PHYSICAL REVIEW C VOLUME 16, NUMBER 6 DECEMBER 1977

Stretched two-neutron configurations in ^{30}Si studied with the ^{28}Si(α, ^{2}He)^{30}Si reaction

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(Received 5 May 1977)

The ^{28}Si(α,^{2}He)^{30}Si reaction is found to be highly selective in the population of high-spin states. Under the assumption of (simple) shell-model wave functions the angular distributions can be well described by distorted-wave Born approximation calculations with an optical-model parameter set identical to that used in the analysis of the ^{28}Si(α,d)^{30}P reaction at E_α = 50 MeV. Two previously unobserved states at E_x = 8.93 and 10.64 MeV are suggested to both have $J^\pi = 6^+$.

[NUCLEAR REACTIONS ^{28}Si(α, ^{2}He), E=65 MeV: measured $\sigma(E,\theta)$. Natural target; θ=11°–37° calculated $\sigma(\theta)$.]

Recently Jahn *et al.*[1] found that states formed by the transfer of a $(d_{5/2})^2_{4^+}$ neutron pair were preferentially populated in the (α, ^{2}He) reaction at E_α = 65 MeV on C and O target nuclei. This selectivity is similar to that observed in (α, d) reactions at $E_\alpha \approx 50$ MeV where this reaction is a valuable spectroscopic tool in the investigation of ΔS=1; ΔT =0 transfers to high-spin states in light nuclei.[2-7] Since the presently available triton beams for (t, p) reactions (the ΔS = 0; ΔT =1 counterpart) have low energy, the kinematic conditions, which favor the large angular momentum transfer in the (α, d) case, are not present. Because the Q values of the (α, ^{2}He) and (α, d) reactions are comparable, similar features might be expected in the transfer to high-spin stretched configuration states in light nuclei.

We report here on the investigation of the ^{28}Si(α, ^{2}He)^{30}Si reaction with a 65 MeV α-particle beam from the Kernfysisch Versneller Instituut cyclotron. A similar selectivity as in the (α, d) reaction has been found. The angular distributions are fitted with DWBA curves calculated with optical-model parameters, which give satisfactory fits to the (α, d) data at E_α = 50 MeV.

In our measurements we have used a detection system similar to that developed by Jahn *et al.*[1] A schematic drawing of the system is given in Fig. 1. It consists of two ΔE-E silicon counter telescopes in a vertical plane. The ΔE and E detector thicknesses are 0.15 and 5 mm, respectively. The vertical acceptance angle θ_v of the system matches the size of the breakup cone of the two protons arising from the unbound ^{2}He. The collimators, with areas of 0.4 ×0.7 cm^2, were located at 7.5 cm from the target such that the acceptance angles are θ_h = 3.1° and 3.8° < θ_v < 9.1°. The effective solid angle of the detection system, typically 0.1 msr, was calculated from the geometry, the Q value of the reaction, and the shape of the breakup distribution. The ^{2}He events were detected by requiring coincidence between the "software identified" protons. A correction for accidental coincidences was made from the time spectra between the two telescopes. The systematic error in the absolute cross section is estimated to be less than 20%.

Figure 2 shows a spectrum of the ^{28}Si(α, ^{2}He)^{30}Si reaction at θ = 15°. The experimental energy resolution of 250 keV is mainly due to the kinematic broadening and the target thickness ($\approx$ 1.2 mg/cm^2). The high selectivity of the reaction is clearly borne out by the spectrum. The spectrum is dominated by the transitions to the known $J^\pi = 5^-$ state at E_x = 7.04 and two unknown states at E_x = 8.93 and 10.64 MeV. In addition, weak transitions to the ground state, the E_x = 2.24 MeV ($J^\pi = 2^+$), and the E_x = 5.49 MeV ($J^\pi = 3^-$) states are observed, which are also seen in the ^{28}Si(t, p)^{30}Si reaction[8] although with different relative intensities.

Figure 3 shows the angular distributions for transitions in the ^{28}Si(α, ^{2}He)^{30}Si reaction together with the fits obtained from the program DWUCK IV. For the DWBA analysis we have taken the following optical-model parameters from the ^{28}Si(α, d)^{30}P analysis[7]: V = 180 MeV, r = 1.2 fm, a = 0.61 fm, W = 26.9 MeV, r' = 1.5 fm, a' = 0.515 fm, and V = 85

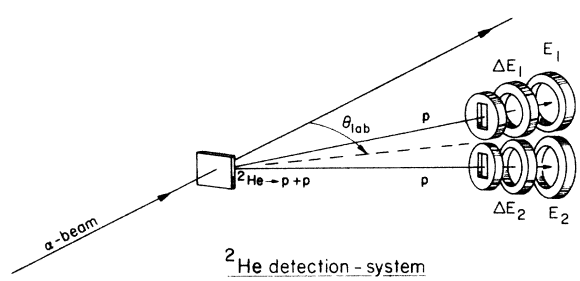

FIG. 1. A schematic view of the ^{2}He detection system.

