I. 4. Single-particle States in the ^{59}Co Nuclei

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A deuteron stripping reaction at higher incident energy, is a very useful tool to study a one-proton state as a target nucleus plus one proton. From spectroscopic factors derived as a ratio of experimental differential cross section to one calculated with distorted wave Born approximation (DWBA), we can get some information for the ground state of a target nucleus, such as proton occupation probabilities and single-particle energies of shell-model orbits. Therefore, the (d,n) reaction plays an important role in the nuclear spectroscopic study.

In nuclear shell-model, Z or N = 20-28 nuclei are expected to have simpler configurations in the ground state wave function, because of large energy gaps between orbits above and below $1f_{7/2}$ and itself. From this point of view, the spectroscopic studies for Sc, Co and Cu isotopes have been done through the (d,n) reactions in the Ca (Z = 20), Fe (Z = 26) and Ni (Z = 28) isotopes at E_d=25MeV, so far[1-4].

It becomes clear from these studies that the ground state wave function for a nucleus cannot be described by a simple shell model, because of change of proton single-particle energies with neutron number, even if the nucleus has the same proton number. Therefore, it is a very interesting problem how much the proton occupation probabilities and energy gaps between each shell-model orbit in $1f_{7/2}$ shell nuclei are. This time, basing on above systematic results, a spectroscopic study has been done by the (d,n) reaction for the ^{58}Fe (Z = 26) target at E_d=25MeV.

The experiment was accomplished at CYRIC using the AVF cyclotron and 44 m time of flight facility[5,6]. The ^{58}Fe target consisted of a self-supporting foil with 5.4 mg/cm^2 thickness, and an it's isotopical enrichment 74±9 % determined with another experiment. Angular distributions of the differential cross section were measured between 0° and 65° at laboratory angles. An excitation energy spectrum at θ=19° is shown in Fig. 1. Energy resolution for the ground state was about 280 keV. The angular distributions were measured for states up to about 11 MeV in excitation energy range.

DWBA calculations were done using the code DWUCK4$^{7,8)}$. Finite range and nonlocality corrections were applied to these calculations and the method of Vincent & Fortune$^{9)}$ was used for DWBA calculations of unbound states. Taking into account of deuteron break-up effect, the adiabatic approximation by Jonson & Soper$^{10)}$ was used for the optical model potential parameters of the incident channel. In this treatment, the potential parameters for a proton and neutron were taken from the systematics of Becchetti & Greenlees$^{11)}$ and Carlson et al$^{12)}$, respectively. The potential parameters of Carlson et al. were also used for the outgoing neutron. Typical differential cross sections for the ^{58}Fe(d,n)^{59}Co reaction are shown in Fig. 2.

For ^{59}Co, the information for the transfer momentum ℓ and spectroscopic factor were restricted the result of (^{3}He, d)$^{13)}$ in 1965, up to about 2 MeV. In the present work, we have observed many proton-single-particle states in the excitation energy region over 2 MeV. And we could assign the transfer momentum ℓ and get the spectroscopic factors for many states, which have never been assigned by one proton transfer reactions up to this time.

Obtained spectroscopic factors for ^{59}Co are shown in Table 1, and excitation energy distributions of the spectroscopic factors for each transfer momentum ℓ are shown in Fig .3. In this figure, entirely, fragmentations have been seen from a comparison between^{55,57}Co and ^{59}Co. Particularly in ℓ =1 states, the fragmentations occur, so the spectroscopic factors disperse into a lot of weak states in the wide exicitaion energy region. In ℓ =3 states, the tendency that 1f$_{7/2}$ states almost concentrate in the ground states, has been observed in ^{55,57,59}Co in common.

The sums of the spectroscopic factors for each orbit are shown in Fig. 4. In the figure, the dotted lines show the simple shell-model limits and the solid lines show the derived values in the present work. That for the 1f$_{7/2}$ orbit reaches the sum rule limit, so almost all strengths for this orbit are considered to be observed. The strengths for the 2p and 1f$_{5/2}$ orbits are smaller than the shell-model limits. This may imply that there exist weak peaks, because of a fragmentation, which has not been observed in the present measurement, or strengths distribute also in the excitation energy region above 11 MeV.

