ABSTRACT

A STUDY OF SEVERAL ODD-ODD s-d SHELL NUCLEI
VIA THE (p,d) REACTION AT 35 MeV

By

James Allen Rice

States in ^{22}Na, ^{34}Cl, ^{36}Cl, and ^{38}K have been studied via the (p,d) reaction at an incident proton energy of 35 MeV. Reaction products were analyzed with the Michigan State University split-pole magnetic spectrograph. The deuteron spectra were recorded both with a single-wire, position-sensitive proportional counter, at a total resolution of $\sim$50 keV, FWHM, and on nuclear emulsion plates, with resolutions of 8-18 keV, FWHM. Levels to 6 MeV of excitation in ^{22}Na, ^{34}Cl, and ^{38}K, and to 8 MeV in ^{36}Cl have been observed and excitation energies assigned to an accuracy of $\leq$1 keV per MeV.

Angular distributions were measured from 3^{o} to 60^{o}, with special emphasis on the region from 3^{o} to 35^{o}. This has allowed a precise definition of the forward angle shapes for ℓ=0 and ℓ=2 single neutron pick-up angular distributions in the s-d shell. A careful screening of deuteron optical-model parameters available from the literature was conducted in an effort to reproduce the experimentally observed

shapes via distorted wave Born approximation calculations. The best overall fits to pure ℓ-transfer distributions for the A>30 nuclei were obtained with standard finite-range, non-locality corrected calculations which include a density-dependent damping of the V_{pn} interaction. A good ℓ=0 fit to the $^{23}Na(p,d)^{22}Na$ data could not be obtained for calculations which also yielded good fits for the A>30 nuclei.

Spectroscopic factors, ℓ-values and parity assignments, and excitation energies from the present work are compared with previous experimental studies and recent shell model calculations. The agreement between the present experimental results and theoretical predictions is good for low-lying levels in the residual nuclei, but observed ℓ=3 angular distributions and spectroscopic factors for higher excited states indicate a need for consideration of 2 (or 4 or 6) particle excitations to the f-p shell in the ground state configurations of the A>30 target nuclei.

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For Linda,
with whom all things are possible.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure

Page

Figure

Page

Figure

Page

I. INTRODUCTION

The nuclear shell-model assumes that a given number of nucleons occupy specified orbitals about an inert "core" much the same as atomic electrons move in orbitals in the electro-magnetic field of the nucleus. These "active" particles are assumed to be responsible for most observable properties of the nucleus. Indeed, spins, parities, and magnetic moments of many nuclei may be predicted solely on the basis of the number and kind of nucleons which occupy the last, or highest energy, subshell consistent with a systematic stacking of nucleons in the lowest unfilled orbitals.

A detailed theoretical description of the nucleus is assumed to be obtainable in terms of a Hamiltonian characterized by a sum of one and two-body matrix elements, which result from interactions of individual nucleons with the core and a two-body interaction between pairs of active nucleons, respectively.

Nuclei with mass numbers between 17 and 40 are members of the s-d shell, i.e., the last nucleons occupy the $1d_{5/2}$, $2s_{1/2}$, or $1d_{3/2}$ orbitals in the simplest picture. Shell-model calculations for these nuclei have shown considerable advancement in the last decade. Early works considered couplings only in the highest occupied orbit, with all other subshells comprising the core. Considerations of this sort led to predictions for only a small number of low-lying excited states. Calculations allowing two-orbital excitations

showed better agreement with available experimental data on spin, parity, and energy assignments for low-lying levels. Sophisticated computer codes and calculational techniques have allowed recent theoretical studies in which the basis states have been expanded to include the entire s-d shell. Both empirical and least-squares adjusted single particle energy parameterizations have been used for the one-body matrix elements, while theoretical and empirical two-body interactions have been studied. In general, the recent results show good correspondence with the data, particularly for those nuclei with either odd-even or even-even combinations of protons and neutrons. Calculated spectra for the odd-odd nuclei, however, are often in even qualitative disagreement with experimental results. The structure of these nuclei appears to be most sensitive to the details of the nuclear Hamiltonian and, therefore, any descriptive theory for the s-d shell would be severely tested in its attempt to reproduce sound experimental data for the odd-odd systems.

A critical comparison of recent Hamiltonians most certainly relies on accurately observed properties of the odd-odd s-d shell nuclei. Excitation energies, spins and parities of nuclear energy levels and spectroscopic factors for single-nucleon transfer may be observed via direct reaction nuclear spectroscopy. Direct reactions take place in a time interval comparable to the time necessary for the projectile to traverse the target nucleus ($\sim 10^{-23}$ seconds)

and therefore, do not "see" collective effects in the target nucleus and are assumed to involve only one-step processes, i.e., the target nucleus is not excited above a ground state configuration before any particle transfer occurs. Those in which the incident projectile absorbs a nucleon from the target nucleus (pick-up) or deposits a nucleon in the target nucleus (stripping) are called single nucleon transfer reactions. The target nucleus, therefore, undergoes a change in mass number (A) of ± 1 and the resulting residual nucleus may be left in any of its energetically and quantum mechanically allowed energy levels. In reality, any nuclear state may be described as a sum of weighted components, each corresponding to the probability that given shell model orbitals are populated by specified numbers of nucleons in particular angular momentum couplings. The spectroscopic factors observed in transfer reaction experiments are a measure of the overlap, a quantum mechanical correspondence, of initial and final state configurations. When only one nucleon is transferred, therefore, one expects to probe specific shell-model wave function components for the initial and final nuclear states.

