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Nuclear-Reaction Studies in the Strontium Isotopes: The $Sr^{88}(d,p)Sr^{89}$ Reaction*

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The $Sr^{88}(d,p)Sr^{89}$ reaction has been studied at 7.0 MeV using the MIT–ONR Van de Graaff generator and the multiple-gap spectrograph. Eighty-five levels in Sr^{89} below 5.86-MeV excitation were identified, compared with the 12 levels below 4.1-MeV excitation recorded previously from (d,p) studies. Among the 85 levels observed, 28 were populated by direct stripping transitions, and the data were used for determining the detailed fractionization of the single-particle strength in this energy region. A distorted-wave Born-approximation analysis was performed in these cases to determine the values of the orbital angular momentum l_n and spectroscopic strengths $(2J+1)S_{l_n,j}$ for the transferred neutron. Sum-rule strengths were subsequently calculated and compared with shell-model limits. Detailed angular distributions for some of the nonstripping states are also presented. An averaged strength function for these weaker transitions is shown and is discussed in terms of possible intermediate structure.

I. INTRODUCTION

THIS paper reports the results of the $Sr^{88}(d,p)Sr^{89}$ reaction at a bombarding energy of 7.0 MeV. The experiment was performed as part of a series of nuclear-reaction studies presently being carried out in this laboratory on the strontium isotopes. Some of the results have been used for comparison with the isobaric analog states of Sr^{89} appearing as resonances in elastic and inelastic proton-excitation functions on Sr^{88}. This was the subject of a previous publication.[1]

The Sr^{88} ground state can be considered in the simple shell model as having a semiclosed shell of 38 protons filling up to the $2p_{1/2}$ orbit and a closed shell of 50 neutrons filling up to the $2d_{5/2}$ orbit. (The last 12 neutrons occupy the $2p_{1/2}$ and $1g_{9/2}$ subshells.) It is expected therefore that strong $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1g_{7/2}$ neutron single-particle states will exist among the low-lying levels in Sr^{89} and that these will appear as enhanced $l_n=2$, 0, and 4 stripping transitions, respectively, in the $Sr^{88}(d,p)Sr^{89}$ reaction. In addition, there may be more complicated configurations at low excitation, corresponding, for example, to a $d_{5/2}$ neutron coupled to the lowest 2^+ or 3^- state in the neighboring Sr^{88} nucleus. In such a simple core-excited model for the 3^- state, a multiplet of six levels with spins $\frac{1}{2}^-$ to $11/2^-$ will be formed. Since there are presumably no low-lying odd-parity orbits to admix with this multiplet, they cannot be populated by direct (d,p) stripping and therefore must appear as weak transitions with angular distributions not expected to follow the calculated distorted-wave Born-approximation (DWBA) patterns.

In the present work, the $Sr^{88}(d,p)Sr^{89}$ reaction was studied with high resolution and with an isotopically pure target, thus enabling the identification of 85 levels in Sr^{89} below 5.86-MeV excitation, compared with the 12 levels below 4.0-MeV excitation identified in previous (d,p) studies.[2–4] The majority of the 85 levels observed were indeed weak transitions. The angular distributions for these transitions showed well-defined maxima and minima but were distinctly dissimilar to the generally more prominent stripping distributions. Thus, they are referred to as nonstripping (ns) shapes. They probably correspond to the more complex configurations, like those mentioned above, and are examples of higher order (d,p) processes; a further discussion of them is given in Sec. III B.

II. EXPERIMENTAL METHODS AND RESULTS

Many of the details of the experimental procedures have been described in a previous paper[5] and therefore only a summary will be given here.

The deuteron beam used in the present work was provided by the MIT-ONR Van de Graaff accelerator, and the reaction particles were recorded simultaneously at 24 different angles in the MIT multiple-gap spectrograph[6] on Eastman Kodak 50 μC NTA nuclear emulsions. The target used consisted of enriched Sr^{88}, vacuum evaporated onto a thin Formvar backing. The strontium sample, which was obtained from Oak Ridge National Laboratory, had an isotopic analysis of Sr^{88}, 99.84%; Sr^{87}, 0.11%; Sr^{86}, 0.05%; and Sr^{84}, less than 0.01%. A Rutherford-scattering run with 3.0-MeV deuterons yielded a target thickness of 28 $\mu g/cm^2$ Sr^{88} and 15 $\mu g/cm^2$ Formvar backing. A (d,d) elastic-scattering experiment at 7.0-MeV incident energy was also performed and this provided data for obtaining the deuteron optical-model parameters used in the DWBA analysis of the stripping data.

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[1] E. R. Cosman, H. A. Enge, and A. Sperduto, Phys. Letters **22**, 195 (1966).

[2] B. L. Cohen, Phys. Rev. **125**, 1358 (1961).

[3] R. L. Preston, M. B. Sampson, and H. J. Martin, Can. J. Phys. **42**, 431 (1964).

[4] R. E. Sass, B. Kossner, and J. Schneid, Phys. Rev. **138**, B399 (1965).

[5] E. R. Cosman, C. H. Paris, A. Sperduto, and H. A. Enge, Phys. Rev. **142**, 673 (1966).

[6] H. A. Enge and W. W. Buechner, Rev. Sci. Instr. **34**, 155 (1963).