In conclusion, we have observed many proton-single-particle states for the ^{59}Co nucleus by the (d,n) reaction at E$_{d}$=25MeV in the excitation energy region up to about 11 MeV and assigned the transfer momentum ℓ for each state, which had been never assigned. In the obtained spectroscopic factors, the fragmentations have been observed from a comparison between ^{55,57}Co and ^{59}Co. The sums of those for each orbit are lower than the sum-rule limits from simple shell-model, but for 1f$_{7/2}$, almost all strengths are observed.

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Table. 1. Experimental spectroscopic factors for ^{59}Co.

Present work E_d=25MeV					^{58}Fe(^{3}He,d)^{59}Co [13] E=22MeV			
No.	Ex	ℓ	j^π	(2j+1)C^{2}S	Ex	ℓ	j^π	(2j+1)C^{2}S
1	g.s	3	$7/2^-$	1.67	g.s	3	$7/2^-$	1.36
2	1.10	1	$(3/2^-)$	0.31	1.10	1	$3/2^-$	0.44
			$(1/2^-)$	0.32				
3	1.34	1	$(3/2^-)$	1.33	1.29	1	$3/2^-$	1.36
			$(1/2^-)$	1.38				
					1.43	1	$1/2^-$	0.74
4	1.74	1+3	$(3/2^-)+5/2^-$	0.04+0.07				
			$(1/2^-)+5/2^-$	0.04+0.08				
5	2.12	3	$(5/2^-)$	1.64	2.08	3		unresolved
			$(7/2^-)$	1.09				multiplet
6	2.80	1	$(3/2^-)$	0.22				
			$(1/2^-)$	0.23				
7	3.15	1+3	$(3/2^-)+5/2^-$	0.07+0.65				
			$(1/2^-)+5/2^-$	0.07+0.66				
8	3.47	1	$(3/2^-)$	0.18				
			$(1/2^-)$	0.19				
9	3.78	1+4	$(3/2^-)+9/2^+$	0.10+0.23				
			$(1/2^-)+9/2^+$	0.10+0.27				
10	4.30	1+4	$(3/2^-)+9/2^+$	0.33+1.50				
			$(1/2^-)+9/2^+$	0.33+1.61				
11	4.92	1	$(3/2^-)$	0.14				
			$(1/2^-)$	0.15				
12	6.43	1+3	$(3/2^-)+5/2^-$	0.13+0.21				
			$(1/2^-)+5/2^-$	0.12+0.16				
13	6.75	1+3	$(3/2^-)+5/2^-$	0.31+0.20				
			$(1/2^-)+5/2^-$	0.29+0.26				
14	7.06	1+4	$(3/2^-)+9/2^+$	0.06+0.10				
			$(1/2^-)+9/2^+$	0.05+0.11				
15	7.36	1+3	$(3/2^-)+5/2^-$	0.07+0.03				
			$(1/2^-)+5/2^-$	0.07+0.05				
16	7.59	1	$(3/2^-)$	0.06				
			$(1/2^-)$	0.08				
17	7.93	1+4	$(3/2^-)+9/2^+$	0.09+0.11				
			$(1/2^-)+9/2^+$	0.09+0.12				
18	8.34	1+4	$(3/2^-)+9/2^+$	0.05+0.09				
			$(1/2^-)+9/2^+$	0.05+0.10				
19	8.66	1	$(3/2^-)$	0.12				
			$(1/2^-)$	0.12				
20	8.91	1	$(3/2^-)$	0.10				
			$(1/2^-)$	0.10				
21	9.27							
22	9.55	2	$(5/2^+)$	0.20				
			$(3/2^+)$	0.22				
23	9.81	1	$(3/2^-)$	0.10				
			$(1/2^-)$	0.10				
24	10.06	1+3	$(3/2^-)+5/2^-$	0.09+0.38				
			$(1/2^-)+5/2^-$	0.08+0.41				
25	10.35	2	$(5/2^+)$	0.09				
			$(3/2^+)$	0.10				
26	10.69	1+4	$(3/2^-)+9/2^+$	0.12+0.13				
			$(1/2^-)+9/2^+$	0.07+0.33				
27	11.10	1+4	$(3/2^-)+9/2^+$	0.19+0.33				
			$(1/2^-)+9/2^+$	0.19+0.38				