The choice of an appropriate reaction for nuclear spectroscopy studies depends on the available projectiles, targets, and detection and analysis apparatus. The Michigan State University cyclotron provides high resolution proton beams with currents sufficient to allow experimental runs of

reasonable brevity. Several of the odd-odd s-d shell nuclei which can be reached through single-neutron pick-up from stable targets are ^{22}Na, ^{34}Cl, ^{36}Cl, and ^{38}K. Natural ^{23}Na and ^{39}K metals and isotopically enriched ^{23}Na-^{35}Cl, ^{7}Li-^{35}Cl, and ^{23}Na-^{37}Cl compounds are commerically available. All are easily evaporated at moderate temperatures and thin targets may be routinely produced. The properties of the MSU cyclotron and split-pole magnetic spectrograph allow charged reaction product groups of closely similar energy to be clearly separated, detected and analyzed. The structures of ^{22}Na, ^{34}Cl, ^{36}Cl, and ^{38}K are, therefore, subject to study via the (p,d) reaction.

Precise excitation energies for these four nuclei have previously been assigned only to those states below the 3-4 MeV region. Any extension of the experimental understanding of these nuclei naturally includes a precise determination of higher lying energies. Accurate extraction peak centroids is allowed by the high particle group resolution (8-10 keV, FWHM) obtained on nuclear emulsion plates in the present work. A comprehensive spectrograph calibration scheme and least-squares fitting procedures have made possible the assignment of excitation energies in the residual nuclei to accuracies of $\lesssim$1 keV/MeV of excitation. This represents a significant improvement over previous charged particle studies, allowing a more critical comparison with calculated spectra and the rationalization of the results

of different kinds of experiments. The spectrum analysis for these studies was performed with the computer code MONSTER2 (see APPENDIX A) on the MSU Sigma-7 computer.

In the direct reaction process, one may attempt to picture the nucleus as a sum of several spherically-symmetric potentials. This approximation is the basis of the Distorted Wave Born Approximation (DWBA) predictions with which the present data are compared. Parities of energy levels in the residual nuclei, orbital angular momenta of the neutrons transferred in (p,d) reactions and spectroscopic factors may be assigned on the basis of such comparisons of individual experimental angular distributions with DWBA predicted distributions calculated for given neutron quantum numbers and appropriate final-state excitation energies. Shape comparisons yield the transferred neutron orbital angular moemtnum quantum numbers (ℓ) and, hence, the parities of the residual states ($\pi_{residual}=\pi_{target}\pi_{neutron}$ with $\pi_{neutron}=(-1)^{\ell}$). Magnitude comparisons indicate relative strengths for the ℓ-values involved in a given transition; hence, a measure of wave-function component amplitudes. Previous single neutron pick-up experiments ((p,d), (d,t), (^{3}He,α)) observed angular distributions which generally did not include angles smaller than 10°-15°. The present work measures distributions in to 3°, providing a critical test of the forward angle DWBA shapes. The use of different currently popular proton optical model

parameters had little effect on the calculated (p,d) distributions. However, the DWBA-predicted differential cross-section shapes were found to be noticeably dependent on the choice of deuteron parameters. The experimentally observed shapes for pure ℓ=0 and ℓ=2 transfers in the A>30 nuclei were best reproduced when the interaction responsible for the reaction, V_{pn}, was damped by a simulated nuclear matter density dependence, and a broadly based set of optical-model potentials was used to describe the outgoing deuteron. The empirical Q-dependence of the $^{23}Na(p,d)^{22}Na$ shapes has not been successfully reproduced, particularly those for ℓ=0 neutron transfers. All of the DWBA calculations were performed with the computer code DWUCK using standard Q-dependence techniques.

The results of the present experiments are presented in three autonomous sections, one for the combined $^{23}Na(p,d)^{22}Na$ and $^{35}Cl(p,d)^{34}Cl$ works, and one each for $^{37}Cl(p,d)^{36}Cl$ and $^{39}K(p,d)^{38}K$. Each section includes a summary of pertinent previous experimental and theoretical studies, and the experimental and analytical techniques employed for the particular work under consideration. Theoretical implications of the present energy level, parity and single neutron pick-up spectroscopic factor assignments are discussed in conjunction with recently utilized shell-model Hamiltonians.

II. THE $^{23}Na(p,d)^{22}Na$ AND $^{35}Cl(p,d)^{34}Cl$ REACTIONS

II.1. Introductory Remarks

Recent shell-model analyses[1-4] of the nuclei in the regions A=18-24 and A=30-38 indicate that the nuclei whose structures depend most sensitively upon details of the model Hamiltonian are those which have odd numbers of both neutrons and protons. While the general features of the spectra of doubly-even and even-odd nuclei emerge more or less satisfactorily from such shell-model calculations, the calculated spectra of the doubly-odd nuclei are often even in qualitative disagreement with the observed level sequences. It thus appears that the definitive test of microscopic many-body theories of the spectroscopy of light-medium nuclei will come in the attempt to explain the rich store of details observed in the experimental study of these particular nuclei.

The nuclei ^{22}Na and ^{34}Cl are pivotal to understanding the structure of the s-d shell. In an s-d shell-model their wave functions are constructed of 6 particles and 6 holes, respectively. This number of active nucleons is large enough to allow the full consequences of the particularities of the two-particle component of the nuclear Hamiltonian to become manifest. At the same time, the dimensionalities of the model states are such that extensive theoretical work, in which the full s-d shell-model space is employed to describe the wave functions of these nuclei, is available. This

latter point is important because it allows the exclusion of the possibility that the theoretical results might be contaminated by effects arising from intra-shell basis truncation.

Shell-model calculations made with Hamiltonians of the Kuo-Brown[5] type or with two-body matrix elements derived from simple central potentials fail to reproduce many simple aspects of the ^{22}Na and ^{34}Cl energy level spectra, such as, for example, the spins of the ground states.[1,2] Hamiltonians derived in less straightforward fashion have been used to achieve some improvement in the agreement between theory and experiment, but it seems fair to say that a full understanding of these systems has not yet been achieved. The aim of the present experiment, part of a systematic study of doubly-odd nuclei in the s-d shell,[6-8] is to provide definitive experimental information on some aspects of ^{22}Na and ^{34}Cl so that a more rigorous critique of present and future structure calculations is possible. The hope is that a clarification of the structure of the A=22 and A=34 systems will facilitate progress in understanding the behavior of the nuclei in the middle of the s-d shell, A=24-32, where the correct details of the effective two-body nuclear interaction are essential.

