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SCATTERING OF 42-MeV (6.7-pJ) ALPHA PARTICLES FROM EVEN ISOTOPES OF CADMIUM

by Norton Baron, Regis F. Leonard, and William M. Stewart

Lewis Research Center
Cleveland, Ohio

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SUMMARY

Angular distributions were measured for the elastic and inelastic scattering of 42-MeV (6.7-pJ) alpha particles from isotopically enriched targets of cadmium 110, 112, 114, and 116. In each isotope, five excited states were seen and their excitation energies were determined to ±30 keV (±4.8 fJ). Angular distributions for three of these states were measured over the angular range 30° to 65°. Their relative phases and excitation energies indicate that these states are the first 2^{+}, the 3^{-}, and the two phonon 2^{+}. It is suggested that the two other excited states result from a quadrupole-octupole two-phonon transition. A tentative spin assignment of 5^{-} was made for one of them.

Elastic angular distributions were analysed using the optical model with a four parameter Woods-Saxon potential. Excellent fits have been obtained for the elastic scattering.

Inelastic scattering has been analyzed using a distorted wave Born approximation (DWBA) calculation. These calculated inelastic angular distributions agree very well with the experimentally measured cross sections for scattering to one phonon states, and allow determination of deformation parameters which are in satisfactory agreement with those obtained elsewhere.

INTRODUCTION

The present work is a continuation of a study of elastic and inelastic scattering of alpha particles from even isotopes in the Z = 50 region of the periodic table. Previously reported work on tin and tellurium (refs. 1 and 2) indicated that such studies could yield information on single quadrupole and octupole vibrational states. In addition to such information, an effort was made here to obtain angular distributions of two phonon excitations, of which several were measured in the previously reported tellurium work.

Furthermore, inelastic scattering from even isotopes serves as an aid in the analysis of collective core excitations (ref. 3) in neighboring odd isotopes.

SYMBOLS

A	nuclear mass number
a	diffuseness parameter in Woods-Saxon potential
R_o	radius parameter in Woods-Saxon potential
r	semiclassical interaction radius
V	strength of the real part of the optical potential
V_c	Coulomb potential
Z	atomic number of nucleus
W	strength of the imaginary part of the optical potential

EXPERIMENTAL ARRANGEMENT

The external 42-MeV (6.7-pJ) alpha-particle beam of the NASA 60-inch (152-cm) cyclotron was used for the present experiment. A schematic diagram of the experimental arrangement is shown in figure 1. Scattered alpha particles were detected at four different scattering angles simultaneously using lithium-drifted silicon semiconductor counters fabricated at NASA Lewis (ref. 4). A block diagram of the elec-

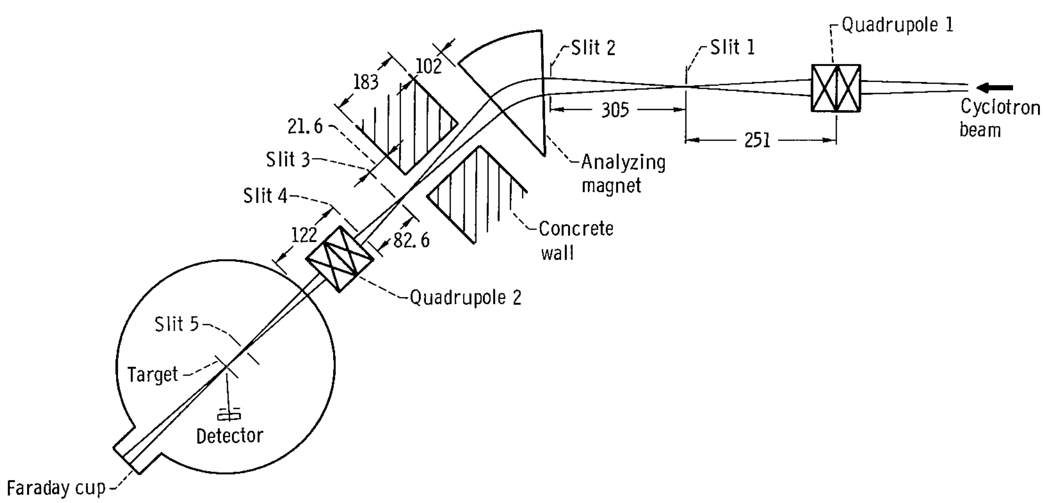


Figure 1. - Schematic diagram of experimental arrangement. (All dimensions are in centimeters.)

