kinds of Al are equivalent. The former alternative seems more likely.

CONCLUSIONS

Measurements of the average range and range straggling of the product 4.1-h Tb^{149} provide strong evidence for production of this nuclide (and its parents by radioactive decay) via pure compound-nucleus reactions. The reactions studied include compound nuclei of atomic numbers 65 to 69. Therefore the nuclide ${}_{65}Tb^{149}$ was formed by reactions involving only neutron emission and also by reactions involving charged particle emission. Seventeen different reactions were studied. The initial excitation energies varied from approx 50 to 150 MeV. Further studies of these reactions should provide information about the properties of nuclei with high excitation energies and angular momenta.

ACKNOWLEDGMENTS

We are indebted to Dan O'Connell and Gordon Steers for their tireless efforts in the preparation of targets. We appreciate the help of Ken Russell with the counting equipment. The operating crew of the Hilac furnished the projectiles.

PHYSICAL REVIEW VOLUME 128, NUMBER 5 DECEMBER 1, 1962

Studies of 15-MeV Inelastic Deuteron Scattering*

R. K. Jolly, E. K. Lin, and B. L. Cohen
University of Pittsburgh, Pittsburgh, Pennsylvania
(Received July 12, 1962)

Angular distributions of inelastically scattered deuterons from Ni leading to many individually resolved states of the final nucleus were measured. The collective 2^+ levels have identical angular distributions, but these are considerably different from those leading to other 2^+, 0^+, and 4^+ levels. Many (but not all) of the latter are strongly similar to each other. The 3^- states in Ni^{60} and Ni^{62} have similar angular distributions, but the 3^- state in Ni^{58} is appreciably different. The predictions of the Blair phase rule on relative phases of elastic scattering angular distributions and those leading to states of positive and negative parity are not valid in Ni, but they apply fairly well to the collective states in Zr and Sn. While the other states in these nuclei have somewhat different angular distributions, the phase rule works well enough to make tentative parity assignments for a large number of levels. The method breaks down badly only for the two phonon levels; all attempts at systematizing data from the latter fail. A survey of energy spectra from 27 elemental and isotopic targets is reported. Corrections to a previous survey are listed.

I. INTRODUCTION AND EXPERIMENTAL METHOD

In a previous paper,[1] a study of inelastic deuteron scattering was presented, including a survey of energy spectra from a large number of nuclei through the periodic table, a few angular distribution measurements, and correlations with stripping and Coulomb excitation experiments. Unfortunately, that work was interrupted by an extended cyclotron breakdown, so that the survey of energy spectra was not as complete as had been intended, and the question of the utility of (d,d') angular distribution measurements for nuclear structure studies was left largely unanswered. It is the purpose of this paper to fill these gaps.

A most useful tool for analyzing direct interaction inelastic scattering experiments is the Blair phase rule,[2] which states that under certain approximations, the angular distribution of the inelastically scattered particle is oscillatory, and the phase of the oscillations is determined only by whether Δl, the angular momentum transferred to the nucleus in the collision, is even or odd; in particular, if Δl is odd the oscillations should be in phase with the oscillations in the elastic scattering angular distributions, and if Δl is even the phase should be shifted relative to these by 180°. Since Δl determines the parity change, this method is generally considered to be a technique for determining parities of nuclear levels. It has been used quite successfully[3] in studies of (α,α') reactions, but has been somewhat less successful in (pp') reactions,[4] probably because the interactions are not concentrated at the nuclear surface as postulated in the theory.[2] This objection is certainly not valid for (d,d') reactions, but there are the additional problems in that the deuteron does not fulfill the assumptions in the theory that the spin of the scattered particle be zero, and its size be much smaller than the radius of the target nucleus. It is thus an open question as to whether (d,d') reactions obey the Blair phase rule, and we here take an experimental approach to answering it by

* Work performed at Scaife Radiation Laboratory and Supported by the National Science Foundation and the Office of Naval Research.
[1] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).
[2] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[3] R. Beurtey, P. Catillon, R. Chaminade, M. M. Crut, H. Fraggi, A. Papineau, J. Saudinos, and J. Thirion, Compt. rend. **12**, 1756 (1961).
[4] Institute for Nuclear Study Report 38, 1961, University of Tokyo (unpublished).

measuring angular distributions in cases where spins and parities are known.

Our conclusion is that the phase rule has some validity under certain conditions, so that we then endeavor to apply it to determine parities for states whose parity is not known. The final section of this paper presents an extension of the survey of energy spectra from (d,d') reactions.

The experimental method is essentially the same as that used in reference 1, except that there have been improvements in the energy resolution and in the energy calibration.[5,6] To recapitulate briefly, the reaction products are magnetically analyzed in passing through a wedge magnet spectrograph, and detected by the tracks they leave in a photographic emulsion located on the focal plane of the spectrograph. The track densities are then determined by counting the tracks under a microscope. Typical data are shown in Fig. 1. The energy resolution is about 40 keV except in cases where it is limited by target thickness.

