ANGULAR DISTRIBUTIONS OF ^{40}Ca (d, p) ^{41}Ca AT 2 MeV BOMBARDING ENERGY

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RESUMEN

En el presente trabajo se estudia la reacción ^{40}*Ca (d, p)* ^{41}*Ca para una energía de bombardeo a 2 MeV. Esto permite analizar la reacción para la región de despojo coulombiano. Se realizó un bombardeo de 4000 μ coul. con el acelerador Dinamitrón de 3 MeV del Instituto de Física, sobre blancos de calcio metálico. El análisis espectroscópico se realizó con un espectrógrafo magnético multiseccional. Se midió la distribución angular en los siguientes niveles: 0, 1, 3, 4 y 5, 6, 10, 11 y 12, 16 y 17, 18 y 19, 20, 21, según nomenclatura de la ref. (1).*

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Se presenta un análisis DWBA usando el código Julie para los niveles 0, 1, 3, 21, comparando los resultados obtenidos con los de trabajos realizados anteriormente para la misma reacción (1)(2)(3). Se dedujeron los factores espectroscópicos de estos niveles, encontrándose acuerdo aceptable con resultados anteriores excepto para el estado base en el cual la discrepancia es del orden del 100%, esta discrepancia se puede atribuir a efectos de resonancia para E_d = 2.0 MeV (3). Finalmente se encuentra distribución angular típica de despojo coulombiano para el nivel 21 y se observa la tendencia a mostrar el máximo de la sección para ángulos hacia atrás conforme el valor Q disminuye.

ABSTRACT

The $^{40}Ca(d,p)^{41}Ca$ reaction has been studied at 2 MeV bombarding energy, in order to analyze this reaction within the Coulomb stripping region. A 4000 μ Coul exposure of metallic calcium targets was performed with the Instituto de Física Dynamitron Accelerator and was analyzed using a multigap magnetic spectograph. Angular distributions of the following levels in ^{41}Ca (ref. 1) were studied: 0, 1, 3, 4 and 5, 6, 10, 11 and 12, 16 and 17, 18 and 19, 20, 21. A DWBA calculation was carried out for levels 0, 1, 3 and 21, and the results were compared to previous work on the same reactions (ref. 1, 2, 3). Spectroscopic factors calculated agree reasonably with earlier work, except for the ground state, where the discrepancy of the order of 100% may be attributed to resonance effects at 2 MeV (ref. 3). Level 21 shows a typical Coulomb stripping pattern, and other distributions show the tendency toward large-angle maximum as the Q-value decreases.

I. INTRODUCTION

The $^{40}Ca\,(d,p)\,^{41}Ca$ reaction has been amply studied at bombarding energies above the Coulomb barrier, which is in this case about 4.3 MeV. There is a study at 7 MeV (1) which is used as basis for the present work. There is also another report at 1.9 and 2.0 MeV deuteron energy (2), but only angular distributions for the ground, first and second excited states were studied. The excitation function for the ground state between 1.5 and 4.3 MeV is also known (3).

Recently the problems of Coulomb stripping has been the object of theoretical consideration (4), and some experiments (5, 6, 7) have been carried out in order to investigate the usefulness of this method to obtain spectroscopic information in nuclei.

Calculations of the stripping amplitude have been made using different modifications to existing DWBA programs. All these use different methods of approximation, but they all produce essentially the same shape for the angular distributions, showing maximum cross sections for angles above 90°, the limiting case being with the maximum at 180° when the Coulomb parameters for both deuteron and proton are large. These calculations agree with the semiclassical predictions of Lemmer (8). Other characteristics of the Coulomb stripping regions are: the shape of the angular distribution is insensitive to the angular momentum of the captured neutrons, and the shape is also insensitive to changes in the optical parameters used to calculate the distorted wave functions for deuteron and proton (5).

II. EXPERIMENT AND RESULTS

A 4000 μCoul run was carried out on three targets of 171, 150, and 145 $\mu gr/cm^2$ of metallic calcium (96.97% ^{40}Ca) evaporated onto Formvar plus gold backings, using the 2 MeV deuteron beam from the Dynamitron accelerator of the Instituto de Física, University of Mexico. The target thicknesses were determined by weighing in a microbalance (9). Because of target breaking due to bombardment, three targets were used, the average being taken to calculate cross sections. The average thickness was later corrected to account for some silicon contamination. The final value used for ^{40}Ca was 151 $\pm$ 15% $\mu gr/cm^2$.