We present in this report the results of a study of the (p,d) reaction on ^{23}Na and ^{35}Cl at 35 MeV. The principle results obtained relate to excitation energies and angular distributions of states in ^{22}Na and ^{34}Cl, and the ℓ-values and associated spectroscopic factors of the neutrons picked up

in the formation of these levels. There is considerable experimental knowledge[9-14] of the levels of ^{22}Na and a rapidly growing body of data[15-23] on ^{34}Cl. Work relevant to the characteristics of the T=1 states of these nuclei has also been done with the nuclei ^{22}Ne[24,25] and ^{34}S.[26,27] Since an extensive particle-transfer study with good energy resolution is available[10] for ^{22}Na, a large amount of fundamentally new information was not expected to emerge from our ^{23}Na(p,d)^{22}Na data. Rather, we aimed to obtain more precise experimental excitation energies for higher lying states, an alternate set of spectroscopic factors to complement those from the (^{3}He,^{4}He) reaction, and, with the aid of the higher energy resolution of the present work, a clarification of a few (but important) questions concerning the low-lying states.

Our results for ^{34}Cl make a considerably more significant contribution to the state of knowledge about this nucleus. We are able to resolve many more states than has been possible in previous experiments[22] and, even for easily resolved states, our extensive angular distributions provide evidence for reversing some previous ℓ-value assignments. These ℓ-values and their associated spectroscopic factors, and the precise excitation-energy assignment made in the 3-5 MeV region of excitation, serve to advance our experimental comprehension of the mass 34 system to a condition almost comparable with that of A=22.

The present data are of interest from a reaction theory standpoint also, in that the angular range, energy resolution, statistical accuracy, and large number of transitions combine to provide stringent criteria for evaluating the usefulness of ordinary DWBA calculations for the (p,d) reaction at these energies for medium-light nuclei. The value of this aspect of the present study is enhanced by the concurrent analyses of (p,d) data[6,8] on neighboring nuclei.

II.2. Experimental Procedures and Results

The present experiments were performed with the MSU Cyclotron[28] and Enge-type[29] split-pole magnetic spectrograph. The beam energies for the various experimental periods ranged from 34.9 to 35.0 MeV, and beam currents on target ranged between 300 and 800 nanoamps. The beam on target had a coherent energy spread of about 20 keV, but by using dispersion matching[30] in the spectrograph in conjunction with the techniques discussed by Blosser, et al.,[31] resolutions of better than 8 keV (FWHM) were obtained for 20-25 MeV deuterons at the focal plane under optimum conditions.

Particle detection at the focal plane was accomplished either with nuclear emulsions or with a position-sensitive wire proportional counter.[32] The latter type of data, limited to a resolution of about 50 keV by the characteristics of

the counter, was used to supplement and confirm the results obtained by scanning the nuclear emulsions.

Three different types of targets were used in the present experiment in order to circumvent the difficulty of obtaining a clean Cl target. Targets of LiCl (^{35}Cl enrichment $\geq$99%) were used to obtain spectra free from sharp states which would arise from other chlorine compound contaminants. However, the continuous background resulting from the (p,d) reaction on the Li isotopes lowered the quality of these spectra and made it difficult to obtain accurate cross-sections for weak transitions. Sodium chloride targets (^{35}Cl enrichment $\geq$99%) provided data on Cl transitions which nicely complement those from the LiCl targets. Finally, in order to remove ambiguities resulting from overlaps of peaks from Na and Cl levels, a target of Na metal was bombarded. All of these targets were fabricated by vacuum evaporation onto thin carbon foils.

Figure 1 displays spectra, measured at 14^{o} with nuclear emulsions, which result from bombardment of the three types of targets used. These targets were of moderate thickness and the combined spectrograph-cyclotron energy resolution was not fully optimized, resulting in peak widths at half-maximum intensity of 15-20 keV. Representative particle groups in Fig. 1 are labeled as to energy of excitation. Figure 2 displays a spectrum measured at 8^{o}, with a NaCl target, for

which the energy resolution for deuterons at the focal plane was at the best level obtained in this set of experiments.

The excitation energies measured for levels of ^{22}Na and ^{34}Cl in the present experiment are used to label the peaks in Fig. 2 and are presented in Tables 1 and 2. These energies are obtained primarily from spectra measured at 8°, 11°, and 16° with a resolution of ∿8 keV, FWHM. In the case of many weakly excited levels, these data were supplemented by the data from the thicker targets of all three compositions. The energies were assigned as follows. The nuclear emulsion plates were scanned with a computer-linked microscope system[33] in which a 25-cm-long precision screw served to position the plate under the microscope objective. A stepping motor on the screw served to increment both the plate position and a position signal which was read into the computer whenever a contact was activated to signal the observation of a track. In this way, the track-density spectra were generated with high accuracy and reliability as regards both peak positions and intensities. The dominant peaks in the spectra were then tentatively assigned to known levels in ^{22}Na, ^{34}Cl, ^{11}C, ^{15}O, ^{12}C, ^{35}Cl, and ^{23}Na for which accurate ($\leq$1 keV uncertainty) excitation energies exist. All of these residual nuclei were formed from the (p,d) and (p,p) reactions on ^{35}Cl, ^{23}Na, and on the ^{12}C and ^{16}O contaminants in the targets. The momenta of the deuteron and proton groups corresponding to

Figure 1. Complementary spectra from the (p,d) reaction on the ^{23}Na, ^{23}Na-^{35}Cl and Li-^{35}Cl targets, measured at 35 MeV and 14°, as recorded on nuclear emulsion plates. The resolution of the deuteron groups is 15-20 keV, FWHM. Selected peaks are labeled with excitation energy assignments from the present work, the "boxed" values indicating levels in ^{34}Cl.