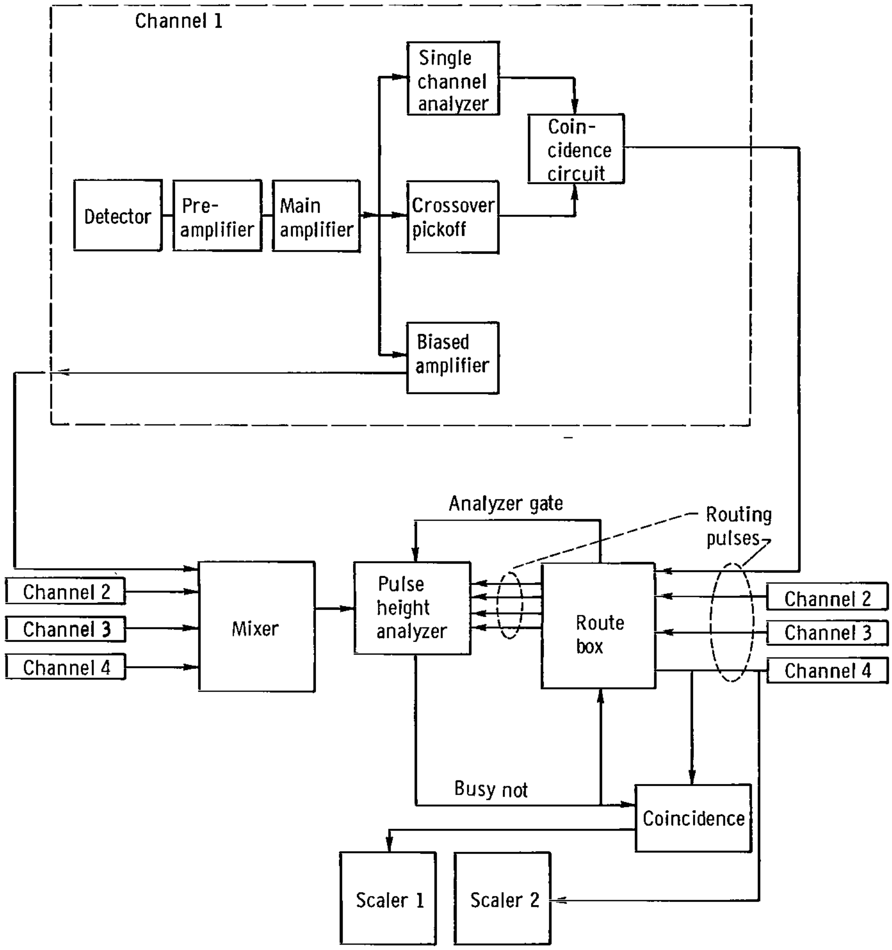


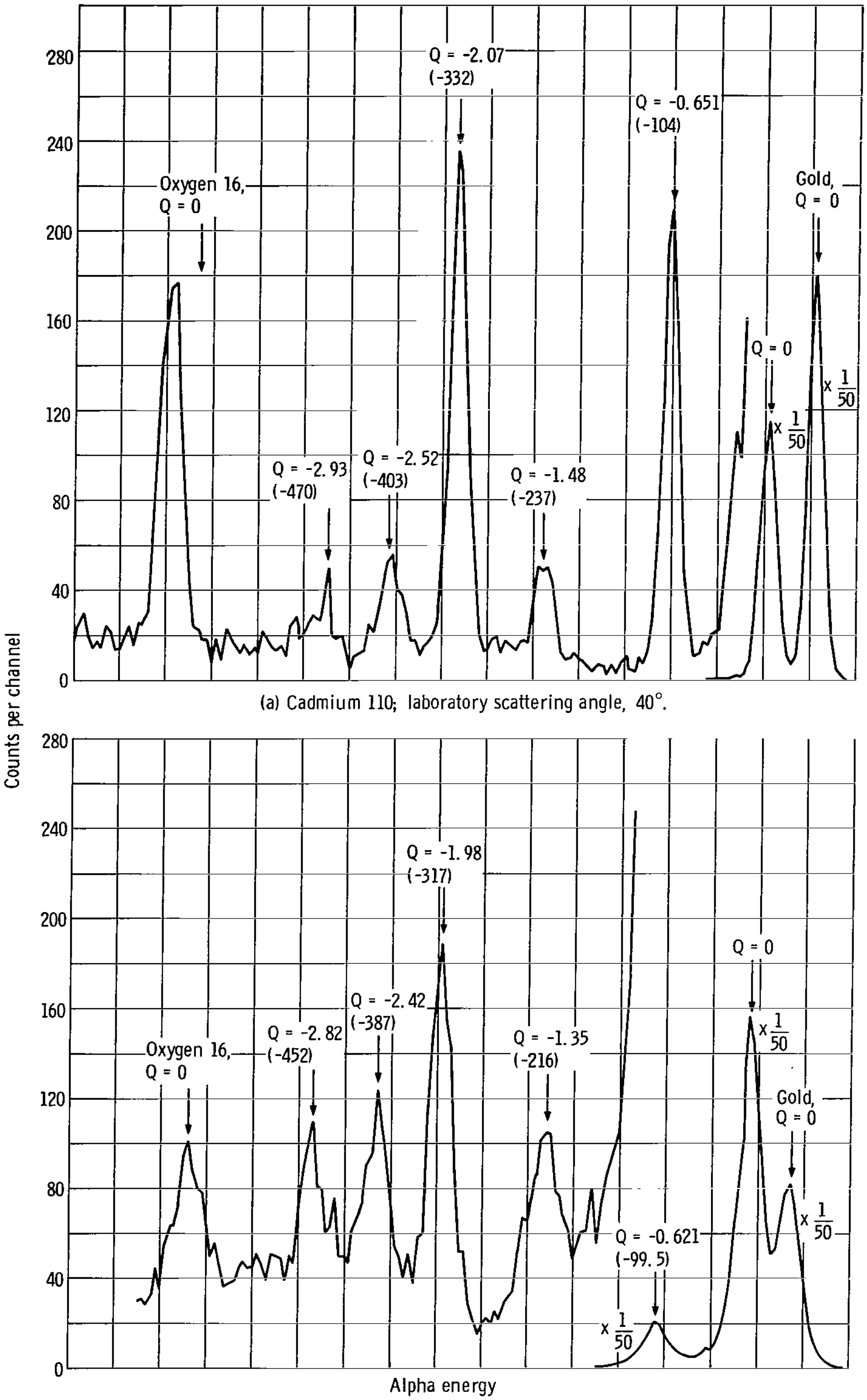
Figure 2. - Block diagram of electronics. (Channel 1 is shown in detail and is representative of channels 2, 3, and 4.)

tronics is shown in figure 2. Details of the experimental apparatus are discussed in references 1 and 2. The overall energy resolution of the experiment was approximately 100 keV (16 fJ).