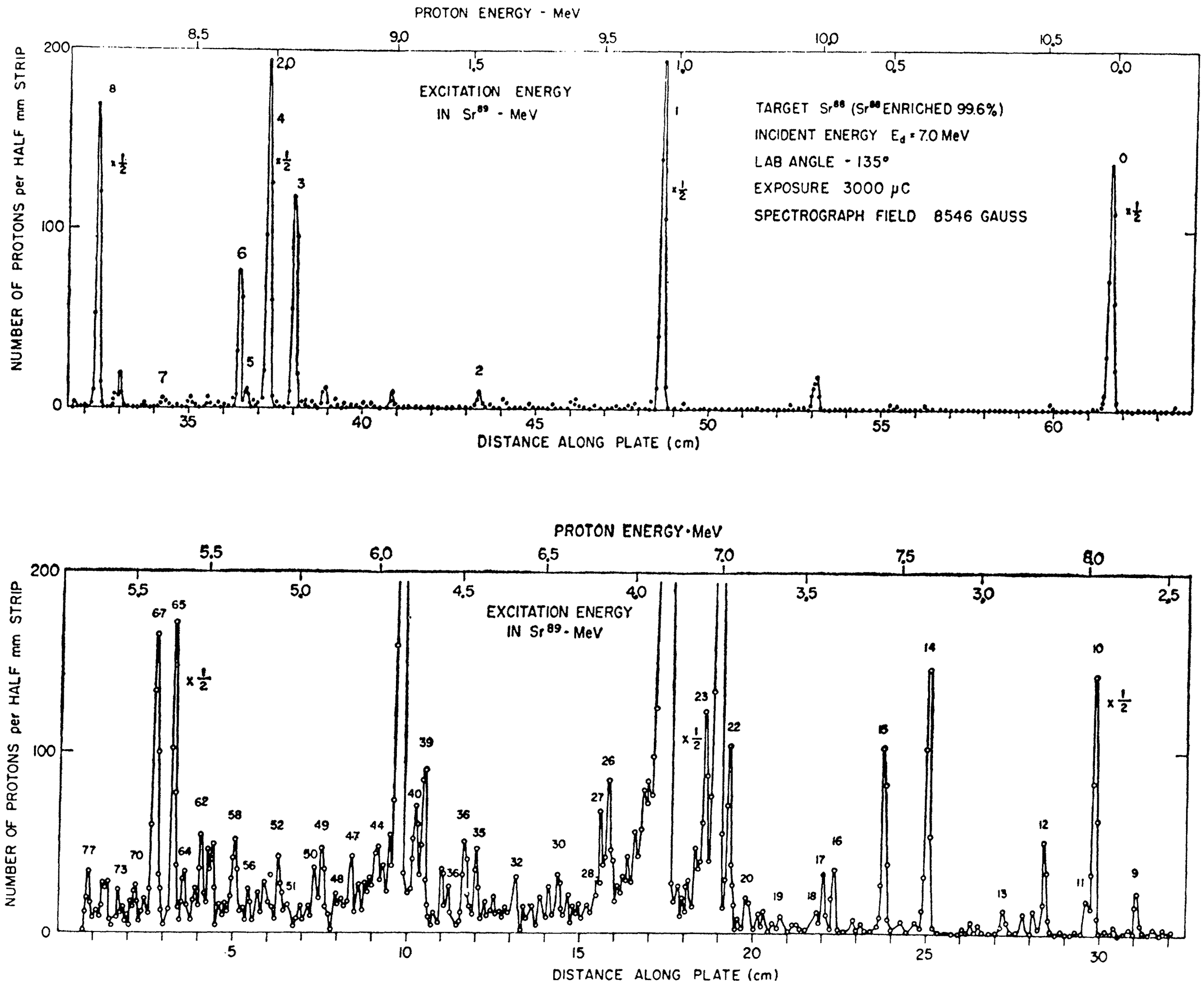

FIG. 1. The proton spectrum from the $Sr^{88}(d,p)Sr^{89}$ reaction measured in the multiple-gap spectrograph at $\theta_{lab}=135°$ and incident deuteron energy of 7.0 MeV. The proton groups are labeled with the numbers used to identify the corresponding states in Sr^{89} listed in Table I.

In the $Sr^{88}(d,p)Sr^{89}$ reaction, the target was exposed to 3000 μC of 7.0-MeV deuterons. Figure 1 shows a typical spectrum of protons measured in the multiple-gap spectrograph at 112.5° to the incident beam. The 85 levels of Sr^{89} extracted from such spectra are listed in Table I. The excitation energies quoted in the table are the arithmetic averages of values determined at a minimum of four scattering angles. The estimated standard errors on excitation energies are ±5 keV for the lowest states and ±10 keV for the higher states. The energy measurements are based on a calibration of the spectrograph with α particles from Po^{210} with an energy taken as 5.3042 ± 0.0012 MeV.[7] The ground-state Q value for the $Sr^{88}(d,p)Sr^{89}$ reaction was found to be 4.133 ± 0.005 MeV.

Figures 2 and 3 show angular distributions of some of the prominent proton groups from the $Sr^{88}(d,p)Sr^{89}$ reaction. The points are the experimental cross sections, and the solid lines are calculated DWBA curves with the values of l_n and Q indicated in the figure. The values of l_n and $(2J+1)S_{l_n,j}$ listed in Table I for the stripping transitions were inferred from such DWBA comparisons as discussed in Secs. III and IV. Several of the lowest-lying nonstripping states are also shown in Figs. 2 and 3, and these are seen to have well-defined structures that are not necessarily isotropic or symmetric about 90°. If a contaminant peak obscures a given Sr^{89} proton group at many reaction angles so that an l_n assignment is uncertain or impossible, the value given in column l_n in Table I is enclosed in parentheses or the space is left blank altogether.

[7] W. W. Buechner, in *Proceedings of the International Conference on Nuclidic Masses*, edited by H. E. Duckworth (The University of Toronto Press, Toronto, 1960), p. 263.

TABLE I. Sr^{89} levels up to 5.85 MeV. $Q_0=4.133\pm0.005$ MeV.

