Analysis of $^{28}Si(^3He,d)^{29}P$†

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Recent data for the reaction $^{28}Si(^3He,d)^{29}P$ at 25.0 MeV have been analyzed with an unbound stripping code. Resulting spectroscopic factors are in good agreement with those extracted from the original analysis using a modified bound-state calculation, and with spectroscopic factors calculated from measure proton widths.

[NUCLEAR REACTIONS $^{28}Si(^3He,d)$, $E=25.0$ MeV; DWBA analysis of published data for unbound final states; deduced S_p, $\Gamma_{p0}/\Gamma_{s.p.}$.]

In a recent study[1] of the $^{28}Si(^3He,d)^{29}P$ reaction, theoretical angular distributions for unbound states were calculated with a modified version of the bound-state code DWUCK.[2] The form factor was matched to an outgoing Coulomb wave function at large distances. Because the resulting spectroscopic factors[1] for some states differed appreciably with the results[3,4] for mirror states in $^{28}Si(d,p)^{29}Si$ (which, however, show large discrepancies for different workers), we have analyzed the data of Ref. 1 with the unbound stripping code DOXY.[5] This code uses a resonant form factor and a modified integration routine.[5]

Potential parameters (listed in Table I) were taken from Ref. 1. The results are compared in Fig. 1 with the data and curves of Ref. 1. Resulting spectroscopic factors are compared in Table II. Table III compares our spectroscopic factors with those extracted from measured proton widths.[6] In Fig. 2, we compare the stripping data with angular distributions calculated using measured proton widths in DOXY.

Each unbound state is discussed in turn below.

3103 keV. The DOXY curve is indistinguishable from the distorted-wave Born-approximation (DWBA) curve of Ref. 1, and gives an identical spectroscopic factor of 0.060. A DWUCK calculation with a fictitious binding energy of 100 keV, but with the correct outgoing deuteron energy, also produces virtually the same shape, but leads to a spectroscopic factor of 0.08. The value $S_p = 0.060$ is in good agreement with the two measurements of S_n for the mirror state, viz. 0.058[3] and 0.070.[4]

The proton width for this state is very small, and has never been measured. The total width is[6] 20 meV, and $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma = 4.1 \pm 0.4$ meV, i.e., $\Gamma_p\Gamma_\gamma/\Gamma = 0.68 \pm 0.07$ meV. The single-particle (s.p.) width for a $1d_{5/2}$ proton resonance at this energy is 22 meV. Thus, a spectroscopic factor of 0.06 implies a proton width of 1.3 meV. Comparing this with the value of Γ, we see that we must have $\Gamma_p \ll \Gamma_\gamma$, so that the (p,γ) results give $\Gamma_p = 0.68 \pm 0.07$ meV.

3445 keV. Again, the DOXY curve is almost identical with the curve of Ref. 1. We get $S = 0.50$, in comparison with $S = 0.46$ in Ref. 1. The corresponding values in ^{29}Si are 0.38 or 0.43—in good agreement. Since the $1f_{7/2}$ s.p. width is 0.6 eV, the present value of S implies a proton width of 0.3 eV.

4075 keV. This supposed $\frac{7}{2}^+$ state is probably not reached via direct single-nucleon transfer. The DOXY curve is identical with the curve of Ref. 1, but the two give quite different spectroscopic factors— we get 1.3×10^{-3}, to be compared with 1.9×10^{-2} in Ref. 1. The difference is crucial, since our result implies $\Gamma_\gamma \sim \Gamma$ whereas the result of Ref. 1 implies $\Gamma_p \sim \Gamma$. A DWUCK calculation with a slightly bound

TABLE I. Optical-model parameters from Ref. 1. Strengths in MeV, lengths in fm.

	V	r_0	a	W	W_D	r_0'	a'	V_{so}	r_{oc}
^3He	148.7	1.098	0.762	15.32	0	1.755	0.754	0	1.4
d	94.3	1.046	0.807	0	11.0	1.357	0.733	7.0	1.3