EXPERIMENTAL RESULTS

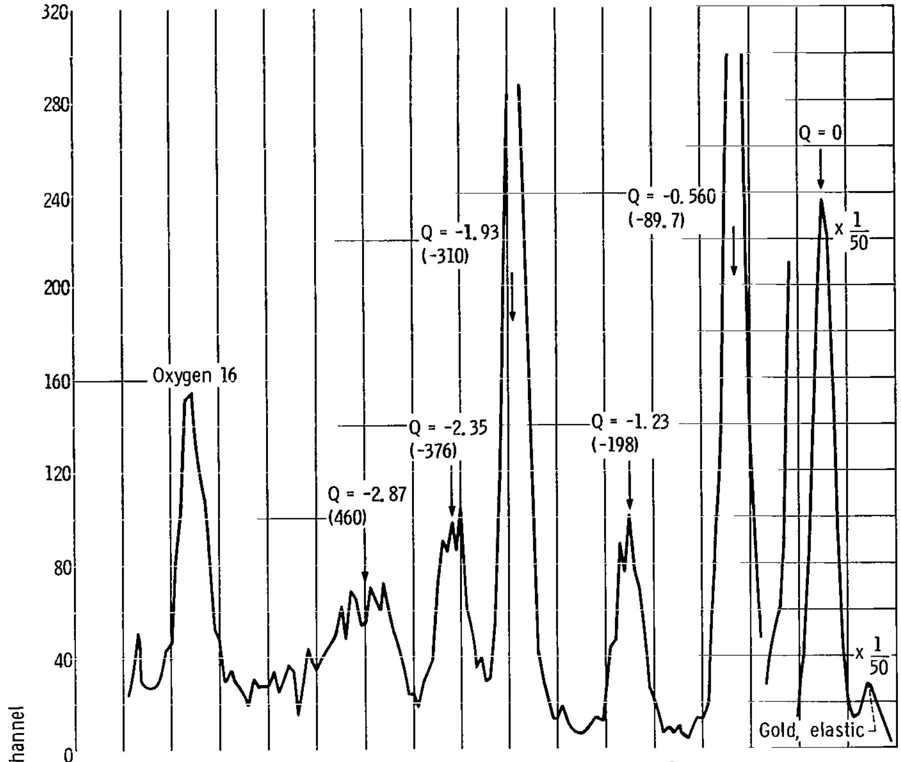
Elastic Scattering

Differential cross sections for elastic scattering from cadmium 110, 112, and 114 (^{110}Cd, ^{112}Cd, and ^{114}Cd) were measured over an angular range of approximately 30° to 65°. The ^{116}Cd data were taken as far forward as 8°. For the other targets, this was not practical because the targets were backed on 10 to 20 micrograms per square

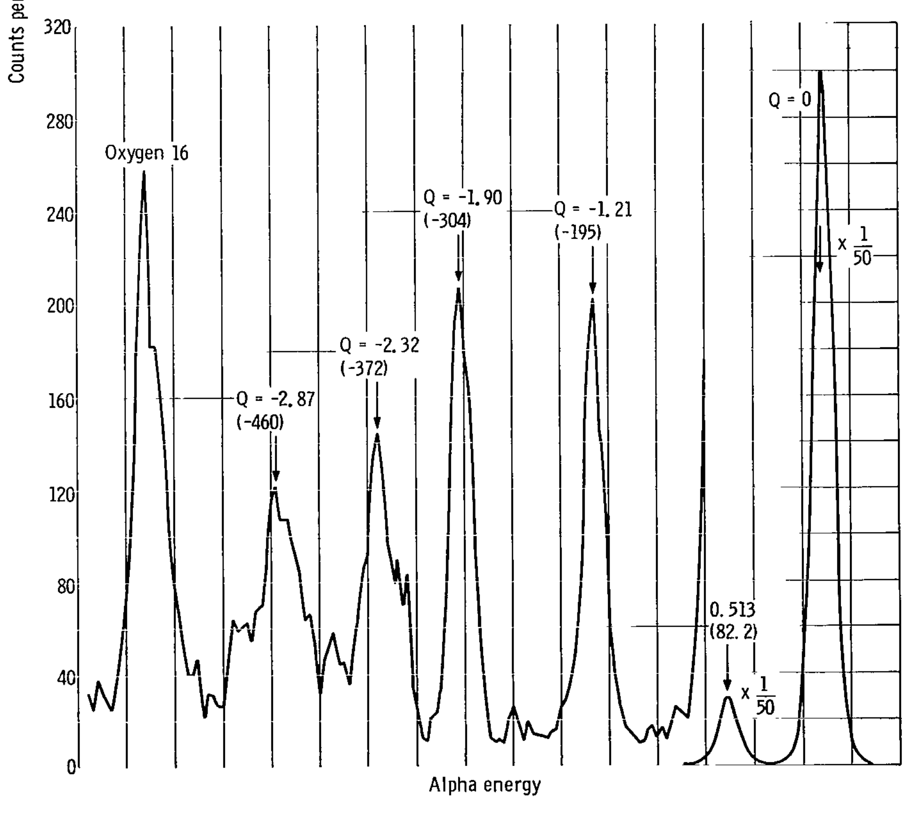


(b) Cadmium 112; laboratory scattering angle, 38°.

Figure 3. - Typical cadmium energy spectra. (Q-values are given in MeV (fJ).)



(c) Cadmium 114, laboratory scattering angle, 40°.



(d) Cadmium 116; laboratory scattering angle, 38°.

Figure 3. - Concluded.

centimeter of gold and a like amount of carbon which interferred strongly with the elastic scattering at angles forward of about 30°. In all four isotopes the differential cross sections were typical of those usually seen with a diffraction type structure with peaks approximately every 10°.

Inelastic Scattering

In each isotope five excited states were seen. Typical energy spectra for each of the four isotopes are shown in figure 3. Differential cross sections were obtained for three states in each isotope. Excitation energies were obtained using the carbon spectrum as a calibration.

The lowest excited state in each isotope has spin and parity 2^{+} and is described as a vibrational excitation. The excitation energies obtained for this state are in good agreement with those previously reported (ref. 5). As is usually the case for scattering to the one quadrupole-phonon state, the differential cross section has a diffraction-like structure and is out-of-phase with the cross section for elastic scattering.