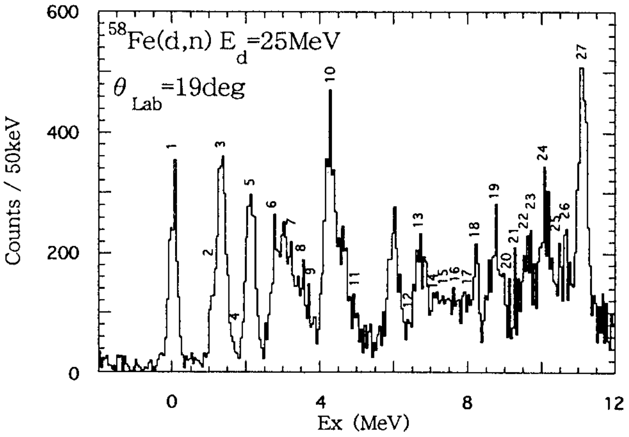

Fig. 1. A typical neutron energy spectrum in the ^{58}Fe(d,n)^{59}Co reaction at E_d = 25MeV.

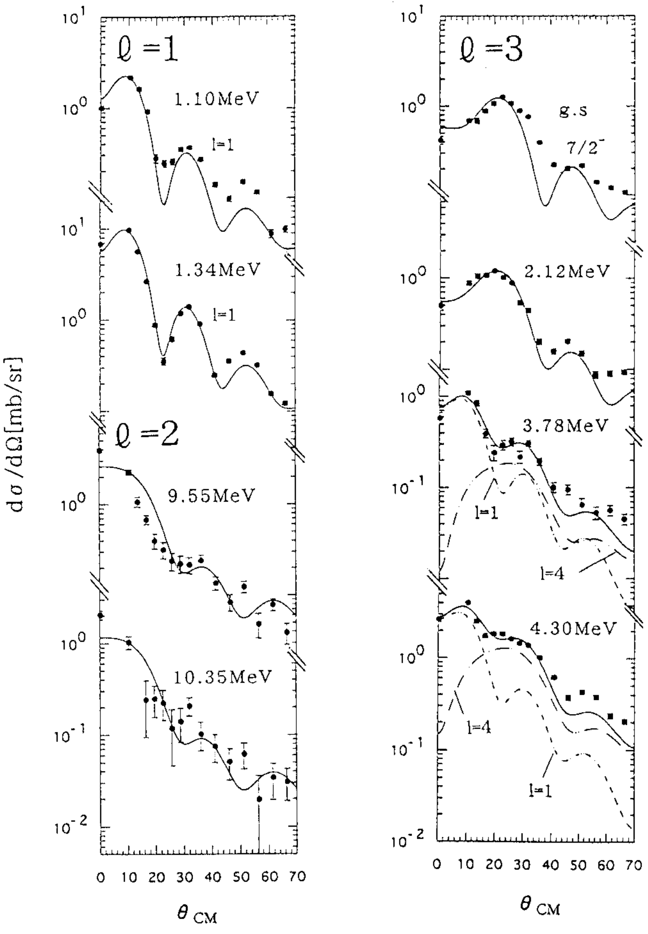

Fig. 2. Typical differential cross sections for the ℓ=1-4 transitions in the ^{58}Fe(d,n)^{59}Co reaction.