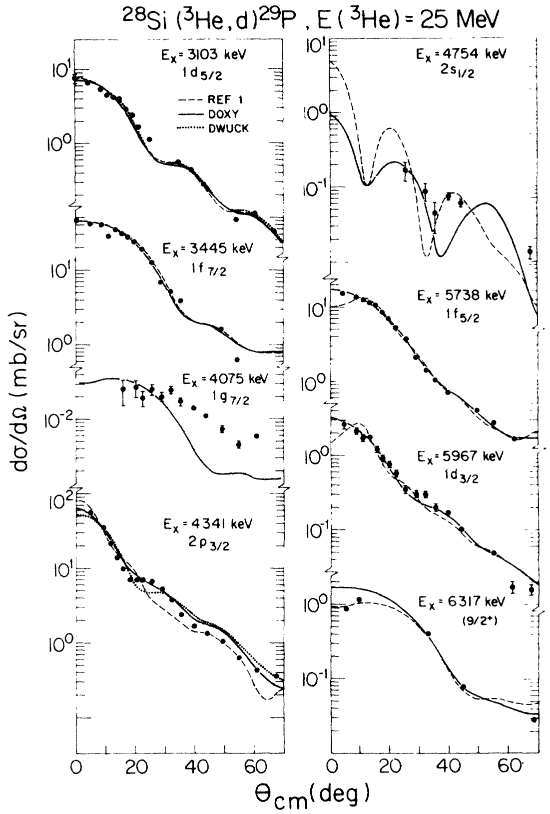

FIG. 1. Angular distributions for the reaction $^{28}Si(^{3}He,d)^{29}P$ leading to unbound states of ^{29}P. Data are from Ref. 1. Curves were calculated with the unbound stripping code DOXY (Ref. 5). Resulting spectroscopic factors are listed in Table I.

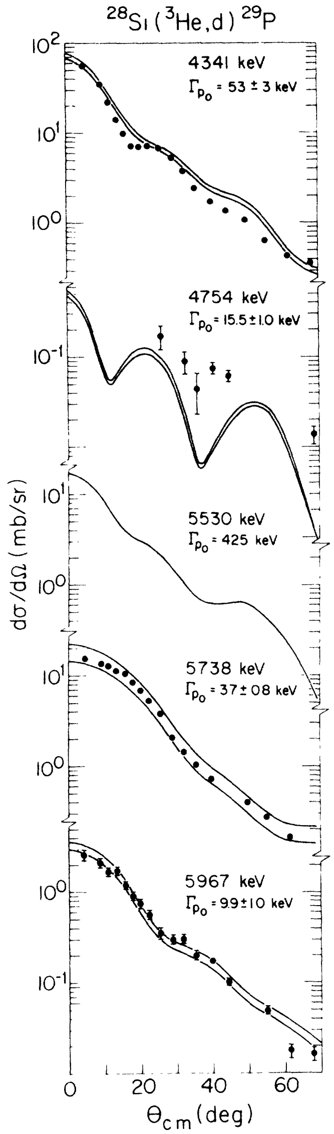

FIG. 2. Angular distributions for $^{28}Si(^{3}He,d)^{29}P$. Data are the same as in Fig. 1. Curves were calculated with the code DOXY, using the measured proton widths given in Table III.

form factor gives $S = 3.9 \times 10^{-3}$. No neutron spectroscopic factors are available for the mirror state in ^{29}Si.

4341 keV. As expected for states with appreciable widths, the DOXY curve for this state differs substantially from that of Ref. 1. We also get a larger strength, $S = 0.64$ to be compared with $S = 0.42$ in Ref. 1. Our result agrees well with the S from Ref. 3, and not with the result of Ref. 4. A DWUCK calculation with a fictitious binding energy produces a different shape and a different spectroscopic factor, $S_p = 0.77$. The measured absolute cross section is in good agreement with that calculated with DOXY when the measured proton width of 53 ± 3 keV is used. The best fit corresponds to $\Gamma_{p_0} = 46$ keV.

4754 keV. This state has a very small proton strength. The two DWBA curves are quite different. Our spectroscopic factor of 0.06 is twice that of Ref. 1. Curiously, the value from Ref. 1 is in better agreement with the ratio of measured proton width to single-particle width $\Gamma_{p_0}(\exp)/\Gamma_{s.p.} = 0.033$. The measured angular distribution has very few points and none at forward angles where the $l = 0$ curve peaks. Good data there should allow extraction of a more accurate spectroscopic factor.

5530 keV. There is no $(^{3}He,d)$ angular distribution for this state. The measured proton width is 425 ± 50 keV. The single-particle width is 784 keV, implying $S_p = 0.54 \pm 0.06$, in good agreement with $S_n = 0.52$ for the mirror state in Ref. 3. The value of $S_n = 0.26$ in Ref. 4 is too low. We show in Fig. 2 the angular distribution expected for

TABLE II. Spectroscopic factors from the present analysis compared with those from other work.