In each isotope the next strongest excitation was the octupole vibrational state at an energy of approximately 2 MeV (320 fJ). These states were also reported previously and the excitation energies obtained here are in excellent agreement with the earlier ones (ref. 6). The differential cross section for scattering to the octupole state is in phase with the elastic cross section.

A group at approximately twice the energy of the first excited state was seen in each isotope. It was weaker by approximately an order of magnitude than the first 2^{+} and the 3^{-} excitations. This implies that this group might arise from the excitation of the two quadrupole-phonon triplet (ref. 7). However, it is possible that more than one member of the triplet is present in this group. Previous works (refs. 5 and 6) have reported excitation energies of the 2^{+} and 4^{+} members of the two phonon triplet to be 1.474 and 1.541 MeV (236.1 and 246.9 fJ) in ^{110}Cd, 1.31 and 1.41 MeV (210 and 226 fJ) in ^{112}Cd, and 1.21 and 1.28 MeV (194 and 205 fJ) in ^{114}Cd. Such states could hardly be resolved here. Comparison of the excitation energies obtained for these levels in the present experiment with those reported in references 5 and 6 indicates that the main strength of this group is due to excitation of the 2^{+} member of the triplet, and that the 4^{+} must be weaker than the 2^{+} by at least a factor of two. The angular distribution for this state is neither exactly in nor out of phase with that for elastic scattering; instead, the maxima are shifted forward approximately 2° to 3° relative to the maxima of the elastic cross section.

Two other states were observed in each isotope at excitation energies near 2.4 and 2.9 MeV (384 and 464 fJ). Their excitation strengths were similar to each other and

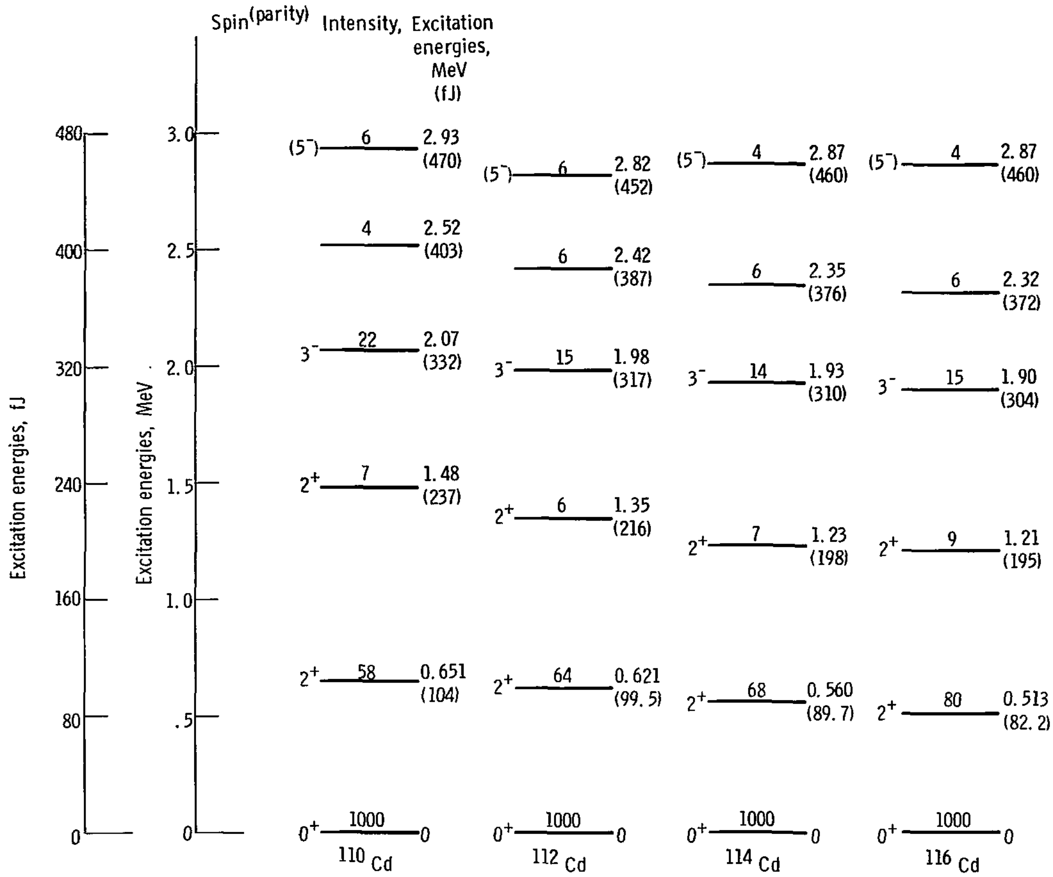


Figure 4. - Energy levels of cadmium isotopes excited in alpha scattering. Energies are accurate to ± 0.030 MeV (± 4.8 fJ).

very nearly equal to those of the two quadrupole-phonon transitions.

A summary of all the states seen, including excitation energies, relative intensities, spins, and parities, is shown in figure 4. Spins shown in parentheses are questionable.

CROSS SECTIONS

The principal difficulty involved in the determination of absolute cross sections was the measurement of the target thickness. The targets employed in the present experiment were backed on a thin layer of gold which, in turn, was deposited on a carbon foil. The thicknesses of the backings were uncertain and consequently the thickness of cadmium was also uncertain. As a result, the absolute magnitude of the elastic cross sections was allowed to vary during the optical model fitting, and that magnitude was selected which would yield the best optical model fits. This procedure resulted in changes of the absolute differential cross section by as much as 24 percent from the values based on

TABLE I. - DIFFERENTIAL CROSS SECTION FOR SCATTERING OF

42-MeV (6.7-pJ) ALPHA PARTICLES FROM CADMIUM 110

(a) Elastic scattering

Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr
31.04	21.5±0.1	47.50	0.538±0.010
33.11	16.7±0.1	49.55	.519±0.010
35.17	9.74±0.04	51.60	.556±0.010
37.23	4.76±0.02	53.64	.386±0.009
39.28	2.93±0.02	55.69	.143±0.006
41.34	2.85±0.02	57.73	.070±0.004
43.40	2.33±0.02	59.77	.114±0.005
45.45	1.19±0.01	61.81	.053±0.003

