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A New Measurement of ^{11}Be(p,d) Transfer Reaction *

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A new ^{11}Be(p,d) transfer reaction experiment is performed in inverse kinematics with a radioactive ^{11}Be beam at 26.9A MeV. Three low-lying states, namely the 0^+ ground state, the 2^+ state at $E_x = 3.37$ MeV, and the multiplet at around 6 MeV in ^{10}Be, are populated by this one-neutron transfer reaction. These three states in ^{10}Be are clearly discriminated from the Q-value spectrum, which is rebuilt from energies and angles of the recoil deuterons in coincidence with ^{10}Be. A spectroscopic factor for each state is extracted by comparing the experimental differential cross sections to the theoretical calculation results using the finite range adiabatic distorted wave approximation method with different global nucleon-nucleus potentials. It is found that the newly extracted spectroscopic factors for the 0^+ and 2^+ states are consistent with the previous ones, but the factor for the multiplet is smaller than the value in the reference, and the possible reason is discussed.

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Direct nuclear reaction is an important tool for studying the structure of exotic nuclei.[1−3] For instance, elastic scattering reflects the global interaction (the so-called optical potential) between colliding nuclei,[4−7] inelastic scattering allows us to extract the nuclear deformation and excitation strengths,[8] and one-nucleon transfer reaction is directly related to the structure and shell occupation of the projectile and target nuclei.[9−14] Proton targeting is important in direct nuclear reaction studies due to its structure-less property and the dominance of nuclear rather than Coulomb interaction.[15]

Beryllium isotopes have rich cluster[16−19] and exotic single-particle[10,20−27] structures. The latter structure has been widely studied using the (d,p) or (p,d) one neutron transfer reaction.[10,21−25] ^{11}Be, with a smaller single-neutron separation energy of 505 keV, is a typical neutron-rich halo nucleus. The spin parity of its ground state was found to be $1/2^+$,[20] in contradiction to $1/2^-$ predicted by the traditional independent particle model. Several different ^{10}Be$_{\rm g.s.}$(d,p) transfer reactions were measured to investigate a certain single-particle component in each populated state of ^{11}Be.[25] A consistent s-wave (p-wave) spectroscopic factor (SF) of 0.71±0.05 (0.62±0.04) for the $1/2^+$ ground ($1/2^-$ excited) state in ^{11}Be, was extracted from four different ^{10}Be$_{\rm g.s.}$(d,p) measurements.[25] The ^{11}Be$_{\rm g.s.}$(p,d) reaction was usually applied to study the exotic structure of ^{11}Be$_{\rm g.s.}$, which may have two configurations, namely (^{10}Be$_{\rm g.s.}$ $\otimes$ $2s_{1/2}$) and (^{10}Be$_{2^+}$ $\otimes$ $1d_{5/2}$). For the former configuration, the valence neutron surrounding the inert core ^{10}Be populates the intruder s-orbit (s-wave component) other than the normal p-shell. However, in the latter case, ^{10}Be is excited to the 2^+ state at $E_x = 3.37$ MeV and the valence neutron fills into the intruder d-orbit (d-wave component). The s- and d-wave components in the ^{11}Be$_{\rm g.s.}$ were deduced to be 84% and 16%, respectively, from the (p,d) reaction with an ^{11}Be beam at 35.3A MeV.[21−24] This conclusion was lately confirmed by a measurement of parallel momentum distribution of ^{10}Be fragments from a 1n knockout reaction of ^{11}Be$_{\rm g.s.}$.[28] Till now, very few experiments were performed to investigate the mixed configurations of ^{11}Be$_{\rm g.s.}$, further similar experiments are still required. In this study, we report on a new measurement of the ^{11}Be(p,d) transfer reaction to the bound low-lying states in ^{10}Be with a radioactive ^{11}Be beam at 26.9A MeV.

A secondary beam of ^{11}Be at 26.9A MeV was produced from a primary beam of ^{13}C bombarding on a 456-mg/cm^2 Be target at the exotic nuclear (EN) beam line in the Research Center for Nuclear Physics (RCNP), Osaka University.[29] The beam intensity and

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purity of ^{11}Be were up to 10^4 particles per second (pps) and 95%, respectively. The energy spread of the secondary beam was about 2.0%. Two parallel plate avalanche counters (PPACs) with a tracking efficiency of about 90% were installed upstream of a plastic scintillator, which provides energy loss (ΔE) and time-of-flight (TOF) information to identify the incoming particles. A polythene $(CH_2)_n$ target with a thickness of 4.0±0.05 mg/cm^2 was used, while a 12.58±0.10 mg/cm^2 thick carbon target was employed to subtract the background from carbon atoms in the $(CH_2)_n$ target. Data was also collected in an empty target to measure the random or accidental coincident events.