Level No.	E_x (MeV)	θ_{max} (deg)	$(d\sigma/d\Omega)_{max}$ (mb/sr)	l_n	$(2j+1)S_{l,j}$
0	0	53	3.50	2	4.76
1	1.031	0	(5.0)	0	1.81
2	1.460	82	0.031	ns	
3	1.931	55	0.58	2	0.548
4	2.000	53	1.95	2	1.85
5	2.057	15	0.075	ns	
6	2.071	93	0.190	ns	
7	2.266	56	0.040	ns	
8	2.455	54	1.680	2	1.36
9	2.558	22	0.115	ns	
10	2.671	82	0.620	4	5.890
11	2.691	0	0.046	ns	
12	2.805	75	0.168	(2)	0.141
13	2.918	82	0.074	(ns)	
14	3.128	60	0.450	2	0.317
15	3.245	60	0.378	2	0.260
16	3.390	(87)	0.085	(4)	0.650
17	3.421	(0)	0.365	ns	
18	(3.438)	(90)	0.020	ns	
19	3.546	(22)	0.070	ns	
20	3.638	(15)	0.046	ns	
21	3.684	···	0.060	ns	
22	3.691	60	0.330	2	0.199
23	3.757	46	1.220	0	0.215
24	3.911	(30)	0.045	ns	
25	4.035	(105)	0.050	ns	
26	4.046	47	0.290	0	0.039
27	4.069	60	0.129	(0,3)	(0.016,0.15)
28	4.084	···	0.025	ns	
29	4.168	(112)	0.040	ns	
30	4.189	37	0.105	ns	
31	4.214	···	0.040	ns	
32	4.315	(87)	0.149	(0,3)	(0.024,0.23)
33	4.359	(90)	0.076	ns	
34	4.388	···	0.030	ns	
35	4.434	(67)	0.155	(2)	0.064
36	4.473	(52)	0.220	0	0.037
37	4.518	90	0.088	ns	
38	4.560	52	0.042	ns	
39	4.594	52	0.294	0	0.053
40	4.614	52	0.195	0	0.034
41	4.626				
42	4.651	47	0.061	0	0.011
43	4.679	82	0.155	2	0.071
44	4.742	45	0.098	(0)	0.015
45	4.759	···	0.035	ns	
46	4.790	···	0.040	ns	
47	4.818	82	0.123	(2)	0.046
48	4.865	···	0.035	ns	
49	4.894	···	0.030	ns	
50	4.928	52	0.088	ns	
51	5.005	(90)	0.042	ns	
52	5.036	75	0.082	(2)	0.037
53	5.067	160	0.049	ns	
54	5.081	75	0.076	2	0.035
55	5.107	···	0.035	ns	
56	5.130	(22)	0.070	ns	
57	5.148	···	0.030	ns	
58	5.169	52	0.205	(0)	0.054
59	5.208	···	0.025	ns	
60	5.242	67	0.125	···	···
61	5.259	45	0.115	ns	
62	5.280	60	0.147	0	0.024
63	5.298				
64	5.333	60	0.116	ns	
65	5.360	52	0.895	0	0.163
66	5.399	···	0.040	ns	
67	5.418	60	0.525	(0)	0.100
68	5.442	···	0.020	ns	
69	5.456	···	0.035	ns	
70	5.480	···	0.050	ns	
71	5.496	···	0.070	···	
72	5.529	···	0.020	ns	
73	5.540	···	0.040	···	
74	5.573	···	0.050	···	
75	5.583	···	0.050	···	
76	5.611	···	0.040	···	
77	5.628	···	0.070	···	
78	5.657	···	0.060	···	
79	5.666	···	0.150	···	
80	5.694	···	0.035	···	
81	5.753	···	0.030	···	
82	5.773	···	0.100	···	
83	5.825	···	0.035	···	
84	5.858	···	0.040	···	

III. DWBA ANALYSIS OF THE (d,p) DATA

The computer code JULIE[8] was used to calculate theoretical DWBA stripping curves for comparison with the experimental data. Specific options used in the calculations reported here include zero-range interactions, no spin-orbit force, no lower cutoffs in the radial integrals, surface absorption, and a neutron well of the Woods-Saxon type.

The deuteron and proton wave functions were calculated from optical wells of the form

$$U(r)=-\frac{V}{1+e^x}+iW\frac{d}{dx'}\frac{1}{1+e^{x'}}+V_c(r,r_c),$$

where $x=(r-r_0A^{1/3})/a$, $x'=(r-r_0'A^{1/3})/a'$, and $r_c=r_{0c}A^{1/3}$. The Coulomb potential V_c is derived from a uniform charged sphere of radius r_c. The proton parameters were extrapolated from those determined by Perey[9] and were $V=55$ MeV, $r_0=1.25$ F, $a=0.65$ F, $W=54$ MeV, $a'=0.47$ F, $r_0'=1.25$ F, and $r_{0c}=1.25$ F.

Two sets of deuteron parameters were tested by comparing calculated angular-distribution curves to experimental curves for the two lowest strong transitions in $Sr^{88}(d,p)Sr^{89}$. The first set was simply another extrapolation to Sr^{88} of parameters recommended by Perey. By use of these Perey parameters as a point of departure, the second set was determined by varying the values of W and V in order to obtain a least-squares fit to the $Sr^{88}(d,d)$ elastic data taken at 7.0 MeV with the MIT multiple-gap spectrograph.[6] The search program used was ABACUS, developed by Auerbach.[10] The elastic-scattering data are shown in Fig. 4, together with the theoretical predictions found by ABACUS (solid line). It was found that the second set of parameters did not fit

[8] R. H. Bassel, R. M. Drisko, G. R. Satchler, L. L. Lee, Jr., J. P. Schiffer, and B. Zeidman, Phys. Rev. 136, B960 (1964); 136, B971 (1964).

[9] F. G. Perey, Phys. Rev. 131, 745 (1963).

[10] E. H. Auerbach, Brookhaven National Laboratory Report No. BNL-6562 (ABACUS-2), 1962 (unpublished).