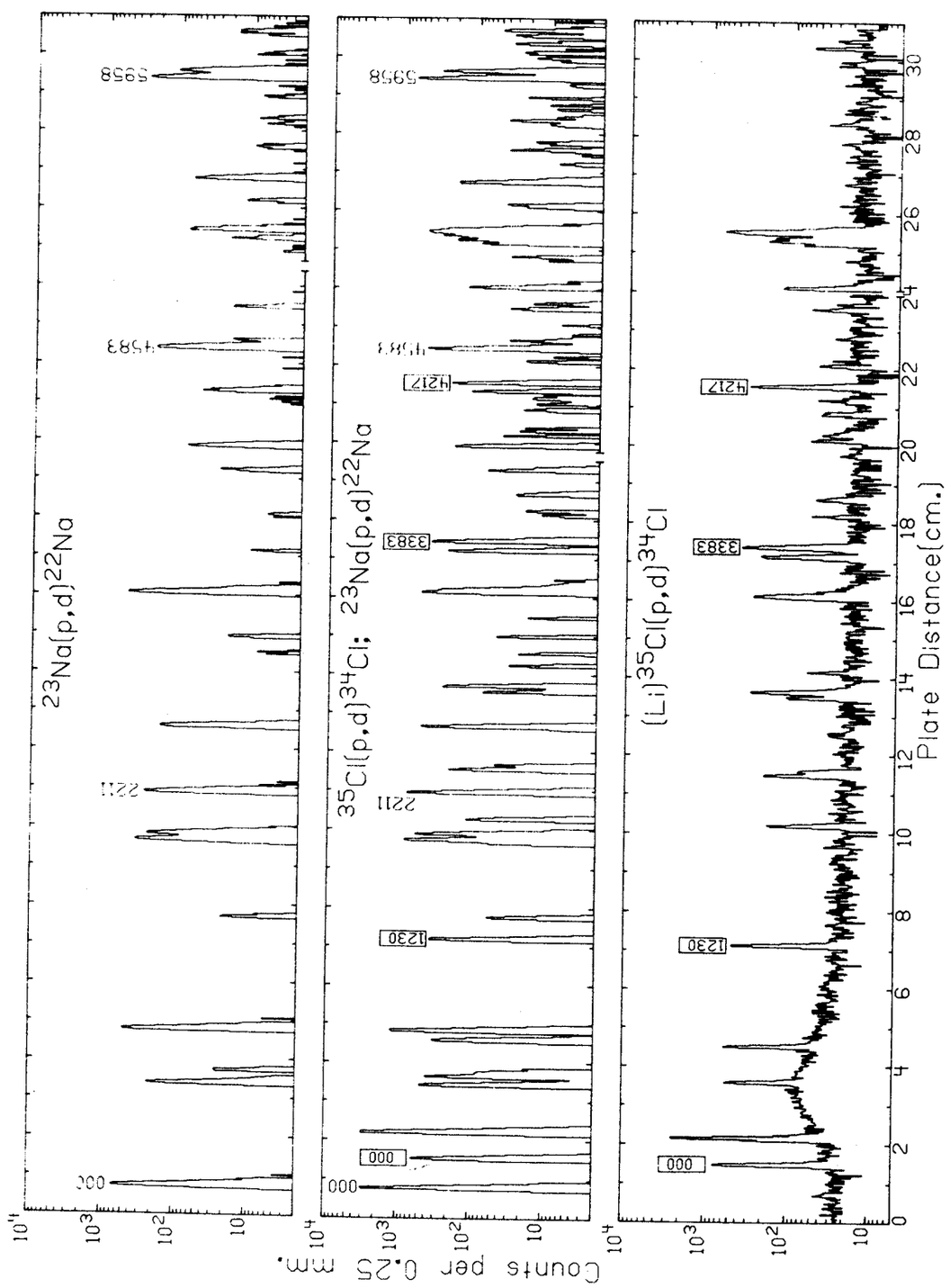
^{23}Na(p,d)^{22}Na
^{35}Cl(p,d)^{34}Cl; ^{23}Na(p,d)^{22}Na
(Li)^{35}Cl(p,d)^{34}Cl
000
2211
1230
3383
4217
4583
5958
Counts per 0.25 mm.
Plate Distance(cm.)

Figure 1

Figure 2. A spectrum from the (p,d) reaction on the ^{23}Na-^{35}Cl target, measured at 35 MeV and 8°, as recorded on nuclear emulsion plates. The resolution of the deuteron groups is 8 keV, FWHM. All excitation energy values are from the present work, with those "boxed" indicating levels in ^{34}Cl.