(b) Inelastic scattering, 0.65 MeV (104 fJ)

31.05	0.349±0.012	47.51	0.155±0.006
33.11	.150±0.007	49.56	.089±0.004
35.18	.269±0.009	51.61	.026±0.002
37.24	.435±0.007	53.66	.032±0.002
39.30	.297±0.007	55.70	.049±0.003
41.35	.099±0.004	57.74	.056±0.003
43.41	.055±0.004	59.78	.026±0.002
45.46	.142±0.004	61.82	.006±0.001

(c) Inelastic scattering, 1.48 MeV (237 fJ)

31.06	0.071±0.007	47.53	0.008±0.001
33.13	.024±0.005	49.59	.025±0.002
35.19	.011±0.004	51.63	.018±0.002
37.25	.038±0.002	53.68	.008±0.001
39.31	.046±0.004	55.72	.005±0.001
41.37	.024±0.002	57.76	.008±0.001
43.42	.015±0.003	59.80	.0077±0.0012
45.48	.011±0.001	61.84	.0064±0.0011

(d) Inelastic scattering, 2.07 MeV (332 fJ)

31.07	0.138±0.009	47.54	0.026±0.002
33.13	.258±0.007	49.59	.033±0.003
35.20	.161±0.007	51.64	.0416±0.0028
37.26	.083±0.003	53.69	.0379±0.0027
39.32	.053±0.004	55.73	.0144±0.0017
41.38	.111±0.004	57.78	.0160±0.0017
43.43	.116±0.005	59.82	.0087±0.0013
45.49	.064±0.003	61.85	.0221±0.0021

TABLE II. - DIFFERENTIAL CROSS SECTION FOR SCATTERING OF

42-MeV (6.7-pJ) ALPHA PARTICLES FROM CADMIUM 112

(a) Elastic scattering

Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr
31.02	27.9±0.1	47.47	0.515±0.005
33.09	21.9±0	49.52	.559±0.006
35.15	10.8±0	51.57	.543±0.006
37.20	6.01±0.02	53.62	.342±0.004
39.26	3.12±0.02	55.66	.118±0.003
41.32	3.79±0.02	57.70	.074±0.002
43.37	2.26±0.01	59.74	.120±0.003
45.42	1.37±0.01	61.78	.122±0.002

(b) Inelastic scattering, 0.621 MeV (99.5 fJ)

31.03	0.279±0.010	47.49	0.156±0.003
33.09	.163±0.007	49.53	.054±0.002
35.16	.239±0.007	51.58	.011±0.001
37.21	.605±0.009	53.63	.031±0.002
39.27	.262±0.008	55.67	.065±0.002
41.33	.102±0.004	57.71	.052±0.002
43.38	.040±0.003	59.75	.0197±0.0012
45.43	.206±0.005	61.79	.0023±0.0006

(c) Inelastic scattering, 1.35 MeV (216 fJ)

31.04	0.0293±0.0043	47.50	0.0139±0.0011
33.10	.0306±0.0040	49.55	.0150±0.0012
35.17	.0109±0.0031	51.60	.0078±0.0010
37.22	.0348±0.0030	53.64	.0043±0.0007
39.28	.0226±0.0030	55.69	.0037±0.0005
41.34	.0345±0.0023	57.73	.0060±0.0006
43.39	.0095±0.0018	59.77	.0093±0.0007
45.45	.0126±0.0017	61.81	.0067±0.0006

(d) Inelastic scattering, 1.98 MeV (317 fJ)

31.05	0.115±0.006	47.51	0.0197±0.0013
33.11	.258±0.006	49.56	.0212±0.0014
35.18	.126±0.005	51.61	.0337±0.0017
37.24	.071±0.003	53.66	.0265±0.0016
39.29	.0249±0.0039	55.70	.0139±0.0009
41.35	.120±0.003	57.74	.0072±0.0007
43.41	.0705±0.0034	59.78	.0125±0.0009
45.46	.0548±0.0029	61.82	.0125±0.0010

TABLE III. - DIFFERENTIAL CROSS SECTION FOR SCATTERING OF

42-MeV (6.7-pJ) ALPHA PARTICLES FROM CADMIUM 114

(a) Elastic scattering

Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr
31.01	27.1±0	47.45	0.630±0.004
33.07	18.5±0	49.50	.678±0.004
35.13	11.3±0	51.54	.670±0.004
37.18	5.35±0.03	53.59	.374±0.003
39.24	3.72±0.02	55.63	.135±0.002
41.29	3.44±0.01	57.67	.0985±0.0017
43.35	2.54±0.01	59.71	.151±0.002
45.40	1.15±0.01	61.74	.138±0.002

(b) Inelastic scattering, 0.560 MeV (89.7 fJ)

31.01	0.602±0.008	47.46	0.160±0.003
33.07	.194±0.003	49.51	.0526±0.0019
35.13	.436±0.006	51.55	.0180±0.0010
37.19	.568±0.007	53.60	.0426±0.0013
39.25	.370±0.005	55.64	.0770±0.0016
41.30	.106±0.003	57.68	.0570±0.0014
43.36	.105±0.003	59.72	.0183±0.0009
45.41	.208±0.004	61.76	.0026±0.0005

(c) Inelastic scattering, 1.23 MeV (198 fJ)

31.02	0.0458±0.0038	47.47	0.0097±0.0008
33.08	.0197±0.0029	49.52	.0155±0.0009
35.14	.0231±0.0023	51.57	.0124±0.0008
37.20	.0298±0.0023	53.61	.0055±0.0005
39.26	.0460±0.0019	55.65	.0030±0.0004
41.31	.0309±0.0016	57.69	.0072±0.0005
43.37	.0207±0.0015	59.73	.0084±0.0006
45.42	.0070±0.0010	61.77	.0069±0.0005