A schematic view of the experimental setup was shown in Ref. [30]. A set of annular double-side silicon strip detectors (ADSSD) and three sets of telescopes (TELE0, TELE1, TELE2) were used to detect the charged particles.[10,30–32] In this work, we concentrate on TELE0 and TELE2, which were used to detect ^{10}Be and d from the ^{11}Be(p,d)^{10}Be transfer reaction, respectively. The telescope TELE0, comprised of a double-sided silicon strip detector (DSSD) with a thickness of 1000 µm and two large surface silicon detectors (SSDs) with a thickness of 1500 µm, was centered at the beam line with a distance of 200 mm away from the target[30] and covered an angular scope of 0–10° in the laboratory frame. The TELE2, which was placed 235 mm away from the target with a central angle of 25° relative to the beam line, was composed of a 65-µm-thick SSD, a 300-µm-thick DSSD, a 1500-µm-thick SSD and a layer of four CsI(Tl) crystals. Each crystal has an active area of 4.0×4.0 cm^2 and a length of 4.1 cm. All the SSDs and DSSDs have an active area of 62.5×62.5 mm^2. The width of each DSSD strip is 2 mm, bringing in an angular resolution of less than 0.6° for the detection of ^{10}Be and deuterons. The energy resolution for all the silicon detectors was less than 1% for the 5.486-MeV α particle.

To have a better discrimination of various reaction channels, similar to the ^{11}Be+p and ^{11}Be+d elastic scattering channels,[30,31] the (p,d) transfer reaction was also performed in inverse kinematics, in which the projectile-like fragments ^{10}Be emitting at forward angles were measured in coincidence with the recoil deuterons. The Beryllium isotopes from different reaction channels were measured by the TELE0, and identified based on a basic ΔE–E method. With the coincidence of all particles detected by the TELE2, the particle identification (PID) spectrum is shown in Fig. 1(a) (black points). It is obvious that ^{10}Be is discriminated clearly from ^{11}Be and ^{9}Be.

The event number of the recoil particles detected by the TELE2 is found to be more sensitive to boundaries of the ^{10}Be cut, especially the upper border which separates ^{10}Be from ^{11}Be. To reasonably select the ^{10}Be scope in the PID spectrum, a simulation was performed with the Geant4 package,[33] considering the realistic beam profile, the factual target thickness, the energy threshold of 1 MeV, dead layers of the silicon strip detectors, energy loss in the target and detector material, and the actual geometry of the TELE0 and TELE2. Assuming that ^{10}Be from the ^{11}Be(p,d) transfer reaction populates all its bound low-lying states and the corresponding deuteron emits to its low-energy branch, namely the high-cross-section part, the ^{10}Be distributions in the ΔE–E spectra are shown by red points in Fig. 1(a). Apparently the ^{10}Be fragments from the ^{11}Be(p,d) reaction only populate the high-energy portion, while the low-energy part may come from some other reaction channels, such as the deuteron high-energy branch of the ^{11}Be(p,d) reaction, the elastic breakup of ^{11}Be on the C- or H-component in the $(CH_2)_n$ target,[10] or the interaction between ^{11}Be with the silicon detector in the TELE0.[4] To reduce the effects of other reaction channels, a cut, corresponding to the red frame in Fig. 1(a), was applied for ^{10}Be. The simulated locations of ^{10}Be with about 3% extension were adopted to determine the boundaries of the ^{10}Be cut.