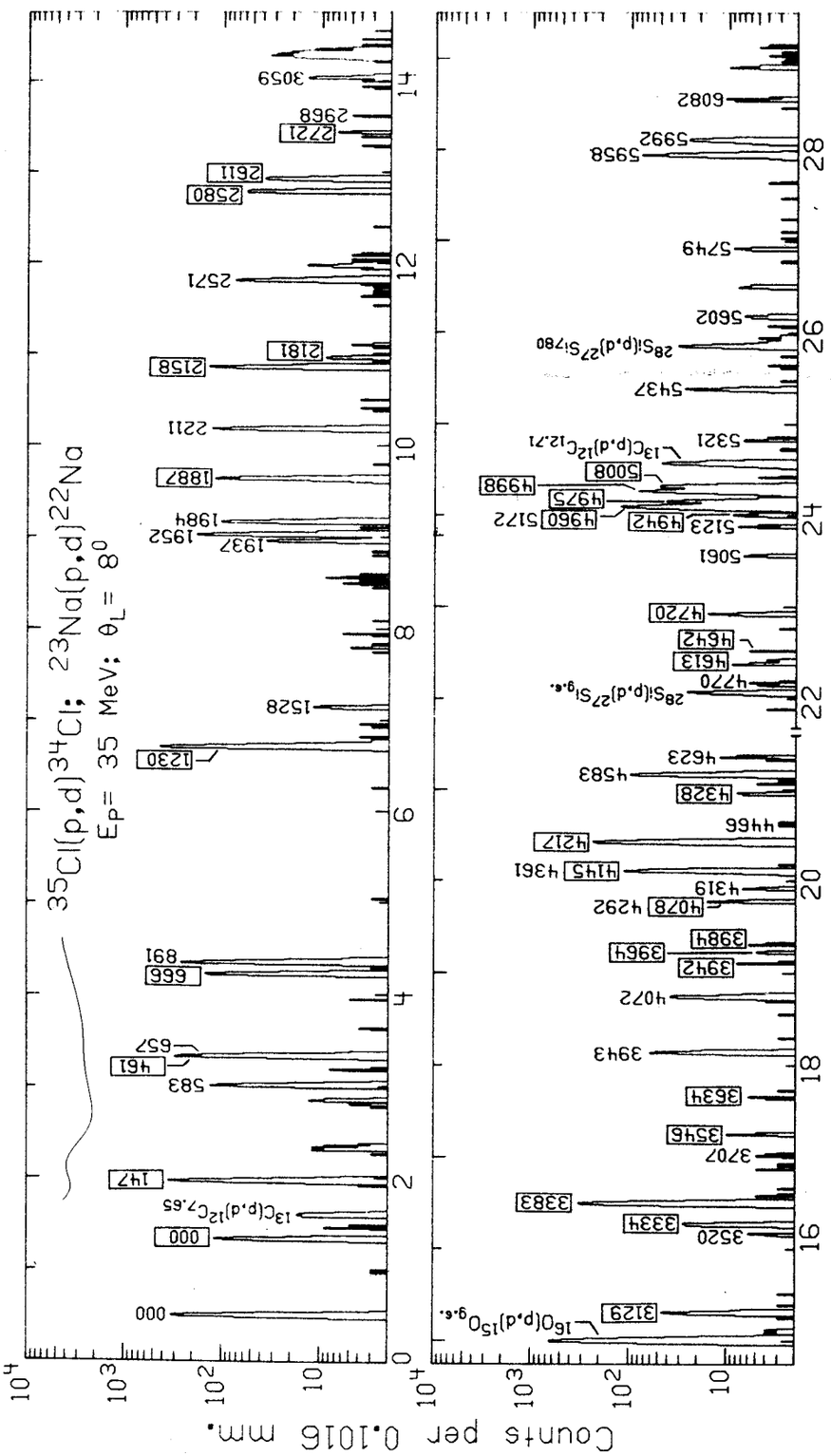
$^{35}Cl(p,d)^{34}Cl$; $^{23}Na(p,d)^{22}Na$
E_P= 35 MeV; θ_L= 8°
000
$^{13}C(p,d)^{12}C_{7.65}$
147
000
666
891
583
461
657
1230
1528
1937
1952
1984
1887
2211
2158
2181
2571
2580
2611
2721
2968
3059
$^{16}O(p,d)^{15}O_{g.s.}$
3129
3520
3334
3383
3707
3546
3634
3943
4072
3942
3984
3964
4078
4292
4319
4145
4361
4466
4217
4328
4583
4623
$^{28}Si(p,d)^{27}Si_{g.s.}$
4770
4613
4642
4720
5061
5123
4942
4960
5172
4975
4998
5008
$^{13}C(p,d)^{12}C_{12.71}$
5321
5437
$^{28}Si(p,d)^{27}Si_{780}$
5602
5749
5958
5992
6082
Counts per 0.1016 mm.
Plate Distance(cm.)

Figure 2

population of these states were then calculated from the nominal settings and operating parameters of the cyclotron (beam energy) and spectrograph (scattering angle, magnetic field strength, position of emulsion plates, and non-linear corrections to the focal plane position vs. radius of curvature line) and from the nominal Q-values for the reactions. When the total spectrum spanned two emulsion plates the gap between the plates was also specified.

At this point all, or any desired subset, of the above parameters were adjusted so as to produce a least-squares fit between the set of precision energies used as input and the energies calculated to correspond to the measured peak positions. The changes in the nominal parameter values which occur when an adequately large data set is used as input are well within the experimental uncertainties associated with the various parameters. For example, typical beam energy changes are $\lesssim$10 keV out of 35 MeV, angle changes are $\leq 0.1^{o}$, and plate-gap changes are 0.0 to 0.1 mm. The appropriate final calculated excitation energies agree with the input values to ± 1 keV on the average. As input, we used essentially all level energies in ^{22}Na and ^{34}Cl below 3 MeV excitation,[9,15,18,34] the ground[34] and first excited states[67,89] of ^{11}C and ^{12}C, the ground states[34] of ^{15}O and ^{16}O, and the ground[34] and first two excited states[68,97] of ^{23}Na and ^{35}Cl.

We found that a statistically significant better fit to the input energies could be obtained if the $^{35}Cl(p,d)^{34}Cl$ Q-value was changed from its nominal value[34] of -10.422 MeV to -10.420 MeV and the $^{23}Na(p,d)^{22}Na$ Q-value was changed from -10.193 MeV to -10.195 MeV. These changes are not inconsistent with the assigned uncertainties of the nominal Q-values,[34] and at any rate, the excitation energy assignments depend only slightly upon whether the nominal or the adjusted Q-values are used. The levels whose excitation energies are of primary interest fall in the middle 15 cm of the 50 cm (two adjacent 25 cm plates) of exposed emulsion. The 15 cm on either side of this region are thus simultaneously calibrated to many precisely known energies and this calibration is interpolated into the middle region, where it is confirmed by one or two additional known states.

The uncertainties we assign to the excitation energies listed in Tables 1 and 2 are consistent with the scatter obtained both in analyzing the same data with different variants of the analysis procedure described above and in analyzing data taken at different angles with the same procedural details. The uncertainties are compounded from jitter in the measured peak positions, irregularities in the detailed magnetic field and focal plane structure, and inaccuracies and incompleteness in the set of input energies.