(d) Inelastic scattering, 1.93 MeV (310 fJ)

31.03	0.206±0.004	47.48	0.0119±0.0010
33.09	.229±0.005	49.53	.0170±0.0010
35.15	.1471±0.0035	51.58	.0341±0.0012
37.21	.0540±0.0023	53.63	.0251±0.0010
39.27	.0630±0.0022	55.67	.0111±0.0007
41.33	.0881±0.0026	57.71	.0057±0.0005
43.38	.0917±0.0026	59.75	.0093±0.0006
45.43	.0365±0.0018	61.79	.0105±0.0008

TABLE IV. - DIFFERENTIAL CROSS SECTION FOR SCATTERING OF

42-MeV (6.7-pJ) ALPHA PARTICLES FROM CADMIUM 116

(a) Elastic scattering

Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr	Center-of-mass scattering angle, θ_{cm}, deg	Differential cross section, $d\sigma/d\Omega$, fm^2/sr
8.28	21 100±26	35.11	12.2±0.037	57.64	0.119±0.0020
10.34	10 300±18	37.16	5.03±0.028	59.70	.158±0.0027
12.41	5 310±13	39.22	4.32±0.022	61.71	.0995±0.0018
14.48	2 620±9	41.27	3.68±0.020	63.75	.0395±0.0014
16.55	1 430±6.9	43.32	2.72±0.017	65.78	.0147±0.0007
18.61	745±4.9	45.37	1.04±0.012	67.81	.0253±0.0010
20.68	367±3.5	47.42	.690±0.005	69.83	.0333±0.0010
22.74	221±2.7	49.47	.770±0.010	71.86	.0253±0.0009
24.80	136±0.13	51.52	.636±0.0055	73.88	.00815±0.0004
28.93	35.2±0.067	53.56	.310±0.004	75.90	.00283±0.0003
30.99	29.6±0.057	55.60	.112±0.0023	77.92	.00516±0.0003
33.05	18.6±0.049				

(b) Inelastic scattering, 0.513 MeV (82.2 fJ)

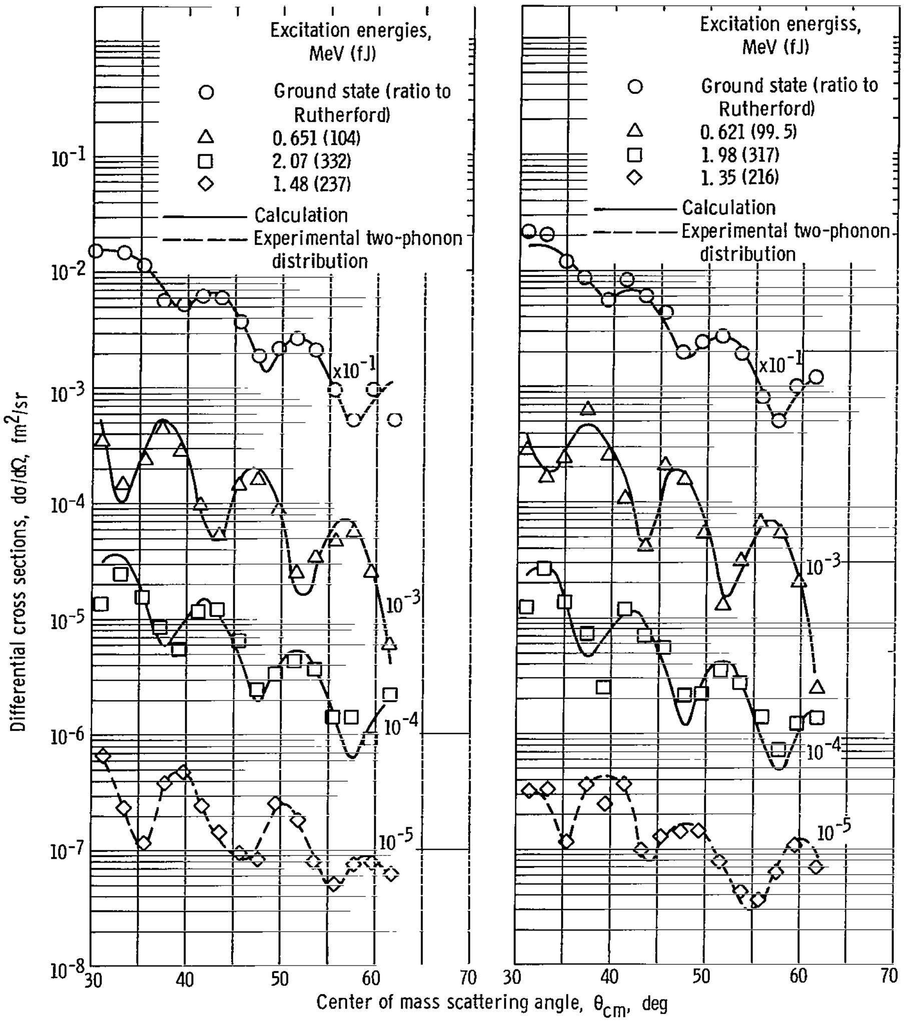
31.00	0.648±0.009	47.43	0.185±0.003	63.76	0.0282±0.0010
33.06	.145±0.004	49.48	.0593±0.003	65.79	.0287±0.0009
35.11	.531±0.007	51.53	.0226±0.001	67.82	.0136±0.0007
37.17	.658±0.009	53.57	.0731±0.0019	69.85	.0022±0.0003
39.23	.357±0.005	55.61	.0810±0.0018	71.87	.0037±0.0003
41.28	.103±0.004	57.65	.0406±0.0010	73.89	.0095±0.0004
43.33	.112±0.004	59.69	.0166±0.0008	75.91	.0110±0.0005
45.38	.271±0.006	61.72	.0107±0.0005	77.93	.0059±0.0003