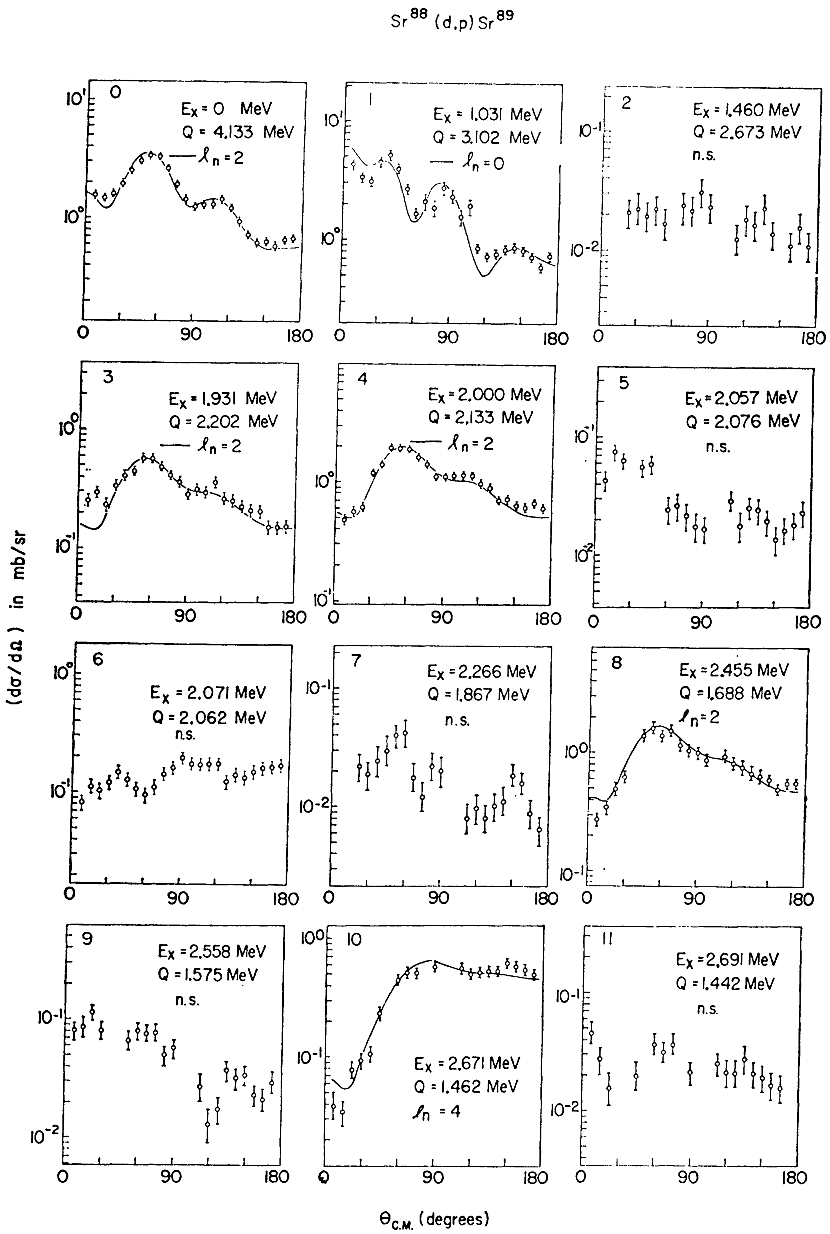

FIG. 2. Angular distributions for the first 12 proton groups from the $Sr^{88}(d,p)Sr^{89}$ reaction. At the top left of each figure is the level number found in Table I. The circles are the experimental data, the vertical bars are the statistical errors, and the solid curves are the calculated DWBA shapes assuming the indicated values of l_n and Q.

the (d,p) angular distributions so well as the first did, and therefore the original Perey parameters were chosen to extract the spectroscopic factors throughout the energy region covered in the (d,p) reaction. These deuteron parameters were $V=96.0$ MeV, $r_0=1.15$ F, $a=0.81$ F, $W=80$ MeV, $a'=0.68$ F, $r_0'=1.34$ F, and $r_{0c}=1.30$ F. Undoubtedly, other families of parameters could have been found that would have given equally good fits to the (d,p) data and also would have minimized χ^2 in fitting the $Sr^{88}(d,d)$ data; however, no extensive search for such parameters was undertaken.

To extract the spectroscopic strengths $(2J_f+1)S_{l_n,j}$ for the stripping transitions, we have used the following relationship between the experimental cross section $d\sigma/d\Omega$ and the calculated reaction function $\sigma(l_n,Q,E_d,\theta)$:

$$d\sigma/d\Omega=1.48[(2J_f+1)/(2J_i+1)]S_{l_n,j}\sigma(l_n,Q,E_d,\theta).$$

In the present case, the spin of the Sr^{88} target is $J_i=0$, and therefore the spin of the final nuclear state J_f must equal j, the total angular momentum of the transferred neutron. Furthermore, j is restricted to $l_n\pm\frac{1}{2}$, where l_n is the orbital angular momentum of the transferred neutron. In calculating σ, the depth of the neutron well was adjusted to give the correct separation energy for the last neutron in Sr^{89} in the residual state considered. All the values of $(2J_f+1)S_{l_n j}$ presented in Table I were evaluated from the above equation by

