Investigation of ^{67}Zn states by the ^{66}Zn(d,p) and ^{65}Cu(^{3}He,p) reactions*

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The ^{66}Zn(d,p)^{67}Zn and ^{65}Cu(^{3}He,p)^{67}Zn reactions have been studied at bombarding energies of 7.5 and 13.0 MeV, respectively. Below E_x = 3.78 MeV, 44 levels were observed in the (d,p) reaction while 25 levels below E_x = 5.21 were observed in the (^{3}He,p) reaction.

[NUCLEAR REACTIONS ^{66}Zn(d,p), (d,d), E_d = 7.5 MeV; measured $\sigma(E_p, \theta)$, Q. ^{67}Zn deduced levels, J, l_n, π. Enriched target. ^{65}Cu(^{3}He,p), (^{3}He, ^{3}He), E = 13.0 MeV; measured $\sigma(E_p, \theta)$, Q. ^{67}Zn deduced levels, L. Enriched target.]

The level structure of ^{67}Zn has been previously investigated with (p,d) reactions,[1] (d,t) reactions,[2] (^{3}He, α) reactions,[3] β decay of ^{67}Ga (Ref. 4), and Coulomb excitation.[5,6] The ^{66}Zn(d,p)^{67}Zn reaction which we have studied has also been investigated by others,[2,7,8] but with relatively poor resolution. We have identified 44 levels in ^{67}Zn below E_x = 3.78 MeV, 15 of which are reported for the first time.

The two-nucleon stripping reaction ^{65}Cu(^{3}He,p)-^{67}Zn was done to excite those states where the correlation of the valence particles is quite different from that in states reached by single-particle transfer and, hence, are weakly excited in the (d,p) reaction. 25 levels below E_x = 5.21 MeV were identified in ^{67}Zn, 10 of which are reported for the first time, although 5 of these levels were seen in our (d,p) work.

The Massachusetts Institute of Technology-Office of Naval Research Van de Graaff accelerator was used to obtain the deuteron ($^2H_2^+$) and $^3He^{++}$ beams. The reaction products were momentum analyzed using the MIT multiple-gap spectrograph.[9] In addition to the reaction studies, deuteron and ^{3}He elastic scattering spectra were recorded in order to

TABLE I. Excitation energies in MeV for low-lying ^{67}Zn levels.

Level	Present work					
No.	(d,p)	(^{3}He,p)	(d,p) [a]	(^{3}He,α) [b]	(p,d) [c]	β decay [d]
0	0.0		0.0		0.0	0.0
1	0.091		0.093		0.09	0.093 317
2	0.184		0.184		0.18	0.184 592
3	0.388		0.390		0.40	0.3936
4	0.598		0.602		0.63	0.600
			0.74 [e]			
5	0.870	0.850	0.86 [e]	0.83	0.87	0.8879
6	0.979	0.995	0.978	1.00	1.00	
7	1.140	1.110	1.142	1.15	1.18	
8	1.363	1.345		1.37		
9	1.407					
10	1.442		1.444			
11	1.517					
12	1.539	1.550	1.542		1.59	
			1.642			
13	1.672	1.665	1.676	1.66		
14	1.790	1.787	1.782			
			1.808	1.8	1.71	
15	1.840		1.842			
16	1.870	1.896			1.88	
17	2.030					
18	2.100	2.090				
19	2.170	2.165	2.172		2.16	
			2.246			
20	2.271	2.280	2.273		2.31	
21	2.402		2.407			

TABLE I *(Continued)*

Level No.	Present work (d,p)	Present work (^{3}He,p)	(d,p) [a]	(^{3}He,α) [b]	(p,d) [c]	β decay [d]
22	2.422	2.430	2.430			
23	2.490					
24	2.557	2.550				
25	2.580					
26	2.600		2.609			
27	2.650		2.648			
28	2.732					
29	2.795	2.781	2.797			
30	2.842	2.835	2.849		2.85	
31	2.934	2.930				
32	2.990					
33	3.070	3.055				
34	3.095					
35	3.125					
36	3.160	3.180				
37	3.223		3.233			
38	3.287		3.295	3.285		
39	3.383		3.395			
40	3.465		3.480			
41	3.524					
			3.538			
			3.557			
42	3.598		3.607			
			3.651			
			3.670	3.68		
43	3.780	3.679	3.770			
		3.785				
			3.822			
			3.840	3.85	3.85	
			3.863			
			4.06 [e]			
		4.315	4.30 [e]			
		4.410				
		4.540				
		5.070				
		5.210				

[a] Reference 7.
[b] Reference 3.
[c] Reference 1.
[d] Reference 4.
[e] Reference 2.

determine the optical-model parameters for the incident channels and to determine the effective target thicknesses by normalizing the elastic scattering cross sections to the Rutherford cross sections. The latter measurements were done with 6-MeV $^2H_2^+$ 5-MeV $^3He^+$ beams.