(c) Inelastic scattering, 1.21 MeV (195 fJ)

28.94	0.0668±0.0027	47.45	0.0228±0.0009	63.77	0.00167±0.00024
31.00	.0924±0.0029	49.49	.0210±0.0016	65.81	.00258±0.00025
33.06	.0287±0.0017	51.54	.0129±0.0007	67.84	.00374±0.00036
35.12	.0361±0.0018	53.58	.00452±0.00055	69.86	.00410±0.00034
37.18	.0683±0.0032	55.63	.00578±0.00051	71.89	.00169±0.00021
39.24	.0516±0.0022	57.67	.00875±0.00048	73.91	.00075±0.00011
41.29	.0326±0.0022	59.70	.00606±0.00049	75.93	.00092±0.00015
43.34	.0152±0.0012	61.74	.00192±0.00023	77.95	.00137±0.00014
45.40	.0167±0.0016				

(d) Inelastic scattering, 1.90 MeV (304 fJ)

31.01	0.214±0.005	47.46	0.0206±0.0009	63.79	0.00612±0.0005
33.07	.194±0.005	49.51	.0264±0.0012	65.82	.00246±0.00025
35.13	.158±0.004	51.55	.0353±0.0012	67.85	.00276±0.00032
37.19	.0499±0.0025	53.60	.0228±0.0012	69.88	.00392±0.00031
39.25	.0748±0.0026	55.64	.00805±0.0007	71.90	.00482±0.00036
41.30	.108±0.004	57.68	.00655±0.00041	73.93	.00268±0.00020
43.36	.088±0.003	59.72	.0105±0.0006	75.45	.00121±0.00017
45.41	.0382±0.0020	61.76	.0107±0.0005	77.97	.00062±0.00010



(a) Cadmium 110. (b) Cadmium 112.

Figure 5. - Angular distributions for elastic and inelastic scattering of 42-MeV (6.7 pJ) alpha particles.

absolute measurement of the target thickness alone. The renormalized cross sections are listed in tables I to IV. The differential cross sections are plotted in figure 5.

ANALYSIS OF ELASTIC SCATTERING

The elastic scattering data were analyzed using the optical model assuming a four-parameter Woods-Saxon potential given by

$$V(r) = -(V + iW)\left\{1 + \exp\left[\left(r - R_0 A^{1/3}\right)/a\right]\right\}^{-1} + V_c(r)$$

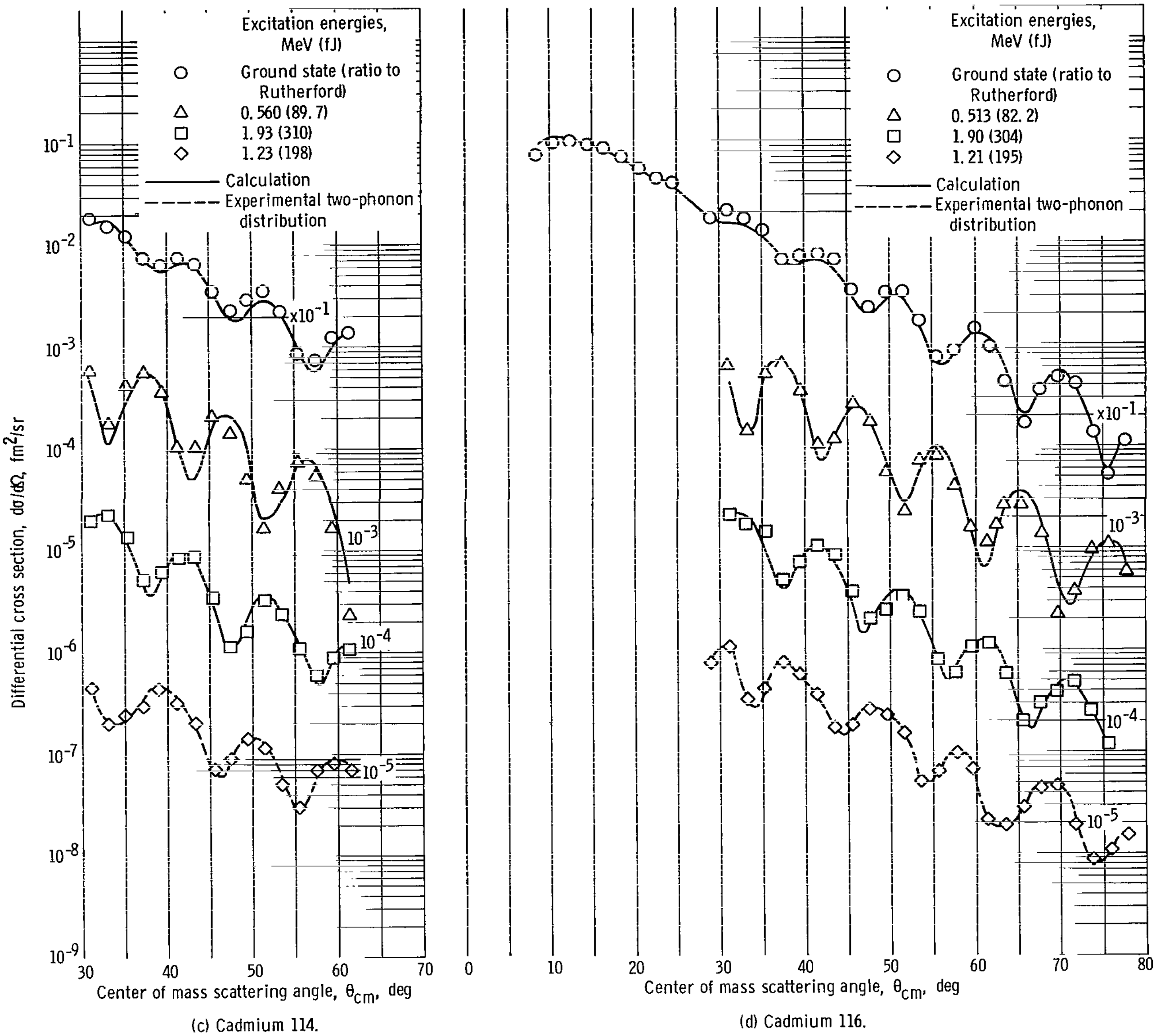


Figure 5. - Concluded.