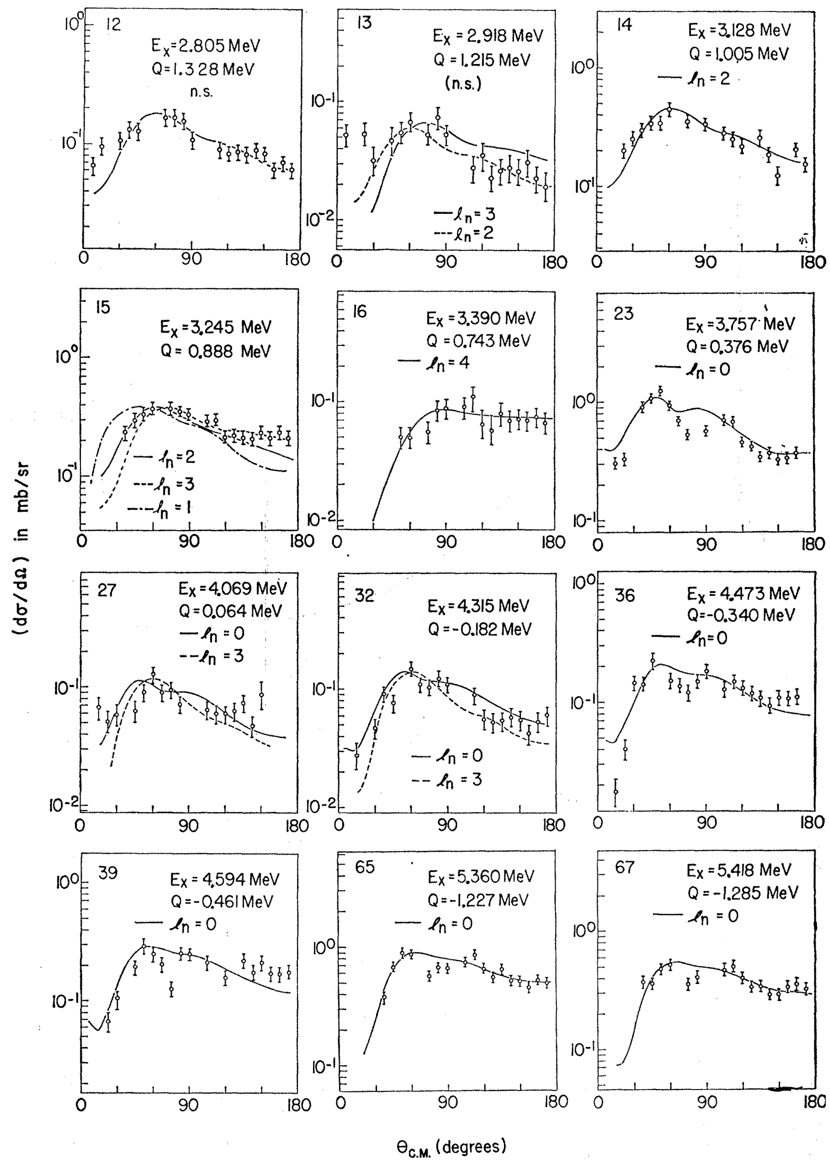

FIG. 3. Some typical angular distributions from $Sr^{88}(d,p)Sr^{89}$ at higher excitation energies.

matching the DWBA curve to the average shape of the experimental points at the forward angles.

IV. DISCUSSION

A. Level Schemes, Spectroscopic Factors, and Sum Rules

In Fig. 5 are shown the level schemes for Sr^{88} and Sr^{89}. The Sr^{88} levels were determined elsewhere,[11] and, as indicated, they are uncertain above 3.5 MeV. The existence of the level indicated by the dotted line at 2.0 MeV is also not definite. The Sr^{89} spectrum shown was obtained from the present $Sr^{88}(d,p)Sr^{89}$ experiment which allowed many previously unresolved levels to be examined in detail. Figure 6 shows the distribution of spectroscopic strengths to each of the levels with $l_n = 0, 2, 3$, and 4 seen as stripping transitions. The $l_n = 0$ and 2 strengths are spread over at least 5.5 MeV of excitation, indicating strong fragmentation of the single-particle strengths for these angular momenta. The $l_n = 2$ groups presumably correspond to $2d_{5/2}$ and $2d_{3/2}$ states. Judging from the steep drop in the envelope for this strength function with increasing excitation energy, it would be expected that the majority of these levels have been seen here and that, at most, only a few weak groups have been missed above 5.5 MeV. We have assigned $l_n = 4$ to two levels, probably corresponding to $g_{7/2}$ configurations. The first $l_n = 4$ level at 2.671 MeV is very strong and unambiguous, but the second $l_n = 4$ assignment for the 3.390-MeV level is uncertain, as

[11] *Nuclear Data Sheets*, compiled by K. Way *et al.* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 20418.

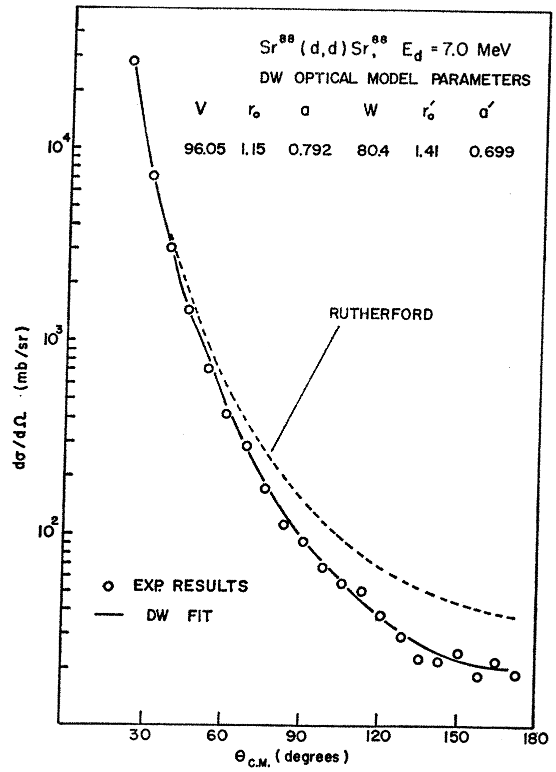

FIG. 4. The angular distributions of elastically scattered deuterons from Sr^{88} at 7.0 MeV. The circles represent experimental data, and the solid curve is a DW prediction using optical-model parameters shown in the figure.

indicated with parentheses in Table I. As seen in Fig. 3, some of the forward-angle data in the latter case were missing, and this made a conclusive comparison with DWBA curves impossible. No $l_n=1$ strength seemed to be present, indicating that the $2p$ orbit in the Sr^{88} ground state is closed. However, three groups, Nos. 13, 27, and 32, were found that might be given a tentative $l_n=3$ assignment, suggesting possible $1f_{5/2}$ holes in the target. In the case of level No. 13, $l_n=2$ and $l_n=3$ shapes appear to fit the data equally well near the experimental maximum cross section, but since the rest of the distribution departs strongly from both DWBA curves, the level was designated (ns) in Table I. Similarly, level No. 27 was given an (ns,3) assignment. Level No. 32 is an example where a definite assignment becomes difficult because of the resemblance of the DWBA curves for $l_n=0$ and $l_n=3$ in the region of Q values near zero. Since these two values produce equally good fits to the data, this group was assigned $l_n=(0,3)$ in the table. Finally, transitions with $l_n=5$ corresponding to $h_{11/2}$ single-particle states were not detected in the excitation region covered here, and this would mean that, either such groups are too weak to be identified clearly, or they all lie above 4.4 MeV in Sr^{89}.