The angular distributions we present for the $^{23}Na(p,d)^{22}Na$ and $^{35}Cl(p,d)^{34}Cl$ reactions were compounded from all of the

Table 1. Excitation energies, ℓ-values, J^π and T values, and pick-up spectroscopic factors for states of ^{22}Na. All C^2S values extracted from the present data have been normalized to yield 0.59 for the ground state.

Ex (keV)		J^π,T	$\ell(^{23}Na+^{22}Na)$		$100 \times C^2S(\ell), C^2S(\ell+2)--(^{23}Na+^{22}Na)$		
000[a]	000[b,c,d]	3^+,0[b,c,f]	2[a]	2[c]	,59[a]	,59[g]	,59[c]
583±1	583	1^+,0	0,2	2	2,19	1,22	,24
657±1	657	0^+,1	2	2	,2	, 1	,<7
891±1	891	4^+,0	2	2	,47	,58	,57
1528±1	1528	5^+,0					
1937±1	1937	1^+,0	0		3,	3, 3	
1952±1	1952	2^+,1	2	2	,41	7,49	,57
1984±1	1983	3^+,0	2	2	,26	,37	,29
2211±1	2211	1^-,0	1	1	27,		27,
2571±1	2572	2^-,0	1	1	20,		21,
2968±2	2969	3^+,0	(2)	(2)	, 1	,13	,<2
3059±1	3059	2^+,0	2	2	, 3	0, 3	, 3
3520±1	3521	3^-,0	(3)		,(2)		
3707±2	3708	6^+,0					
3943±2	3944	1^+,0	0,2	0	1, 3	2, 0	3,
4072±2	4069	4^+,1	2	2	,12	14,14	,17
4292±3	4294	,0					
4319±3	4319	1^+,0	0,2		<1, 1	1, 0	
4361±2	4360	2^+,0	0,2	0,2	1, 5	4, 3	2, 2
4466±3	4466	(4^-),0					
4525±4	4522	(7^+),0					
4583±2	4583	2^-,0	1	1	40,		34,
4623±2	4622	,0					
	4708	(5^+) 0					
4770±2	4770	$0-4^+$ 0		(2)			, 9
5061±4	5061	$1-2^+$,		0,2			1, 2
5096±4	5099						
5123±3	5117						
5172±3	5165	$(2)^+$,1	0,2	0,2	2,18	, 9	7,15
5321±3	5317						
5437±3	5440	-,	1	1	11,		8,
5602±3	5605	+,		0,2			1, 2
5719±4 / 5749±4	5740						
5826±6	5830			n.s.			
5861±5	5858			0,2			<1, 2
	5938						
5958±4	5953	,1	1	1	50,		58,
5992±4	5995		2	2	,15		,13
6082±4	6088						

[a] Present work.
[b] Reference 9.
[c] Reference 10.
[d] Reference 11.
[e] Reference 13.
[f] Reference 12.
[g] Reference 4.

Table 2. Excitation energies, ℓ values, J^π and T values, and pick-up spectroscopic factors for states of ^{34}Cl. All C^2S values extracted from the present data are normalized such that C^2S=0.35 for the ground state.

Ex (keV)			J^π,T	ℓ		100 x $C^2S(\ell)$,$C^2S(\ell+2)$--(^{35}Cl→^{34}Cl)			
000[a]	000[b,c,d]	e	0^+,1[b,c,d]	2[a]	2[d]	, 35[a]	,43[f]	, 31[g]	, 45[h]
147±1	146		3^+,0	2	2	,105		,106	,120
461±1	461		1^+,0	0,2	0,(2)	11, 23		18, 15	0, 28
666±1	666		1^+,0	0,2	2,(0)	4, 28		1, 32	16, 0
1230±1	1230		2^+,0	0,2	0	23, 20		18, 9	50, 0
1887±1	1888		2^+,0	0,2	(0)	5, 11		2, 14	16, 0
2158±1	2159	2127	2^+,1	0,2	2	8, 11	12,	5, 11	32, 0
2181±1	2181		2,3^+,0	2		, 4		, 0	assume J=2
2377±3	2377		4^+,0	(2)		, 3		, 0	
2580±1	2579		1^+,0	0,2	(0)	5, 5		0, 4	
2611±1	2611		,0	2	(2)	, 25		0, 42	assume J=4
2721±2	2722		2^-,0	3	3	, 3			
3129±2	3126		1^+,0	0,2	2	1, 20		4, 6	
3334±2	3332		,0	2	(2)	, 25		, 34	assume J=3
3383±2	3381	3303	2^+,1	0,2	2	26, 25	35,	25, 12	75, 0
3546±2	3545		3^-,0		1				
3602±3	3601		4(-),0						
3634±3	3632		5^-,0		3				
	3771		1^-,0		(1)				
3865±5									
3942±4	394(0)	3914	0^+,1					, 1	
3964±4									
3984±4	3982		3^-,0		3				
4078±4	4075		4^-,0		3				
4145±4	4140		2^-,0		1,3				
4217±2		{ 4072	1^+,1					{ 17, 4	
4328±4		{ 4115	2^+,1	0,2		16,20	30,	{ 0, 18	30,0
	4352		(1)-,0		1				
	4416		(1-3)-,0		1				
4465±5	4460		(2,3)-,0		1				
	4514		(2)-,0		1				
4613±4	4605		(1-3)-,0		1				
4642±5	4636	4622	(1-3)-,1		1				
4720±5	4720	4687	4^+,1	2		, 21	,21	, 5	
4860±6		(4875)	(3+)						
4942±5		(4891)	(2+)						
4960±5									
4975±5	497(0)	5227	0^+,1				,40		
4998±3									
5008±3		5318							0,170
5560±6		5380							

[a] Present Work.

[b] Reference 15.

[c] Reference 16.

[d] Reference 17.

[e] Energies for states in ^{34}S; References 26,27.