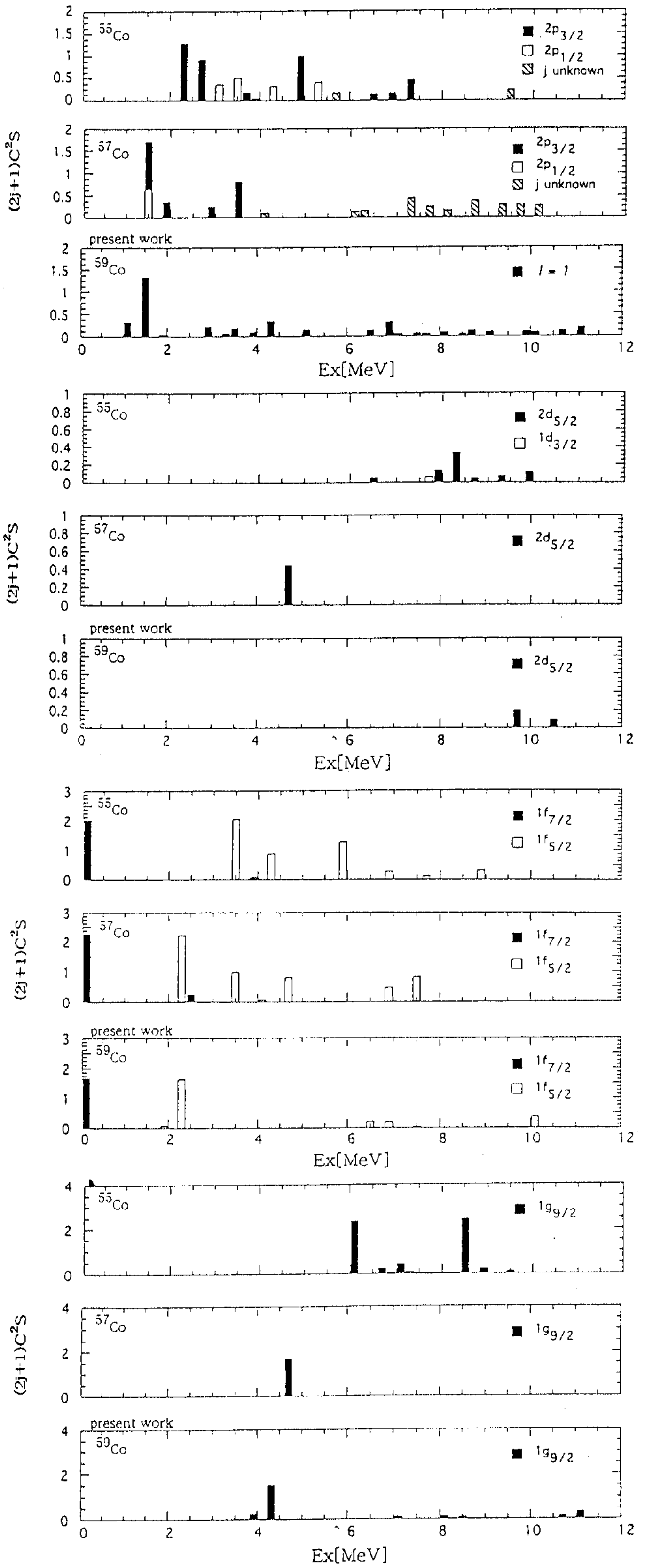

Fig. 3. Excitation energy distributions of single particle strengths for each orbit in ^{55,57,59}Co.

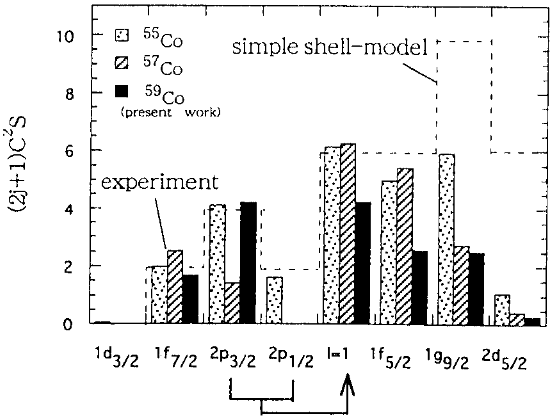

Fig. 4. Summed spectroscopic factors of ^{59}Co for each ℓ, together with those of ^{55,57}Co.