A conventional sum-rule analysis has been applied to the present data. We use the relationship

$$\sum_a \frac{(2J_f+1)S_{l_n,j}{}^a}{(2J+1)} = \text{number of } (l_n,j)$$

neutron holes in the target.

The sum is taken over all final states of a given l_n and j, and for the case studied, we put $J_i=0$ and $J_f=j$. Line 1 of Table II gives the sum derived from the experimentally deduced values of $(2J_f+1)S_{l_n,j}$ (from Table I) for the cases $l_n=0$, 1, 2, 3, and 4. It is assumed here that the transitions would populate only the $3s_{1/2}$, $2p$, $2d$, $1f_{5/2}$, and $1g_{7/2}$ states, respectively. Line 2 of Table II gives the predictions of the simple shell model, as discussed in the introduction. Line 3 indicates the single-particle energies for the $3s_{1/2}$ and $1g_{7/2}$ orbits calculated from the formula,

$$E_{l_n,j} = \sum S_{l_n,j} E_{l_n,j} / \sum S_{l_n,j}.$$

As seen from the table, the experimental results are in good agreement with the simple shell-model predictions. In view of the 30% uncertainty of the DWBA prediction, not too much significance should be attached to a close agreement. However, it appears that most of the $3s_{1/2}$, $2d$,, and $1g_{7/2}$ strengths in the simple shell model have been accounted for in this experiment. Furthermore, because of the apparent absence of weak $l_n=1$ stripping and the tentative and, at most, small

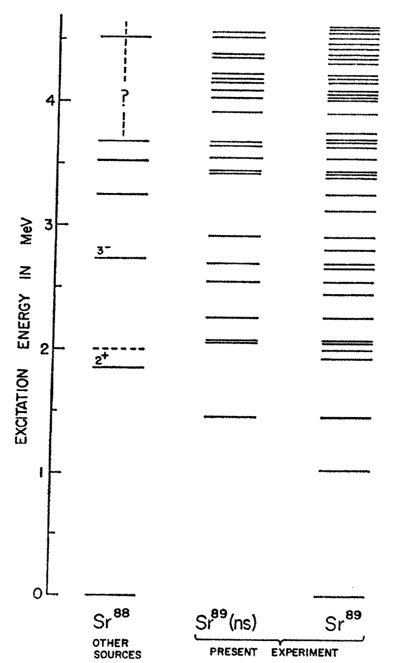

FIG. 5. The energy spectra of Sr^{88} and Sr^{89} below 4.5 MeV. The Sr^{88} levels were determined from other sources (Ref. 11) and those of Sr^{89} were located in the present (d,p) experiment. The center scheme shows only the nonstripping levels (ns) determined here, while the column on the right includes all the levels observed in Sr^{89}.

$l_n=3$ strength, the assumption of a tight neutron core in $Sr^{88}(0)$ is approximately valid. As indicated in the table, a rough upper limit on the possible number of $f_{5/2}$ holes in the target of 0.60 might be made by tentatively assigning $f_{5/2}$ stripping to level Nos. 13, 27, and 32, whose questionable distributions were discussed above.

Also, it is possible to make a reasonable estimate of the individual sum rules for the $d_{5/2}$ and $d_{3/2}$ states, even though the spins of many of the $l_n=2$ states found here are not known. In fact, the only measured spin is the $\frac{5}{2}^+$ ground state.[11] There are also strong indications that the 2.000-MeV level, No. 4, is $\frac{3}{2}^+$.[12] Assuming that these two spin assignments are correct and that we have observed all of the $l_n=2$ strength, then the only assignments that can be made for the remaining very strong d states, Nos. 3 and 8, that will keep the ratio of total $\frac{5}{2}^+$ to $\frac{3}{2}^+$ strength nearest 6:4 and at the same time maintain an expected spin-orbit splitting of about 2.0 MeV are $\frac{5}{2}^+$ and $\frac{3}{2}^+$, respectively. Moreover, since there is no reason for less fragmentation of the $d_{5/2}$ state than the $d_{3/2}$ state, we arbitrarily assign $\frac{5}{2}^+$ to the lower member, No. 14, of the pronounced $l_n=2$ pair at 3.128 and 3.245 MeV. The remainder of the $l_n=2$ states are given $\frac{3}{2}^+$. With this speculative distribution of spins, we find the spectroscopic factors and single-particle energies to be $S_{5/2}=0.94$, $E_{5/2}=0.364$ MeV and $S_{3/2}=0.98$, $E_{3/2}=2.504$ MeV. These values are fairly insensitive to the way the spins are distributed over the higher and relatively weak $l_n=2$ transitions.

TABLE II. Sum-rule strengths and single-particle energies.

	$3s_{1/2}$	$2p$	$2d$	$2f_{5/2}$	$1g_{7/2}$
$\sum (2j+1)S_{l_n,j}$					
Experiment	2.58	0	9.69	≤ 0.60	6.72
Shell model	2.0	0	10.0	0	8.0
$E_{l_n,j}$ (MeV)					
Experiment	2.11	···	···	···	2.74

B. Comparison with Other Data on Sr^{89}

Table III summarizes the $Sr^{88}(d,p)Sr^{89}$ reaction results of Cohen[2] and Preston *et al.*,[3] along with information about Sr^{89} levels from determined $\beta-\gamma$ decay of Rb^{89}, as measured by Kitching and Jones.[12] The (d,p) results of Sass *et al.*[4] were not included in the table because, in that work, only three levels were seen at 0.0, 1.05, and 2.02 MeV.