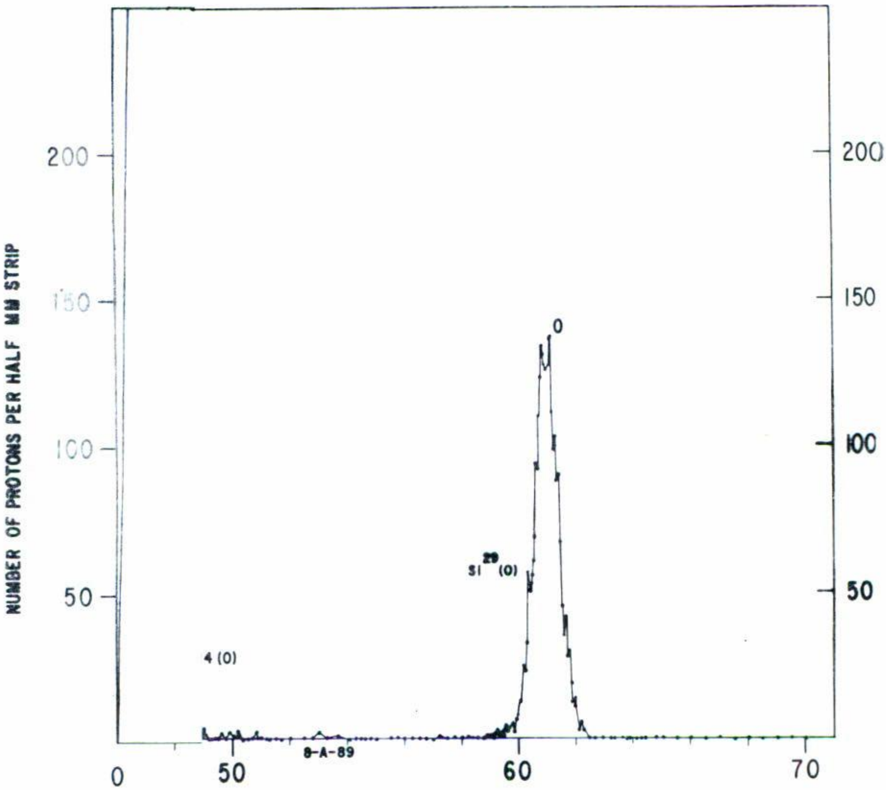
A 3 μ Coul exposure was made on the 171 $\mu gr/cm^2$ Target to determine the ^{40}Ca thickness through elastic scattering, the value obtained being 7% higher than from weighing. These thicknesses were chosen in order to have good statistics in the proton peaks, at the same time keeping adjacent peaks as well separated as possible.

The magnetic analysis was carried out in a multigap spectrograph (10), which in a single bombardment yields the angular distribution from 10° to 170° in 10° intervals. The field in the spectrograph was 7.06 kgauss, with which the proton groups corresponding to the ground state of ^{41}Ca fell near the top of the focal surface, and 4.2 MeV excitation peaks at the bottom, covering in this way up to level number 25 in some cases. Three NTA 100 micron Eastman Kodak plates at each angle covered the 75 cm focal surface. All the lower plates were covered with aluminum filters for stopping all particles except protons. The plates were later scanned every 0.5 mm.

Figure 1 shows a typical spectrum at 90° laboratory angle. The numbers identify the various ^{41}Ca levels. The most important contaminants were $^{12}C(d,p)^{13}C(0)$ and $^{16}O(d,p)^{17}O(0)$, the first appearing at all angles, the second only below 80°. Also identified was a $^{28}Si(d,p)^{29}Si$ ground state and six excited states contamination, the peaks marked accordingly in the figure. Where the silicon contaminant peaks overlapped calcium peaks the corrections were made substracting the silicon intensities at different angles, this information being obtained from angular distributions studied previously at 2 MeV (11). The carbon and oxygen peaks, however, completely covered calcium peaks in their vicinities.

Figure 2 shows angular distributions obtained for the ground state and various excited states of ^{41}Ca. Center of mass differential cross section in mb/sterad is plotted against center of mass angle. The vertical bars over experimental points indicate errors estimated according to different sources: peak separation from contaminants and other ^{41}Ca levels, statistics (not more than 5%), and determination of average thickness due to target breaking. The following observations are made on the individual levels.

The ground state peak is affected by the silicon ground state contamination, which was determined to be $3.7 \pm 15\% \mu gr/cm^2$ from some angles where this contaminant was well separated. The angular distribution was corrected as mentioned using known silicon angular distributions at this energy. Information for this level was lost at several angles because the magnetic field varies from gap to gap and the proton peak fell outside the photographic plates.