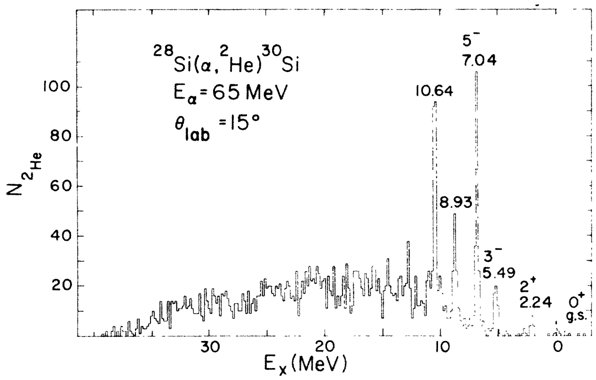

FIG. 2. A spectrum of the ^{28}Si(α, ^{2}He)^{30}Si reaction at θ_{lab} = 15°.

MeV, r = 1.2 fm, a = 0.75 fm, $4W_D$ = 85 MeV, r' = 1.25 fm, a' = 0.75 fm for α and ^{2}He, respectively. The α optical-model parameter set is derived from elastic-scattering data [9] on ^{32}S at E_α = 56 MeV. The deuteron parameter set was taken from the ^{32}S(d, ^{3}He)^{31}P reaction.[10] Both sets were modified in the real well depth and real radius according to the Del Vecchio prescription.[11] Furthermore, the deuteron surface absorption was changed from 56.8 to 85 MeV to fit the backward angle data of the (α, d) transition to the E_x = 7.20 MeV J^π = (7$^+$) state in ^{30}P. With these parameters also good fits to other states in the ^{28}Si(α, d) and ^{32}S(α, d) reactions have been obtained. In the present calculation microscopic form factors were used, calculated with the configurations as presented in Table I. From Fig. 3 it is clear that even in this case where the cross sections are rather

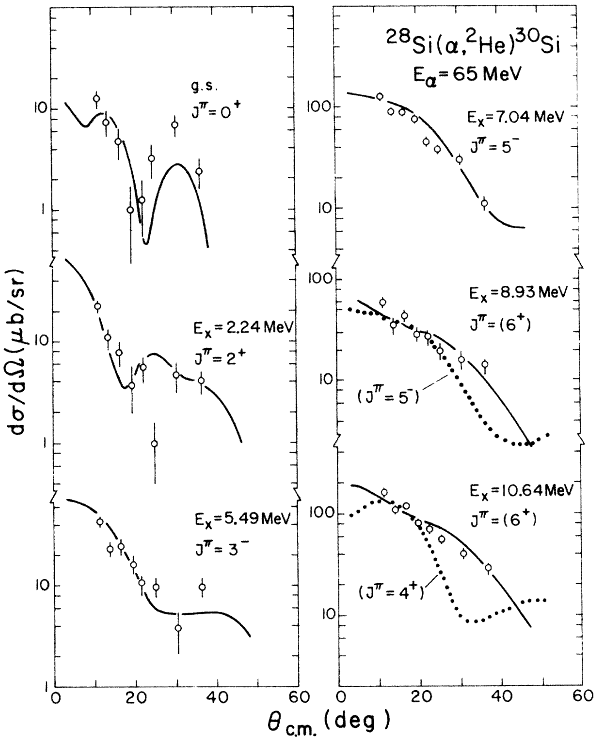

FIG. 3. The angular distributions for transitions to states observed in the ^{28}Si(α, ^{2}He)^{30}Si reaction at E_α = 65 MeV. The solid line represents DWUCK IV calculations in which optical-model parameters of the (α, d) reaction were used (Ref. 7).

small (1–100 μb/sr) reasonable fits to the data can be obtained. Furthermore, one sees that the angular distributions for the E_x = 8.93 and 10.64 MeV states are almost identical in shape. This suggests that

TABLE I. Excitation energies, spin and parity values, transition amplitudes, and normalization constants for the ^{28}Si(α, ^{2}He)^{30}Si reaction.