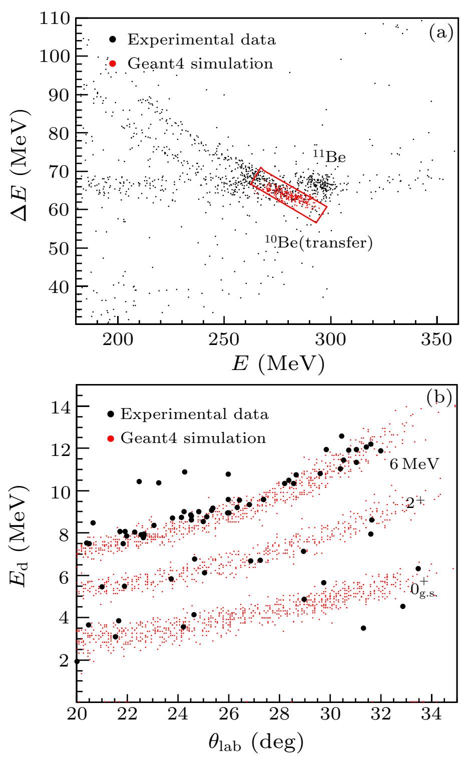

Fig. 1. (a) Particle identification (PID) spectrum taken by the TELE0 in coincidence with the recoil particles measured by the TELE2. (b) Energies of deuterons as a function of their angles in the lab frame. The red and black scattering points stand for the simulated and experimental data, respectively.

If the projectile ^{11}Be is excited to resonant states with excitation energies of 0.6–10 MeV, the energy scope of ^{10}Be that breakup from ^{11}Be on the C- or H-component in the $(CH_2)_n$ target is 238–290 MeV, which means that most ^{10}Be particles from breakup reactions are mixed into the red-frame gate in

Fig. 1(a). Thus it is difficult to distinguish the source of ^{10}Be just based on the energy of ^{10}Be. The breakup on the C-component can be easily removed by subtracting the C-target data normalized to the same incident ^{11}Be particle number, but the breakup on the H-component, which was found to be un-negligible in Ref. [30], is hardly to be excluded. It is necessary to use kinematics of the recoil deuterons to further select events belonging to the ^{11}Be(p,d) channel. In Fig. 1(b), with coincidence of ^{10}Be gated by the red frame in Fig. 1(a), the energies of the recoil deuteron as a function of its angles were mapped out (large black points). The energy losses in the $(CH_2)_n$ target (50 µm thick) and in the thin silicon detector of the TELE2, which were damaged after exposure to a high-dose radiation, are hardly to be exactly measured. Therefore, only the energy measured in DSSD of the TELE2 is shown in Fig. 1(b), which is slightly lower than the calculated ones from kinematics for the ^{11}Be(p,d) transfer reaction to the ground state, 2^+ state and multiplet at around 6 MeV in ^{10}Be, and further causes the peak shift on the Q-value spectrum. The simulated ones measured by the DSSD were also given as small red points in Fig. 1(b). The band for the ground state is obviously broader than others due to the fact that the energy dispersion of the lower-energy deuteron in the thick target (and also the damaged SSD) is larger. This fact also leads to the effect that each band is broader at smaller angles, where deuterons have lower energies than those at larger angles. Most experimental points lie on the simulated bands, which manifests that these events are indeed from the ^{11}Be(p,d) transfer reaction.

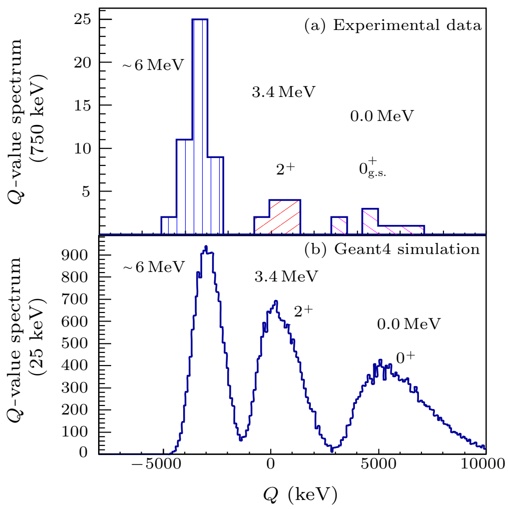

Fig. 2. The Q-value spectrum for the ^{11}Be(p,d) transfer reaction to the low-lying states in ^{10}Be, deduced from the energies and scattering angles of the recoil deuterons. The upper (a) and lower (b) panels are the experimental and the simulated one, respectively.