NUMBER OF PROTONS PER HALF MM STRIP
200
150
100
50
4 (0)
8-A-89
SI 29 (0)
0
50
60
70

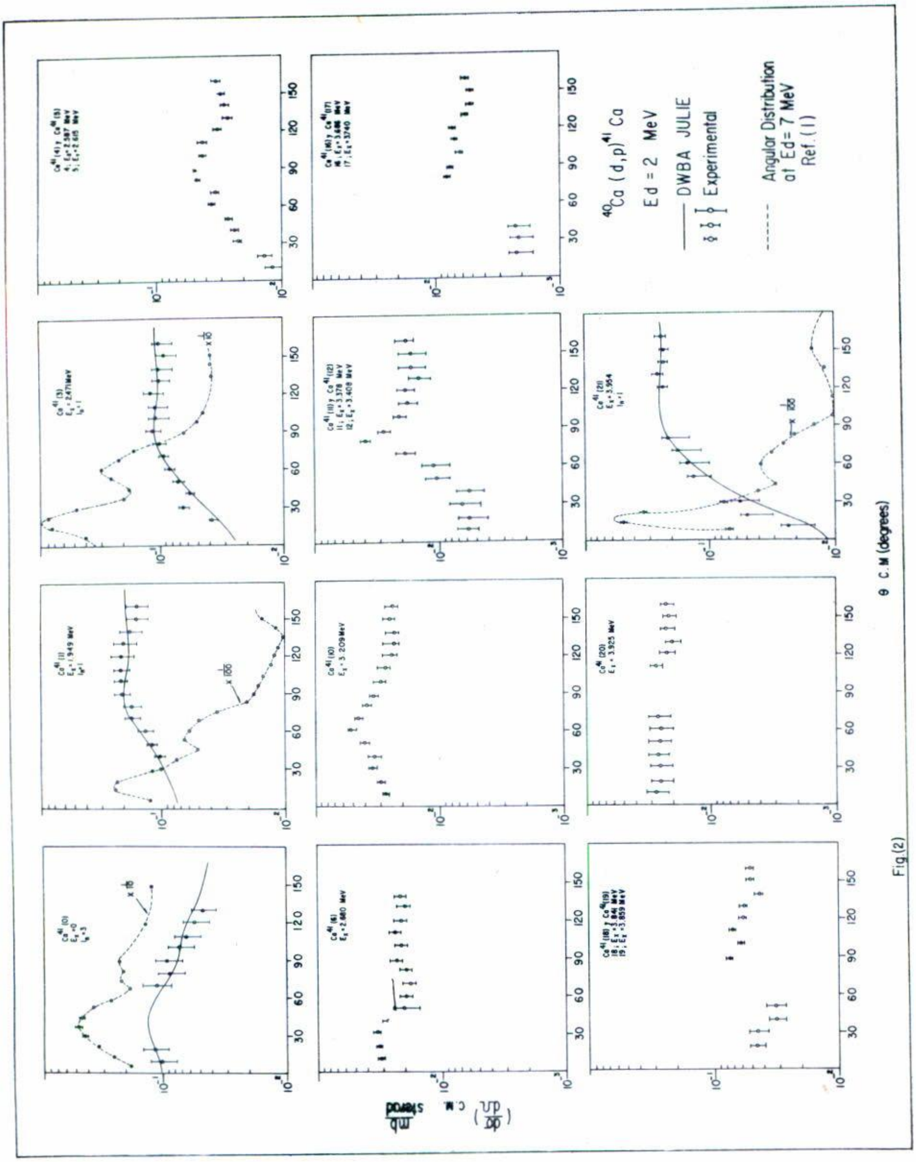


Fig. (2). Angular distributions from the ^{40}Ca $(d,p)^{41}$Ca reaction at E_d = 2 MeV. Angular distributions at E_d = 7 MeV ref. (1), are shown for comparison.

The first excited state is affected by the proximity of the second excited state at all angles and of level (2) in ^{29}Si bellow 90°; the same corrections were carried out.

Level (3) is affected above 90° by level (3) in ^{29}Si.

Levels (4) and (5) are reported together because it was impossible to separate them. The principal source of error is statistical.

Level (6) is not affected by contamination. The most important error is the separation from level (5).

Level (10) is affected above 90° by level (4) in ^{29}Si. Errors are due to the contaminant and separation from level (9).

Levels (11) and (12) are reported together. The principal error is statistics. According to reference (1) level (11) is about 6% as strong as level (12) at 7 MeV, so it is assumed that level (12) contributes most of the intensity.

Levels (16) and (17) are reported together. For the same reason as above, level (17) is expected to be responsible for most of the intensity. Errors are due to separation from other calcium peaks and from carbon.

