **48**, 860 (1982).

[6] A. Ling *et al.*, Phys. Rev. C **44**, 2794 (1991).

[7] N. Anantaraman *et al.*, Phys. Rev. C **44**, 398 (1991).

[8] D. P. Stahel, R. Jahn, G. J. Wozniak, and J. Cerny, Phys. Rev. C **20**, 1680 (1979).

[9] K. B. Beard *et al.*, Phys. Rev. C **26**, 720 (1982).

[10] T. Motobayashi *et al.*, Phys. Rev. C **34**, 2365 (1986); J. Phys. G **14**, L137 (1988).

[11] C. Ellegaard *et al.*, Phys. Rev. Lett. **59**, 974 (1987).

[12] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988); **A506**, 1 (1990); **A523**, 1 (1991).

[13] P. M. Endt and C. van der Leun, Nucl. Phys. **A521**, 1 (1990).

[14] H. Ohnuma *et al.*, in *Proceedings of the Second IN2P3-RIKEN Symposium on Heavy-ion Collisions,* edited by B. Heusch and M. Ishihara (World Scientific, Singapore, 1990), p. 26.

[15] C. Gaarde *et al.*, Nucl. Phys. **A422**, 189 (1984).

[16] J. Rapaport *et al.*, Phys. Rev. C **36**, 500 (1987).

[17] I. Bergqcist *et al.*, Nucl. Phys. **A469**, 648 (1987).

[18] F. P. Brady *et al.*, Phys. Rev. C **43**, 2284 (1991).

[19] J. Rapaport *et al.*, Phys. Rev. C **41**, 1920 (1990).

[20] F. P. Brady *et al.*, J. Phys. G **10**, 363 (1984).

[21] B. H. Wildenthal, in *Progress in Particle and Nuclear Physics,* Vol. 11, edited by D. H. Wilkinson (Pergamon, New York, 1984), p. 5.

[22] K. M. Watson, Phys. Rev. **88**, 1163 (1952); A. B. Migdal, Zh. Eksp. Teor. Fiz. **28**, 3 (1955) [Sov. Phys. JETP **1**, 2 (1955)].