In coincidence with ^{10}Be, the Q-value spectrum, rebuilt from the energies and angles of deuterons within the simulated bands (Fig. 1(b)), is displayed in Fig. 2(a). Three peaks, corresponding to the 0^+ ground state, the 2^+ state at 3.37 MeV and the multiplet at around 6 MeV of ^{10}Be, are clearly separated. The full width at half maximum (FWHM) of each peak gradually increases with the rise of the Q-value, which could also be attributed to the larger energy-losses dispersion in the target and the thin SSD of the recoil deuterons with lower energies. The experimental Q-value spectrum shows a good consistency with the simulated one given in Fig. 2(b). The event number of each state in Fig. 2(b) is meaningless because this simulation does not consider the reaction cross sections.

Differential cross sections (DCSs) for the ^{11}Be (p,d) ^{10}Be transfer reaction are presented in Fig. 3, deduced from the recoil deuterons and gated on each low-lying state of ^{10}Be in the Q-value spectrum. The ground state events are chosen by a cut from 3 to 10 MeV on the Q-value spectrum (Fig. 2(a)). A gate between −1.5 and 3 MeV is used to select the 2^+ state, and from −5 to −1.5 MeV to opt for the multiple states. The error bars in the figure are statistical only. The systematic error is less than 10%, taking into consideration of the uncertainties in the detection efficiency determination (5%), the $(CH_2)_n$ target thickness (1%), and the cuts on the PID spectrum (2%) and on the Q-value spectrum (1%).

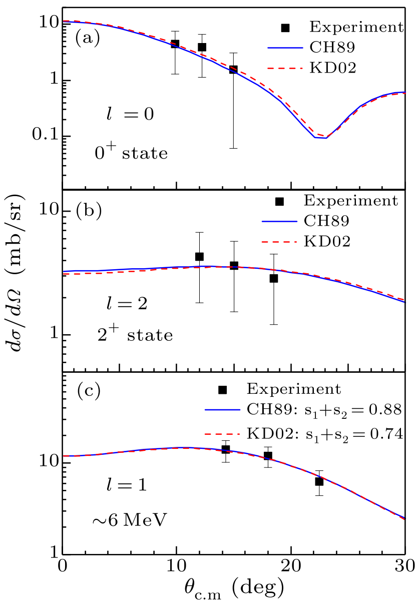

Fig. 3. Differential cross sections for the ^{11}Be(p,d) transfer reaction to the 0^+ (a), 2^+ (b) states and multiplet at around 6 MeV (c) in ^{10}Be. The black point, and the solid and dashed curves represent experimental data with an error bar, and the FR-ADWA calculations using the CH89 and KD02 potentials, respectively.

The SFs were extracted for the low-lying states of ^{10}Be using the finite range adiabatic distorted wave approximation (FR-ADWA) method, which uses the nucleon-nucleus potential, and also includes the coupling effect of deuteron breakup.[25,34] This method can provide consistent SFs for ^{10}Be(d,p) reactions at four different incident energies.[25] The optical model potentials (OMPs) of the entrance channel were obtained from the best fit to the DCSs of the ^{11}Be+p elastic scattering measured in the present experiment.[30] Two renormalization factors for depths of both real and imaginary parts of global nucleon-nucleus potentials CH89[35] and KD02[36] were required to best reproduce the elastic scattering data based on the minimum χ^2 method. For the exit channel of ^{10}Be+d, the OMP was derived from folding the ^{10}Be+n and ^{10}Be+p potentials, which were both deduced from the global nucleon-nucleus OMPs, such as CH89 or KD02. A Reid soft-core interaction was taken for the proton-neutron system.[37] For the ^{10}Be+n binding potential, a Woods–Saxon form with fixed radius and diffuseness parameters of 1.25 fm and 0.65 fm, respectively, was used. The calculations were performed with the computer code FRESCO.[38]

According to the χ^2-minimization method,[39] the extracted SFs of $S(0^+)$ and $S(2^+)$ for $l = 0$ and $l = 2$ transferring to the 0^+ and 2^+ states in ^{10}Be, respectively, are listed in Table 1. The extracted $S(0^+)$ and $S(2^+)$ values are 0.73±0.12 and 0.23±0.08, respectively, if the KD02 potential was employed for both entrance and exit channels. The $S(0^+) = 0.82 \pm 0.15$ and $S(2^+) = 0.26 \pm 0.09$ when the CH89 potential was adopted. The error bars correspond to a 68% confidence level ($\chi^2 + 1$).[10,39] The obtained $S(0^+)$ and $S(2^+)$ with the error bars are in agreement with those deduced from the previous ^{11}Be$_{g.s.}$(p,d) experiment using the adiabatic potentials P_3D_3, and also consistent with the values of 0.74 and 0.19 predicted from the shell model using the Warburton and Brown interaction.[21] Within the error bar, the s-wave SFs $S(0^+)$ agree well with the average value of 0.71±0.05 deduced from four different measurements of the ^{10}Be(d,p)^{11}Be$_{g.s.}$ reaction.[25] The calculated DCSs multiplied by the corresponding SFs were shown as curves in Fig. 3, in comparison to the experimental data. The solid and dashed curves represent the calculations using the CH89 and the KD02 potentials, respectively.