The same may be said for levels (18) and (19), where (19) is probably more intense.

The errors and loss of information for level (20) are due to the carbon contaminant, and to separation from other calcium peaks. The distribution is isotropic, as in reference (1).

For level (21) errors and loss of information are due to carbon and silicon contaminants. It was not possible to substract the ^{29}Si (6) contaminant because the angular distribution was not available at this energy; at other energies it is reported isotropic.

III. ANALYSIS

Figure 2 shows also angular distributions calculated using a DWBA Julie program (12) for levels (0), (1), (3), and (21). Agreement between theoretical and experimental results is through the following expression:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \frac{(2J_B+1)}{(2J_A+1)} S \left(\frac{d\sigma}{d\Omega}\right)_{\text{teor.}}$$

Since ^{40}Ca has J_A equal zero,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = (2J_B+1)\, S \left(\frac{d\sigma}{d\Omega}\right)_{\text{teor.}}$$

The optical parameters used in this work are shown in Table 1. For the distributions shown in the figure the parameters $c/A/n_0$ were used. Adding the experimental cross sections for all angles and comparing the sum to the corresponding calculated sum, the factor $(2J_B+1)\,S$ is obtained, and if the spin of the final state J_B is known, the spectroscopic factors S is extracted.

Table 2 shows the spectroscopic factors obtained for each level with three sets of parameters used, as compared to those obtained at 7 MeV (1). The following comments may be made.

The neutron capture angular momentum assignment for the ground state is $l_n = 3$ and the spectroscopic assignment according to the shell model is $J_B = \frac{7}{2}^-$. With this information we obtain the value 19.6 for the factor $(2J_B+1)\,S$ using the combination $c/A/n_0$. Calculations with other sets of parameters ($a/A/n_0$ and $b/A/n_0$) produced variations up to 30%.

The first excited state corresponds to a single particle level ($2p$ 3/2) with $l_n = 1$. The value of $(2J_B+1)\,S$ obtained is 3.54, so the spectroscopic factor is 0.88 using set $c/A/n_0$. With the other parameters just mentioned 20% differences were found.

The third excited state is also a ($2p$ 3/2) level. The spectroscopic factor obtained is 0.37 and with the other parameters variations are up to 16%.

According to the shell model, level (21) is a $2p$ 1/2). The spectroscopic factor is 0.71 and with the other parameters differences are less than 10%. The shape of this distribution is typical of Coulomb stripping, since the incoming

TABLE 1

Optical-model parameters used in $^{40}Ca(d,p)^{41}Ca$ for $E_d = 2$ MeV.

Set	Particle	V MeV	4W MeV	r_0 fm	a fm	r'_0 fm	a' fm	r_{0c} fm
a	d	118.6	50.64	1.0	.752	1.465	.656	1.30
b	d	119.1	52.32	1.0	.738	1.591	.660	1.30
c	d	121.2	49.72	1.0	.753	1.464	.638	1.30
A	p	53.0	41.0	1.25	.65	1.25	.470	1.25
n_0	n	+	-	1.25	.65	-	-	-

+ Adjusted to give the transferred neutron a binding energy of Q (d,p) + 2.23 MeV.

The Form of the optical potential used was:

$$V_{opt} = -V(e^x+1)^{-1} + 4iW(d/dx)(e^{x'}+1)^{-1} + V_c(r,r_c)$$

with

$$x = (r - r_0 A^{1/3})/a\,;\; x' = (r - r'_0 A^{1/3})/a'\,;\; r_c = r_{0c}A^{1/3}$$

Where V_c is the Coulomb potential from a homogeneously charged sphere of radius r_c. The sets a, b, A, were obtained by extrapolation of ^{avg}Ca parameters from 7 MeV. Set c was obtained by extrapolation of ^{avg}Ca parameters from 7.2 MeV. (T.A. Belote, W.E. Dorenbusch and J. Rapaport, Nuclear Phys. A120 (1968) 401). The extrapolation was carried out following C.M. Perey and F.G. Perey (Phys. Rev. 132 (1963) 755).