E_x (keV)[a]	J^{π} [b]	S (Ref. 1)	S (Present)	^{29}Si E_x (keV)	S (Ref. 3)	S (Ref. 4)
3103 ± 5	$\frac{5}{2}^+$	0.060	0.060	3067	0.058	0.070
3445 ± 5	$\frac{7}{2}^-$	0.46	0.50	3624	0.375	0.43
4075 ± 5	$\frac{7}{2}^+$	(0.019)	1.3×10^{-3}	4080	⋯	⋯
4341 ± 5	$\frac{3}{2}^-$	0.42	0.64	4934	0.56	0.35
4754 ± 5	$\frac{1}{2}^+$	0.03	0.060	4840	⋯	0.025
(5530)	$\frac{1}{2}^-$	⋯	⋯	6381	0.52	0.26
5738 ± 10	$\frac{5}{2}^-$	0.22	0.23	6191	0.20	0.25
5967 ± 10	$\frac{3}{2}^+$	0.05	0.051	5949	0.062	0.02
6317 ± 10	$(\frac{9}{2}^+)$ [a]	(0.042)	0.024	6770	0.06	⋯

[a] From Ref. 1.
[b] From Ref. 6 unless otherwise noted.

this state calculated with $\Gamma_{p_0}=425$ keV in DOXY.

5738 keV. The DOXY and DWUCK curves differ only at extreme forward angles. Our spectroscopic factor of 0.23 is in very good agreement with $S=0.22$ of Ref. 1. The ^{29}Si spectroscopic factors of 0.20 or 0.25 also agree. The total width[6] of this state is 12.5 ± 0.7 keV, but the bulk of this comes from decay to the first excited state of ^{28}Si. The ground-state width is $\Gamma_{p_0}=3.7\pm0.8$ keV, giving $\Gamma_{p_0}/\Gamma_{\text{s.p.}}=0.25\pm0.05$, in very good agreement with all the above.

5967 keV. The DOXY and DWUCK curves differ appreciably, with the DOXY result giving a somewhat better fit. However, the spectroscopic factors are identical (0.051 and 0.05). The two available spectroscopic factors for the corresponding state in ^{29}Si are 0.062[3] and 0.02.[4] The measured proton width of 9.9 ± 1.0 keV gives $\Gamma_{p_0}/\Gamma_{\text{s.p.}}=0.055\pm0.006$, in very good agreement with the (^{3}He, d) results.

6317 keV. This state was suggested in Ref. 1 to be $\frac{9}{2}^+$. The DOXY and DWUCK curves for $g_{9/2}$ differ at forward angles, with the DWUCK curve giving a somewhat better fit. Our spectroscopic factor is 0.024, to be compared with 0.042 in Ref. 1. The value for the analog state in ^{29}Si is

TABLE III. Spectroscopic factors in ^{29}P.

E_x [a] (keV)	J^{π} [b]	Γ_{p_0} [b] (keV)	nlj	$\Gamma_{p_0}/\Gamma_{\text{s.p.}}$	S_{DOXY}
3103	$\frac{5}{2}^+$	7×10^{-7} [b]	$1d_{5/2}$	0.032	0.060
3445	$\frac{7}{2}^-$	<2	$1f_{7/2}$		0.50
4075	$\frac{7}{2}^+$	$(2\pm1)\times10^{-6}$ [c]	$1g_{7/2}$	$(0.76\pm0.38)\times10^{-3}$	1.3×10^{-3}
4341	$\frac{3}{2}^-$	53 ± 3	$2p_{3/2}$	0.74 ± 0.04	0.64
4754	$\frac{1}{2}^+$	15.5 ± 1.0	$2s_{1/2}$	0.033 ± 0.002	0.06
(5530)	$\frac{1}{2}^-$	425 ± 50	$2p_{1/2}$	0.54 ± 0.06	⋯
5738	$\frac{5}{2}^-$	3.7 ± 0.8	$1f_{5/2}$	0.25 ± 0.05	0.23
5967	$\frac{3}{2}^+$	9.9 ± 1.0	$1d_{3/2}$	0.055 ± 0.006	0.051
6317	$(\frac{9}{2}^+)$ [a]	⋯	$1g_{9/2}$	⋯	0.024

[a] From Ref. 1.
[b] From Ref. 6 unless otherwise noted.
[c] See text.

0.06. This state has no measured width. The $g_{9/2}$ s.p. width is 3.5 keV, so that if the state is reached in ($^3He,d$) by $g_{9/2}$ stripping, its proton width is 84 eV.

We conclude that for most states, the spectroscopic factors calculated with the unbound stripping code DOXY agree with those of Ref. 1, and with the values expected from measured proton widths. Whenever there is a significant discrepancy between the results of Refs. 3 and 4 for the mirror states in ^{29}Si, our results are in better agreement with Ref. 3.

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