[f] Spectroscopic factors for $^{35}Cl(d,^3He)^{34}S$; Reference 25.

[g] Reference 2.

[h] Reference 22.

data accumulated from the different targets and with the different detection mechanisms. Of course, when lack of resolution prevented unambiguous values from being obtained in particular cases, such data were rejected. Also, in some cases the track density of strongly excited levels was too high to permit accurate counting by the scanners, so that counter data alone was relied upon. The angular distributions for states in ^{22}Na are shown in Figs. 3, 4, and 5 and those for levels in ^{34}Cl in Figs. 6 and 7. Not all states listed in Tables 1 and 2 could be observed at enough angles to permit measurement of meaningful angular distributions. These states were at best weakly populated and are not included in Figs. 3-7.

The cross-section scales in Figs. 3-7 were assigned by comparing the (p,d) differential cross-sections as measured with the wire proportional counter to the (p,p) elastic differential scattering cross-sections in the vincity of the maximum in the 30°-50° region. The counting rates for the elastic scattering were manageable for the counter in this region and the Na and Cl peaks could be resolved clearly. The elastic scattering distributions were normalized to the predictions obtained from the Becchetti-Greenlees optical model potential formula[37] (see APPENDIX B). The experimental angular distributions for ^{23}Na and ^{35}Cl in this region are rather dissimilar and both were simultaneously well fit with the Becchetti-Greenlees predictions. We estimate a 10% uncertainty for the

accuracy of the optical model cross-sections in this region, and estimate a 10% probable error for the mechanics of relating the experimental (p,d) yields to the (p,p) yields. Thus, the combined total uncertainty in the overall cross-section normalization of our angular distributions is estimated to be in the range of 15%.

The relative uncertainties from distribution to distribution should be less than 2%. The chemical stability of sodium chloride appears to be maintained under evaporation and bombardment, so the relative Na to Cl cross-sections should also be good to 2%.

II.3. Analysis of the Angular Distributions

The angular distributions displayed in Figs. 3-7 were analyzed with the distorted-wave Born approximation (DWBA)[38] to obtain ℓ-values for the neutrons transferred in the (p,d) pick-up process and the associated strengths, or spectroscopic factors. This analysis was carried out by least-squares fitting a combination of ℓ=0 and ℓ=2 (or ℓ=1 and ℓ=3) curves, predicted for a transition of given Q-value, to the 3^{o}-35^{o} experimental data for each state. The solid curves in Figs. 3-7 show the combined-ℓ theoretical distribution fits from which the spectroscopic factors were obtained. The dotted curves indicate the contribution of the smaller ℓ-value pattern to the combined (solid line) distribution curves.

Figure 3. Experimental angular distributions for states in ^{22}Na as observed in the ^{23}Na(p,d)^{22}Na reaction at 35 MeV. The solid curves are fits of the DFRNL calculations to the data in the angular range from 3° to 35°. The dotted curves show the contribution of the first indicated ℓ-value for mixed-ℓ distributions.

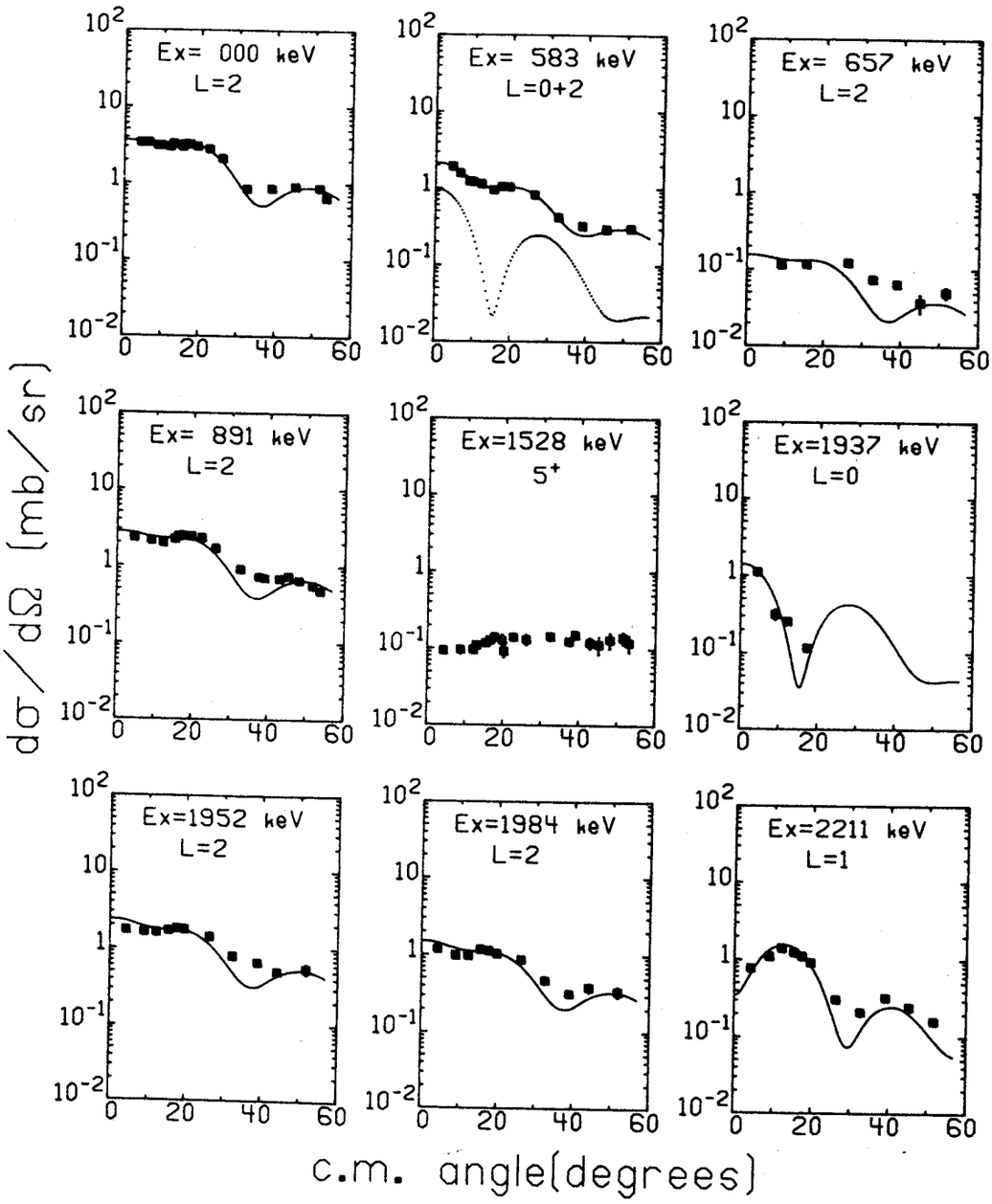
Ex= 000 keV
L=2
Ex= 583 keV
L=0+2
Ex= 657 keV
L=2
Ex= 891 keV
L=2
Ex=1528 keV
5+
Ex=1937 keV
L=0
Ex=1952 keV
L=2
Ex=1984 keV
L=2
Ex=2211 keV
L=1
dσ/dΩ (mb/sr)
c.m. angle(degrees)