TABLE 2

Comparison between present results and the ones obtained for E_d = 7 MeV,

Level	Ref. (1) Ex. (MeV)	ln	$(2J+1)S$	Assignment	S	$c/A/n_0$ $(2J+1)S$	S	$a/A/n_0$ $(2J+1)S$	$b/A/n_0$ $(2J+1)S$
0	0	3	8.00	$(1f\ 7/2)$	1	19.6	2.4	20.06	25.01
1	1.949	1	3.76	$(2p\ 3/2)$	0.99	3.54	0.88	3.51	4.25
2	2.017	2	0.78						
3	2.471	1	1.11	$(2p\ 3/2)$	0.28	1.5	0.37	1.49	1.75
4	2.587								
5	2.615								
6	2.680	0	.0352	$(3s\ 1/2)$	0.018				
7	2.893								
8	2.970								
9	3.059								
9a	3.131								
10	3.209								
11	3.378								
12	3.408	0	.308	$(3s\ 1/2)$	0.015				
13	3.504								
14	3.536								
15	3.623	1	.219	$(2p\ 1/2)$					
16	3.686								
17	3.740								
18	3.841								
19	3.859	0	.0093	$(3s\ 1/2)$	0.005				
20	3.925								
21	3.954	1	1.45	$(2p\ 1/2)$	0.73	1.43	0.71	1.42	1.57

Ref. (1). The better agreement for level 21 is clear.

deuteron energy (1.9 MeV C.M.) and the outgoing proton energy (4.0 MeV C.M.) are both below the Coulomb barrier.

Spectroscopic factors obtained here differ from those obtained at 7 MeV bombarding energy (1). In particular we note a 100% discrepancy for the ground state and less than 15% for others. These latter are within the experimental errors, but not the one corresponding to the ground state. It is important to note that the angular distribution obtained here for the ground state agrees within 10% with that reported in reference (3), and if the silicon ground state contamination is not substracted, it agrees within 20% with that of reference (2). Furthermore, reference (3) reports the existence of a resonance in this reaction in the vicinity of 2 MeV, so this discrepancy may well be due to compound nucleus effects which, of course, are not considered in the stripping analysis.

It is convenient also to establish a comparison of the results of reference (2) with those of this paper. The ground state angular distributions differ somewhat, especially at 20° where the difference is 50%. If the silicon contaminant is not substracted they agree within 10%, so it is concluded that in that paper a silicon contaminant may have been present but was not detected because of poor resolution of the counters used. There is a better agreement for the first excited state; the 20% difference could be due to the fact that in this paper the second excited state was easily separated and not in reference (2).

Finally, comparing results with those of 7 MeV, in general the position of the maximum is at a higher angle when the bombarding energy is low. In particular, for $l_n = 1$ levels (1), (3), and (21) the principal maximum in the stripping pattern at 2 MeV is always above 90°, while at 7 MeV it is at 20°. The maximum tends to move toward higher angles as the outgoing proton energy diminishes.

IV. CONCLUSIONS

1) The discrepancy in the ground state spectroscopic factor could be attributed to compound nucleus effects, which seem to be strong at 2 MeV. Apparently as the Coulomb stripping region is reached, compound nucleus effects

become smaller and the direct reaction predominates, the reason why there is better agreement for higher excited states.

2) A typical Coulomb stripping pattern is observed only when both deuteron and proton energies are below the Coulomb barrier.

3) As the Q value diminishes, there is a tendency for the stripping peak to move to larger angles.

4) For the Coulomb stripping case (level 21) there is less dependence of the angular distribution shape on the optical parameters used to calculate incoming and outgoing distorted wave functions.

5) In order to obtain more complete and reliable information, it would be well do this experiment with a thinner target, longer run, and eliminating the contaminants during target preparation where possible.

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REFERENCES

1. T.A. Belote, A. Sperduto and W.W. Buechner, Phys.Rev. **139** (1965) B80.
2. Ilona Fodor, I. Szentpetery and J. Zimanyi, Nuclear Phys. **73**, (1965) 155.
3. L.L. Lee and J.P. Schiffer, Phys. Rev. **107** (1957) 1340.
4. F.P. Gibson and A. Kerman, Phys. Rev. **145** (1966) 758.
5. M. Posner, Phys.Rev. **158** (1967) 1018.
6. J. Rapaport and A.K. Kerman, Nuclear Phys. **A119** (1968) 641.
7. J.R. Erskine, W.W. Buechner and H.A. Enge, Phys.Rev. **128** (1962) 720.
8. R.H. Lemmer, Nuclear Phys. **39**, (1962) 680.
9. A. Barragán, Comparación de varios métodos para medir espesores pequeños. Tesis profesional, Fac. de Ciencias UNAM (1967).

10. G. López, Diseño y construcción de un estereoespectrógrafo. Tesis Profesional, Fac. de Ciencias, UNAM (1963).

11. B.H. Wildenthal, R.W. Krone and F.W. Prosser Jr., Phys. Rev. **135** (1964). B680.

12. R.H. Bassel, R.M. Drisko and G.R. Satchler, Oak Ridge Nat. Laboratory Report No. ORNL3240; G.R. Satchler, Nuclear Phys. **55**, 1 (1964).