Table 1. Spectroscopic factors for the ^{11}Be (p,d) reaction to the 0^+ ground state, the 2^+ excited state in ^{10}Be, which were extracted using the FR-ADWA method with different nucleon-nucleus potentials, compared to values from other experiments[21,25] and shell model (SM) calculations.

SF	KD02	CH89	P_3D_3-SE_2[21]	SM[21]	Average[25]
	26.9A (MeV)	26.9A (MeV)	35.3A (MeV)		(d,p)
$S(0^+)$	0.73±0.12	0.82±0.15	0.80[a]	0.74	0.71±0.05
$S(2^+)$	0.23±0.08	0.26±0.09	0.37[a]	0.19	

[a]No error bar was given in Ref. [21], but the statistics error is estimated to be larger than 10% within a 68% confidence level.

Angular distributions for the 6 MeV multiplet are well reproduced by calculations of $l = 1$ transfer to the 1^- and 2^- states at 5.96 and 6.26 MeV, without consideration of a possible coupling of ^{11}Be$_{g.s.}$ to the 2^+ (5.958 MeV) and 0^+ (6.179 MeV) states, which were unresolved in the multiplet. This consideration is similar to Ref. [21]. The summations of these two SFs are 0.74±0.18 with the KD02 potential and 0.88±0.21 using the CH89 potential, which are both smaller than 1.40 from a previous similar measurement using the optical potential combination of P_3D_3.[21] The error bars also correspond to a 68% confidence level (χ^2+2.3) for two-dimension fits.[10,39] Unlike in our experiment where we apply the kinematics of recoil deuterons with a coincidence of ^{10}Be to rebuild and identify the bound low-lying states of ^{10}Be, the previous experiment in Ref. [21] only used the total energy of ^{10}Be measured by the magnetic spectrometer to discriminate each populated state in ^{10}Be. In this case, ^{10}Be from some other reactions, such as ^{11}Be elastic breakup on the H-component of the $(CH_2)_n$ target, and interactions of ^{11}Be with zero-degree detectors, were not ruled out in the extractions of the experimental DCSs, leading to slightly larger DCSs and larger SFs. In fact, the summed SF of 1.40 is indeed larger than the shell model prediction of 1.21.[21] In our experiment, the gates are more strict. In addition to the energies of ^{10}Be, the kinematics of recoil deuterons are also applied to choose the ^{11}Be(p,d) channel. Therefore, the scattered points outside the simulated 6 MeV band, see Fig. 1(b), which may come from other reactions, were rejected, and the related DCSs are relatively smaller. It is worth noting that, the energy of deuterons from the ^{11}Be(p,d) transfer reaction to the multiplet in ^{10}Be is obviously higher than the detection threshold of silicon detector (∼1 MeV), thus in principle, no events were cut by the threshold.

In summary, a new ^{11}Be(p,d) transfer reaction to the bound low-lying states in ^{10}Be has been measured in inverse kinematics with a radioactive ^{11}Be beam at 26.9A MeV. Differential cross sections for this reaction to the 0^+ ground state, the 2^+ excited state at E_x = 3.37 MeV, and the multiplet at around 6 MeV in ^{10}Be were measured with the coincidence of ^{10}Be and deuterons, which were both chosen according to the simulated results to exclude effects of other reaction channels. The spectroscopic factor for each state was extracted using the finite range adiabatic distorted wave approximation (FR-ADWA) method. It was found that the spectroscopic factors for the 0^+

and 2^+ states are consistent with the values in references and from shell model calculations, but that for the multiplet is smaller, which might be attributed to more strict coincident restrictions to exclude effects of other reaction channels. More structure information of $^{11}Be_{g.s.}$ will be obtained from further shell model calculations in the future.

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