The computer program SCAT 4 (ref. 9) was used to carry out the calculation of differential cross sections and total reaction cross sections. Typically, the computer code was asked to optimize the three parameters V, W, and a for a fixed value of R_o. It was expected from previously reported work (ref. 2) that a continuous set of equivalently good optical model parameters could be found. This hypothesis was verified for ^{116}Cd over the range $1.20 \leq R_o \leq 1.60$ femtometers (fm). For the other isotopes, the value of the nuclear radius parameter R_o was fixed at 1.45 fm. The results of the optical model calculations with $R_o = 1.45$ fm are shown with the elastic cross section data in figure 5. A tabulation of the parameters which resulted from these searches is given in table V.

TABLE V. - ELASTIC SCATTERING ANALYSIS

Cadmium isotope	Strength of real part of nuclear optical potential, V		Strength of imaginary part of nuclear optical potential, W		Diffuseness parameter, a, fm	Nuclear radius constant, R_0, fm	Total reaction cross section, σ_R, fm^2	Goodness of fit, χ^2/N
	MeV	pJ	MeV	pJ				
110	50.0	8.0	25.0	4.0	0.695	1.45	184.7	0.86
112	50.0	8.0	25.0	4.0	.689	1.45	185.9	1.38
114	50.0	8.0	25.0	4.0	.672	1.45	185.3	1.30
116	53.4	8.6	28.8	4.6	.683	1.45	193.1	1.50

ANALYSIS OF INELASTIC SCATTERING DATA

As in previous references (refs. 1 and 2) inelastic data were treated using the direct reaction code of Gibbs et al. (ref. 10) with a surface interaction. The results of these calculations are shown with the inelastic cross sections in figure 5. The fits are excellent in shape. The nuclear deformation parameter is obtained by normalizing the calculated cross sections to the experimental data. This deformation parameter may be compared with those obtained by other methods, principally Coulomb excitation. A listing of the deformation parameters obtained from this experiment as well as those reported by other investigators (refs. 6 and 11) for these nuclei is given in table VI. In no case is there more than a 15-percent disagreement. It was shown previously (ref. 2) that calculated values of the deformation parameter are relatively insensitive (±10 percent) to the

TABLE VI. - INELASTIC SCATTERING ANALYSIS

Cadmium isotope	Present work		Previous work	
	Nuclear deformation parameters			
	β_2	β_3	β_2 (a)	β_3 (b)
110	0.21	0.15	0.19	0.15
112	.19	.13	.19	.15
114	.21	.12	.20	.13
116	.23	.13	.20	.12

[a]Data from ref. 11.
[b]Data from ref. 6.

choice of equivalent optical model parameters used in the nuclear potential when calculating inelastic angular distributions.

No calculations have been done for the two-phonon states, since it is known that a simple DWBA calculation will not describe such transitions and that a coupled channels (ref. 12) or Austern-Blair calculation (ref. 13) is necessary.

CONCLUSIONS

Scattering of 42-MeV (6.7-pJ) alpha particles from the cadmium isotopes is similar to the scattering from other even isotopes in this region in several respects:

(1) The strongest excitations observed are the result of scattering to the first excited (2^+) state and the one octupole-phonon (3^-) state. The cross sections for these two states are out-of-phase and in-phase, respectively, with the elastic scattering.

(2) Excellent fits both to the elastic and inelastic scattering cross sections were obtained by using optical model and distorted wave Born approximation calculations, respectively.

(3) The values of the deformation parameters obtained from fitting the inelastic scattering cross sections agree very well with those obtained in other experiments.

The scattering from cadmium differed from that from tellurium in the nature of the two-phonon excitations seen. In tellurium (ref. 2), it appeared that the most strongly excited state of the two-phonon triplet was the 4^+. On the basis of excitation energies which should be accurate to approximately 30 keV (4.8 fJ), however, it appears that the most strongly excited two-phonon state in all the cadmium nuclei is the 2^+. In addition, the angular distributions for the two-phonon states differed from tellurium to cadmium. In tellurium the two-phonon cross sections were exactly in-phase with the elastic cross sections, a reversal of the usual Blair phase rule. In cadmium, however, the two-phonon distributions shifted approximately 2^o to 3^o from the elastic cross sections.

There are two other states in each cadmium isotope near 2.4 and 2.9 MeV (384 and 464 fJ). States near these energies have been assigned previously spins and parities of 6^+ and 5^-, respectively, in ^{110}Cd (refs. 5 and 8). It has been suggested (ref. 14) that states in this energy region might be members of a quadrupole-octupole two-phonon quintet whose energy centers of gravity are expected to be 2.72, 2.60, 2.49, and 2.41 MeV (436, 416, 398, and 386 fJ) for the ^{110}Cd, ^{112}Cd, ^{114}Cd, and ^{116}Cd, respectively. The possibility that these levels result from such two-phonon transitions is emphasized by the similarity of their excitation strengths to those of the known two quadrupole-phonon transitions. The spins and parities of the members of such a quintet would be 1^-, 2^-, 3^-, 4^-, and 5^-. Such a description for the state near 2.9 MeV (464 fJ) is consistent with the previously reported assignment of 5^-, but it also suggests that the state near 2.4 MeV (384 fJ) is not the 6^+ level observed by other researchers. Although a 6^+ level could result from a three quadrupole-phonon transition, its excitation strength would be expected to be smaller than that experimentally observed for the 2.4 MeV (384 fJ) level.

Lewis Research Center,
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