E_x (keV) [a]	J^π [a]	Transition amplitude	N
0	0$^+$	$1.0(s_{1/2})^2$	71
		$0.225(d_{5/2})^2 + 0.779(s_{1/2})^2$ $+ 0.449(d_{3/2})^2$	53 [b]
2 235.5 ± 0.3	2$^+$	$1.0(d_{3/2})^2$	530
		$1.0(s_{1/2}d_{3/2})$	83
		$-0.039(d_{5/2})^2 - 0.033(d_{5/2}s_{1/2})$ $+ 0.013(d_{5/2}d_{3/2}) + 0.761(d_{5/2}s_{1/2})$ $+ -0.298(d_{3/2})^2$	110 [b]
5 487.3 ± 0.8	3$^-$	$1.0(f_{7/2}s_{1/2})$	50
7 043.5 ± 1.0	5$^-$	$1.0(f_{7/2}d_{3/2})$	39
8 930 ± 40 [c]	(6$^+$) [c]	$1.0(f_{7/2})^2$	49
10 640 ± 40 [c]	(6$^+$) [c]	$1.0(f_{7/2})^2$	170
		$1.0(f_{7/2}f_{5/2})$	25

[a] Reference 8 and references therein unless indicated otherwise.

[b] Transition amplitudes calculated with the wave functions of Ref. 12. The radial wave functions are taken to be positive at infinity.

[c] Present work.

the same L transfer is involved and therefore the states will have the same spin and parity.

From the shape of the angular distributions to the $E_x = 8.93$ and 10.64 MeV states transfers with $L < 5$ can be excluded, whereas $L = 6$ gives a better fit than $L = 5$. A $J^\pi = (6^+)$ assignment for both states is therefore preferred. Except for the two lower states where detailed wave functions are available,[12] several simple configurations have been assumed. In a simple shell-model picture with ^{28}Si taken as an inert core the $J^\pi = 3^-$ and 5^- states have $(f_{7/2}s_{1/2})_{3^-}$ and $(f_{7/2}d_{3/2})_{3^-,5^-}$ configurations. The large spectroscopic factor ($C^2S = 4.0$) for the $f_{7/2}$ transfer in the ^{29}Si$(d,p)^{30}$Si reaction[14] indicates that the $J^\pi = 3^-$ state is a good two-particle state with predominantly a $f_{7/2}$ neutron coupled to the $s_{1/2}$ neutron in the ^{29}Si ground state. If for all states the structure part is properly taken into account the ratio N between the experimental and calculated cross section will be the same for all transitions.[13] From this we conclude (see Table I) that an average normalization constant of about 50 can be adopted, which is about 10 times smaller than the N value for the ^{28}Si$(\alpha,d)^{30}$P reaction at $E_\alpha = 50$ MeV.

In the upper half of the s-d shell strong transitions to $(f_{7/2})^2{}_{7^+}$ states have been observed with the (α,d) reaction, corresponding to a transfer of a $f_{7/2}$ proton-neutron pair in a relative s state coupled to the target core.[4,5] From the comparable kinematic conditions for the $(\alpha,{}^2\text{He})$ reaction and the values of the nine-j coupling coefficients involved one may expect that $(f)^2{}_{6^+}$ states will be strongly populated in the present reaction. The assumption of $(f_{7/2})^2{}_{6^+}$ and $(f_{7/2}f_{5/2})_{6^+}$ transfers to the $E_x = 8.93$ and 10.64 MeV levels, respectively, results in N values in agreement with those for the lower lying states. The agreement in the strength of these transitions thus supports the $J^\pi = (6^+)$ assignments based on the L transfer.

The presence of $f_{5/2}$ components at $E_x \approx 10$ MeV is somewhat surprising since in the Ca isotopes the $f_{7/2} - f_{5/2}$ single-particle splitting is 4 to 5 MeV. On the other hand, in the ^{28}Si$(\alpha,d)^{30}$P reaction three $L = 6$ transfers have been observed[7] in addition to a transition to a state at $E_x = 7.20$ MeV with $J^\pi = (7^+)$, which exhausts almost all of the $(f_{7/2})^2{}_{7^+}$ strength. The strength of the transitions to the states in ^{30}P at $E_x = 7.37$, 8.98, and 9.58 MeV cannot be accounted for by $(f_{7/2})^2$ components only.

The results of this investigation confirm that the $(\alpha,{}^2\text{He})$ reaction is a very useful spectroscopic tool in locating high-spin two-neutron states. The reaction mechanism seems to be similar to the (α,d) reactions at comparable α energies and the ^{2}He optical-model parameters can be taken identical to the deuteron parameters in the (α,d) work. A systematic study of the $(\alpha,{}^2\text{He})$ reaction in the s-d shell and higher shells should reveal many more unobserved stretched two-neutron states with high spin.

The authors like to thank Dr. R.H. Siemssen for the critical reading of the manuscript and Dr. R. Jahn for making the detector efficiency program available to us. This work was performed as part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) with financial support from the Nederlandse Stichting voor Zuiver Wetenschappelijk Onderzoek (ZWO).

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