Isotopically enriched targets of ^{66}Zn and ^{65}Cu were prepared by evaporating the metals onto a Formvar backing. An isotopic mass analysis of the ^{66}Zn target material gave 1.08% ^{64}Zn, 98.55% ^{66}Zn, 0.12% ^{67}Zn, 0.20% ^{68}Zn, and 0.05% ^{70}Zn. The ^{65}Cu target material contained 0.3% ^{63}Cu and 99.7% ^{65}Cu. (The enriched metals were supplied by the Oak Ridge National Laboratory.) The measured target thicknesses were 81 μg/cm^2 for the ^{66}Zn target and 28 μg/cm^2 for the ^{65}Cu target.

The Q values for the ground-state transitions were found to be 4820 ± 5 keV for the (d,p) reaction in agreement with the value of 4827 ± 10 keV given by von Ehrenstein and Schiffer,[7] and 8185 ± 40 keV for the (^{3}He,p) reaction. The energies of the levels excited in ^{67}Zn are given in Table I and are compared with the measurements of other reactions. The excitation energies are arithmetic averages of values determined for a number of reaction angles and, for the (d,p) work, they are expected to be accurate to about ±5 keV for the lowest levels increasing to ±8 keV for the highest levels. In the (^{3}He,p) reaction the uncertainty is about ±20 keV for the levels.

TABLE II. Summary of results from $^{66}Zn(d,p)^{67}Zn$ reaction.

Level No.	E_x (MeV)	$(d\sigma/d\Omega)_{max}$ (mb/sr)	l_n	J^π
0	0.0	0.52	3	$\frac{5}{2}^-$
1	0.091	3.0	1	$\frac{1}{2}^-$
2	0.184	0.29	1	$\frac{1}{2}^-, \frac{3}{2}^-$
3	0.388	2.7	1	$\frac{3}{2}^-$
4	0.598	1.1	4	$\frac{9}{2}^+$
6	0.979	2.1	2	$(\frac{5}{2})^+$
7	1.140	1.3	1	$\frac{1}{2}^-$
10	1.442	0.33	1	$\frac{1}{2}^-, \frac{3}{2}^-$
12	1.539	0.20	1	$\frac{1}{2}^-, \frac{3}{2}^-$
13	1.672	2.6	0	$\frac{1}{2}^+$
20	2.271	0.76	2	$(\frac{5}{2})^+$
21	2.402	0.66	1	$\frac{1}{2}^-, \frac{3}{2}^-$
22	2.422	2.1	0	$\frac{1}{2}^+$
29	2.795	1.0	2	$(\frac{5}{2})^+$
37	3.223	0.41	2	$(\frac{5}{2})^+$
38	3.287	0.80	0	$\frac{1}{2}^+$

TABLE III. Summary of the $^{65}Cu(^3He,p)^{67}Zn$ results.

E_x (MeV)	L [a]	σ_{max} (μb/sr)
1.896	2	5.0
2.090	0	9.7
2.165	0	2.6
2.550	2	5.0
3.055	2	12.0
3.180	2	9.0
3.679	0	1.9
4.315	2	32.0
5.070	2	20.0

[a] $L=0$ implies $J^\pi = \frac{1}{2}^- \rightarrow \frac{5}{2}^-$, $L=2$ implies $J^\pi = \frac{1}{2}^- \rightarrow \frac{9}{2}^-$.

The search routine of the optical-model code ABACUS-II[10] was used to obtain the optical parameters for the incident channel by searching for an over-all least-squares fit to the experimental elastic scattering cross sections. For $d+{}^{66}Zn$ we obtained: $V=118.3$ MeV, $r_0=1.0$ fm, $a=0.812$ fm, $W=0.0$ MeV, $W'=13.15$ MeV, $r_0'=1.415$ fm, $a'=0.68$ fm, and $r_{0c}=1.3$ fm. For $^3He+{}^{65}Cu$ we obtained: $V=167.82$ MeV, $r_0=1.069$ fm, $a=1.4$ fm, $W=16.904$ MeV, $W'=0.0$ MeV, $r_0'=1.659$ fm, $a'=0.60$ fm, and $r_{0c}=1.4$ fm. The proton parameters were taken from the survey by Perey.[11] Distorted-wave Born-approximation calculations were performed using the zero-range code JULIE.[12,13]

The $^{66}Zn(d,p)^{67}Zn$ reaction has been studied previously by Lin and Cohen[2] and by von Ehrenstein and Schiffer.[7] Except for the 2.402-MeV level, our l_n assignments agree with those of von Ehrenstein and Schiffer, and with the exception of the 0.184-MeV level, we agree with the Lin and Cohen assignments. In the latter case, Lin and Cohen[2] tentatively assigned $l_n=3$, but both the present work and that of von Ehrenstein and Schiffer[7] assigned $l_n=1$ to the 0.184 MeV which did not exhibit much single-particle strength. Table II summarizes the (d,p) results.

The ground state of ^{67}Zn has $J^\pi=\frac{5}{2}^-$, thus, in the $(^3He,p)$ reaction, both the neutron and proton can go to the $1f_{5/2}$ state or be transferred to $2p$ orbitals. No quantitative information concerning the precedence of one configuration over the other was found. However, at higher excitation energies the $(2p,2p)$ configuration appeared to give a somewhat better fit to the data. Table III summarizes the $(^3He,p)$ results.

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