The resolution of the (d,p) experiments in Refs. 2, 3, and 4 was low, so that many close-lying levels, such as in the strong $l_n=2$ doublet at 1.931 and 2.000 MeV, were not resolved at all. This factor may also be responsible for the disagreements in l_n assignments between this work and that of Ref. 2. In the Rb^{89} decay study of Kitching and Johns,[12] the energies and spins for the five levels seen below 2.6 MeV are consistent with levels seen here. However, the levels at 2.708, 2.770, 3.225, and 3.500 MeV found in that work do not correspond well in energy with any levels seen in our work. It may be that these states exist and are so weakly populated in the (d,p) reaction that they were not detected here; yet, the possibility of a misinterpretation is not ruled out. One example is the level claimed by Kitching and Johns at 3.225 MeV with spin $\frac{1}{2}^-$. From our data, we see only one state within 100 keV of this energy at 3.245 MeV. From Fig. 3, it is seen that an $l_n=2$ DWBA curve matches the data much better than does an $l_n=1$ curve. Thus, if these levels are indeed the same, then our results are not compatible with a $\frac{1}{2}^-$-spin assignment.

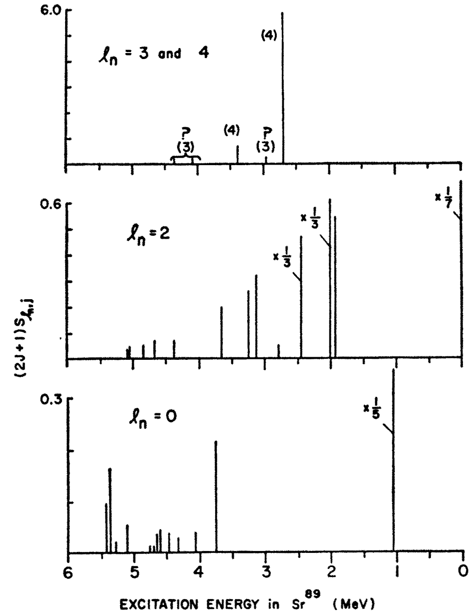

FIG. 6. The spectroscopic strengths $(2J+1)S_{l_n,j}$ listed in Table I are plotted as a function of excitation energy for the observed values of the orbital angular momentum of the transferred neutron l_n. The $l_n=3$ groups in the top graph were discussed in the text and are accompanied by question marks in this figure to indicate the uncertainty of their assignments.

C. The Nonstripping (d,p) Transitions

Of the 85 levels in Sr^{89} below 5.86 MeV reported here, 57 corresponded to weak (d,p) transitions whose angular distributions bear no resemblance to the DWBA-predicted stripping patterns. Several of these distributions are displayed in Figs. 2 and 3. The ones shown are examples at low excitation energies for which good counting statistics and the absence of nearby prominent groups allowed the shapes to be determined with some certainty. It is evident from these cases that they usually have a well-defined oscillatory structure, unlike the nearly isotopic distribution expected from a strictly compound-nuclear process. It may be hoped, therefore, that, with enough high-resolution data, systematic

[12] J. E. Kitching and M. W. Johns, Can. J. Phys. 44, 2661 (1966).

TABLE III. A comparison of the previously existing information on the Sr^{89} levels with the present results. Only those levels from our data that most probably correspond to the levels from the other references are shown. Our complete listing is given in Table I.

Level No.	Present work E_x	l_n	$Sr^{88}(d,p)Sr^{89}$ $E_x{}^a$	$l_n{}^a$	$E_x{}^b$	$l_n{}^b$	Rb^{89} decay E_x	j
0	0	2	0	2	0	2	0	$\frac{5}{2}+$
1	1.031	0	1.05	0	1.04	0	1.031	$\frac{1}{2}+$
3	1.931	2						
4	2.000	2	2.02	2	2.00	2	2.000	$\frac{3}{2}+$
7	2.266	ns					2.277	$\frac{1}{2}-$
8	2.455	2	2.40	0	2.44			
9	2.558	ns					2.567	$\frac{3}{2}\pm$
10	2.671	4	2.68	(2)	2.67			
11	2.691	ns					2.708	$(\frac{5}{2},\frac{3}{2})\pm$
12	2.805	(2)	2.81	(2)			2.770	
13	2.918	(ns)	2.99	(0)				
14	3.128	2	3.12	2	3.18			
15	3.245	2					3.225	$\frac{1}{2}-$
16	3.390	(4)	3.40		3.45			
19	3.546	ns					3.500	$\frac{5}{2}(\frac{3}{2})-$
22	3.691	2	3.69					
23	3.757	0	3.76	3.74	0			
26	4.046	0	4.04	2	4.10			

[a] See Ref. 2.
[b] See Ref. 3.

similarities might be recognized and useful information extracted from them. Some success of this kind has been achieved in the lighter nuclei,[13] Ni^{59} and Ni^{61}, where many ns states with similar patterns have been found and correlated with two-particle, one-hole configurations relative to the targets, Ni^{58} and Ni^{60}, used in the respective (d,p) experiments.

In the low-excitation regions of Sr^{89}, assuming an essentially closed $N=50$ core, it is expected that all odd-parity states will have no single-particle components, since the nearest available odd-parity orbit, $1h_{11/2}$, appears to have no components below 5.8-MeV excitation. The odd-parity states should then be a subgroup of the ns states located here. The $\frac{1}{2}-$ and probable $\frac{3}{2}-$ states at $E_x=2.266$ and 2.488 MeV, discussed in Sec. IV B, are two example of this type. For the reason just stated, the positive-parity states with spin greater than $\frac{7}{2}$ also should not be populated by a stripping mechanism and should therefore be found among the nonstripping (d,p) levels.