Figure 3

Figure 4. Experimental angular distributions for states in ^{22}Na as observed in the ^{23}Na(p,d)^{22}Na reaction at 35 MeV. The solid curves are fits of the DFRNL calculations to the data in the angular range from 3° to 35°. The dotted curves show the contribution of the first indicated ℓ-value for mixed-ℓ distributions.

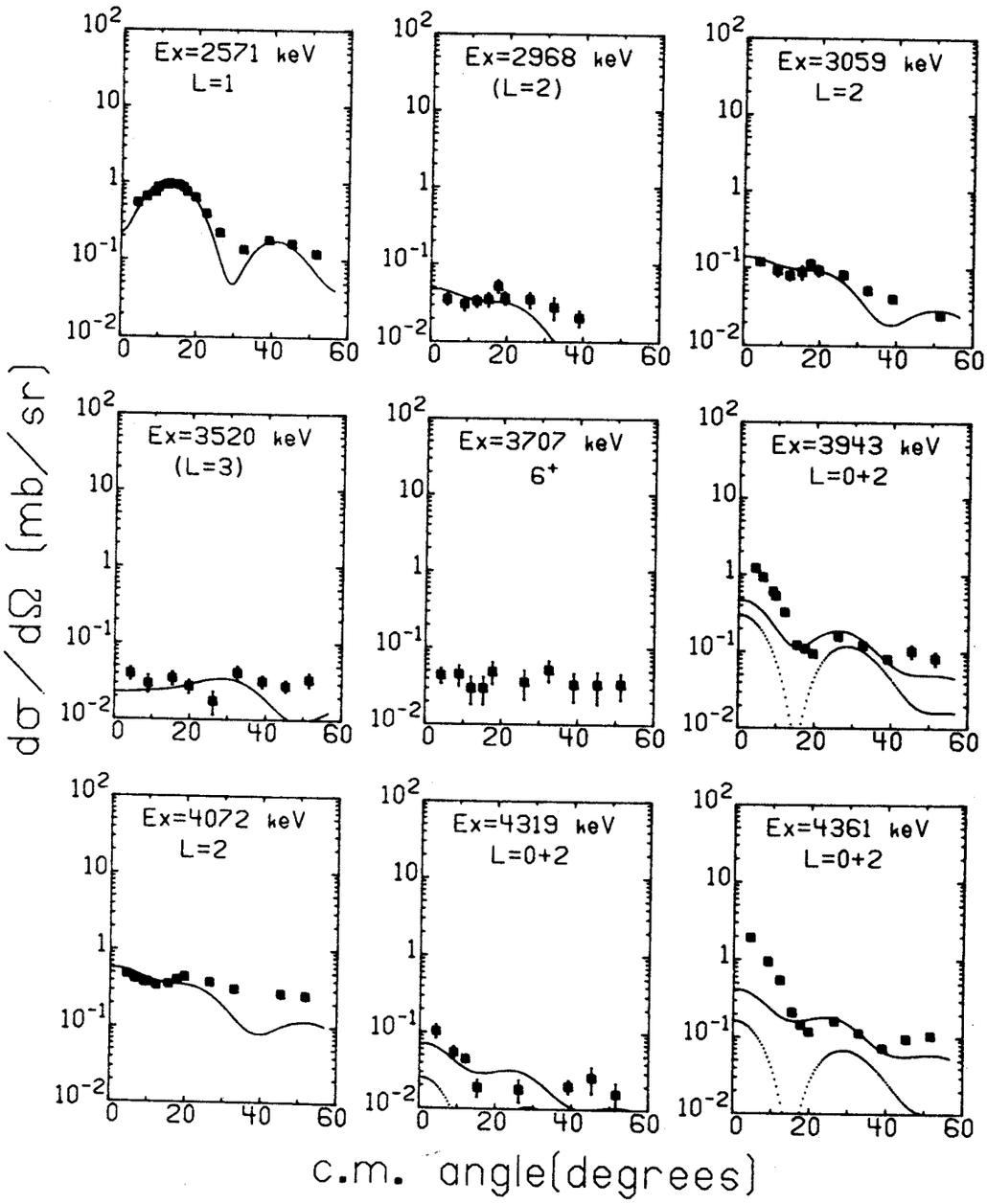
Ex=2571 keV
L=1
Ex=2968 keV
(L=2)
Ex=3059 keV
L=2
Ex=3520 keV
(L=3)
Ex=3707 keV
6+
Ex=3943 keV
L=0+2
Ex=4072 keV
L=2
Ex=4319 keV
L=0+2
Ex=4361 keV
L=0+2
dσ/dΩ (mb/sr)
c.m. angle(degrees)

Figure 4