It is possible to generate many configurations of the two types just discussed as giving rise to ns (d,p) distributions by promoting particles from an assumed closed Sr^{88} core. The ns states in the region of about 1–3 MeV might also be accounted for in a model involving the coupling of a single $d_{5/2}$ neutron to the lowest 2^+ and 3^- collective vibrations of Sr^{88} occurring at 1.835 and 2.74 MeV,[11] respectively. Of the eleven resulting configurations, only seven with $j^\pi=\frac{9}{2}+$, $\frac{1}{2}-$, $\frac{3}{2}-$, $\frac{5}{2}-$, $\frac{7}{2}-$, and $\frac{11}{2}-$ must necessarily appear in the (d,p) reaction as ns transitions, since there are no nearby single-particle states with these spins with which to admix.

From Fig. 5, we see that our data suggest seven ns levels below 3.0 MeV, these being separated from the remaining ns levels at higher excitations by a gap of about 500keV. Two of their spins, $(\frac{1}{2}-)$ for No. 7 and $(\frac{3}{2}-)$ for No. 9, have been assigned tentatively, but until more is known about the rest of this group of states, a conclusive comparison with either model is not possible. One fruitful method for investigating these questions is the study of (p,p) and (p,p') excitation functions on Sr^{88} targets to determine the correlation in the positions of resonances in the $p'(2^+)$ and $p'(3^-)$ channels with the location of analog states of Sr^{89} existing as virtual levels in the Y^{89} system. This would hopefully yield information on spins and parities and on the parentages of the 2^+ and 3^- states to the actual levels of Sr^{89}. Some preliminary work of this kind has already been carried out.[1,14] It has, for example, revealed large resonances in the 3^- transitions at incident energies near those expected to excite the analogs of level Nos. 9, 10, and 12 and numerous resonances in the 2^+ channel corresponding to nearly all the other analogs below $E_x=3.5$ MeV.

As a final remark connected with the nonstripping states, we should like to propose an analysis of the present data which may provide a means of locating the two-particle, one-hole $(2p\text{-}1h)$ configurations (or intermediate structure) relative to the target nucleus Sr^{88}. Bolsterli *et al.*[15] have recently suggested that this can be done by looking at the strength function for the nonstripping transitions obtained from the (d,p) reaction on that target. Since these configurations in Sr^{89} are the next order of complexity after the single-particle states, it might be expected that they will be enhanced in the (d,p) reaction. Just as the single-particle states are fragmented, the $(2p\text{-}1h)$ configurations will be fragmented, and thus, where the level density is high, there should be a clustering of enhanced transitions around the $(2p\text{-}1h)$ positions with typical widths of the order of 100 keV. These have been seen in the $Ni^{58}(d,p)Ni^{59}$, $Ni^{60}(d,p)Ni^{61}$,[5,13] and $Ca^{40}(d,p)Ca^{41}$ [16] reactions and successfully correlated to $(2p\text{-}1h)$ configurations determined from independent sources. Figure 7 shows the results of our attempt to apply the method of Bolsterli *et al.*[15] to the $Sr^{88}(d,p)Sr^{89}$ case. The quantity plotted on the vertical axis is calculated by the formula

$$Id\sigma/d\Omega(E,I)=\sum d\sigma/d\Omega(E',\theta_{\max}),$$
$$E-I<E'\leq E+I.$$

The sum is taken over the ns transitions only, and the quantity $d\sigma/d\Omega(E',\theta_{\max})$ represents the maximum value

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[14] E. R. Cosman, J. M. Joyce, and S. M. Shafroth, Bull. Am. Phys. Soc. 12, 697 (1967).

[15] M. Bolsterli, W. R. Gibbs, A. K. Kerman, and J. E. Young, Phys. Rev. Letters **17**, 878 (1966).

[16] T. A. Belote, Fu Tak Dao, W. E. Dorenbusch, J. Kuperus, and J. Rapaport, Phys. Letters **23**, 480 (1966).

of the cross section for a level with excitation energy E'. We have taken I to be 0.1 MeV, and E, plotted on the horizontal scale, is taken in steps of 0.33 MeV. It is evident from the figure that there are several prominent enhancements at the lower excitations which are outside expected statistical fluctuations. According to Ref. 14, they might then correspond roughly to the locations of ($2p$-$1h$) configurations in Sr^{89}. It should be noted that, although we considered only the nonstripping states, there are two obvious difficulties in sorting them out from the numerous single-partliec fragments. First, there is the inherent admixture of these configurations with single-particle states, and therefore some of the nonstripping strength will be lost because such strength is a relatively small and unaccounted for amplitude in a stripping transition. Second, in many cases, there is no clean division between what could be called stripping or nonstripping, and the classification of the level is in question. Third, there is the fact that stripping transitions are characteristically an order of magnitude more intense than the ns transitions. This means that the smaller group may be obscured at some angles or possibly not seen at all; therefore, it will not be accounted for correctly in the ns strength function. These inaccuracies would manifest themselves as a decrease in amplitude or shift in the energy of the enhancements expected.

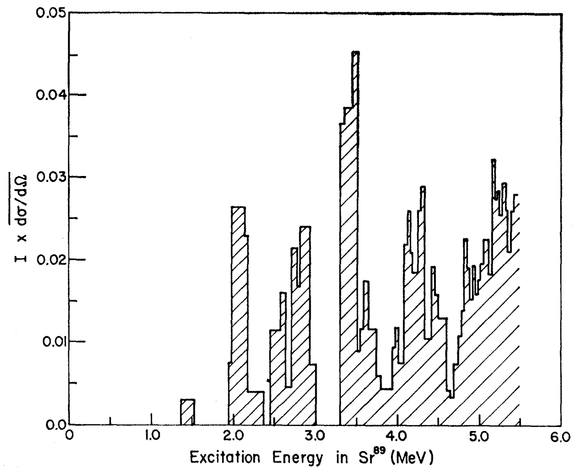

FIG. 7. A strength function determined by averaging the cross sections for the nonstripping transitions determined from the $Sr^{88}(d,p)Sr^{89}$ reaction. An explanation of the graph is given in the text.

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