II. ANGULAR DISTRIBUTIONS

A. Nickel Isotopes

In Ni^{58} and Ni^{60}, there are many levels of known spin and parity, so these nuclei are especially favorable for testing the validity of the Blair phase rule. In addition, the experimental resolution is sufficient to separate individual levels even when the natural

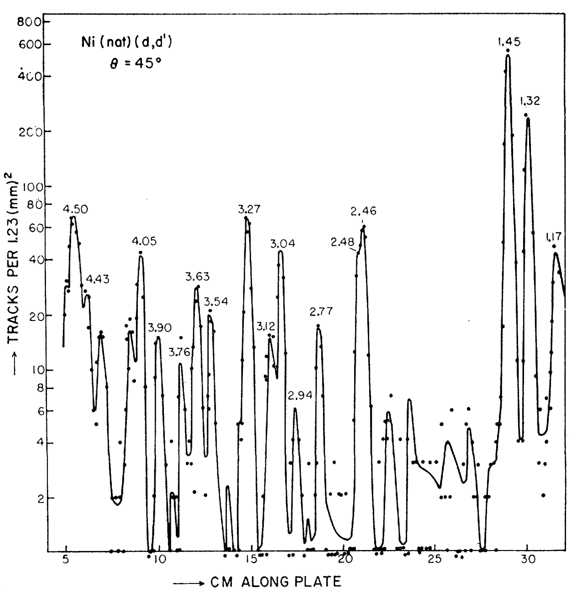

FIG. 1. Typical (d,d') data from Ni at 45°. The ordinates are the number of tracks per 1.23 $(mm)^2$ plotted on the logarithmic scale. The abscissa is the distance along the nuclear emulsion plate in cm. Numbers on the peaks are the corresponding excitation energies in MeV averaged over all scattering angles. The average resolution is ~40 keV.

[5] B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).

[6] B. L. Cohen, Rev. Sci. Instr. **33**, 85 (1962).

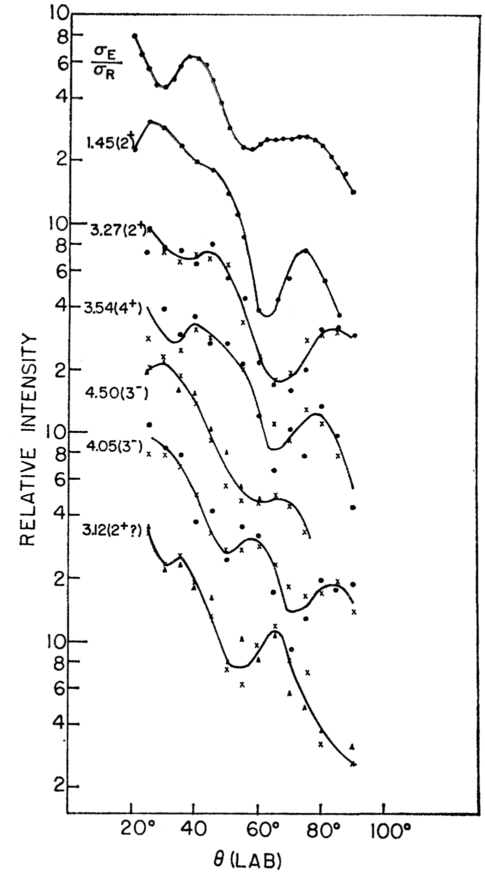

FIG. 2. Data from Ni angular distributions. For the elastic group the ratio of the elastic cross section to Rutherford cross section is plotted against the laboratory scattering angle. For the inelastic groups only a few peaks typical of the different classes mentioned in the text are shown. (See Fig. 3 for angular distributions of other groups.) Every inelastic angular distribution shows two sets of data points, each of which is the result of two or more different (but almost concordant) scannings and analyses of the same data. The numbers outside the parenthesis are the $-Q$ values while within the parentheses are the spins and parities.

isotopic mixture (68% Ni^{58}, 26% Ni^{60}) is used. Thus complete angular distributions (5° intervals from 20° to 90°) were obtained using a natural nickel target, although some checks with separated isotope targets were made. Some of the angular distribution data are shown in Fig. 2, and the compiled results are shown in Fig. 3 where they are compared with the elastic scattering angular distribution from reference.[7]

For purposes of discussing the angular distributions of Fig. 3 we divide them into the following classifications:

A. The 1.45-, 1.32-, and 1.17-MeV groups which lead to the collective 2^+ levels in Ni^{58}, Ni^{60}, and Ni^{62}, respectively.

B. The 4.50- and 4.05-MeV groups, which lead to the collective 3^- levels in these nuclei. There is little chance of wrong identification here because of the large cross sections.

[7] R. K. Jolly, E. K. Lin, and B. L. Cohen (to be published).

C. The 2.77-, 3.04-, 3.27-, 3.54-, 3.90-MeV groups, all of which have somewhat similar angular distributions.

D. All others, each of which is a special case.

Almost any theory would predict that the angular distributions for the three groups in class A should be essentially identical, and likewise for the two groups in class B. In the former case, this is clearly observed in Fig. 3, but in the latter there is a significant difference,

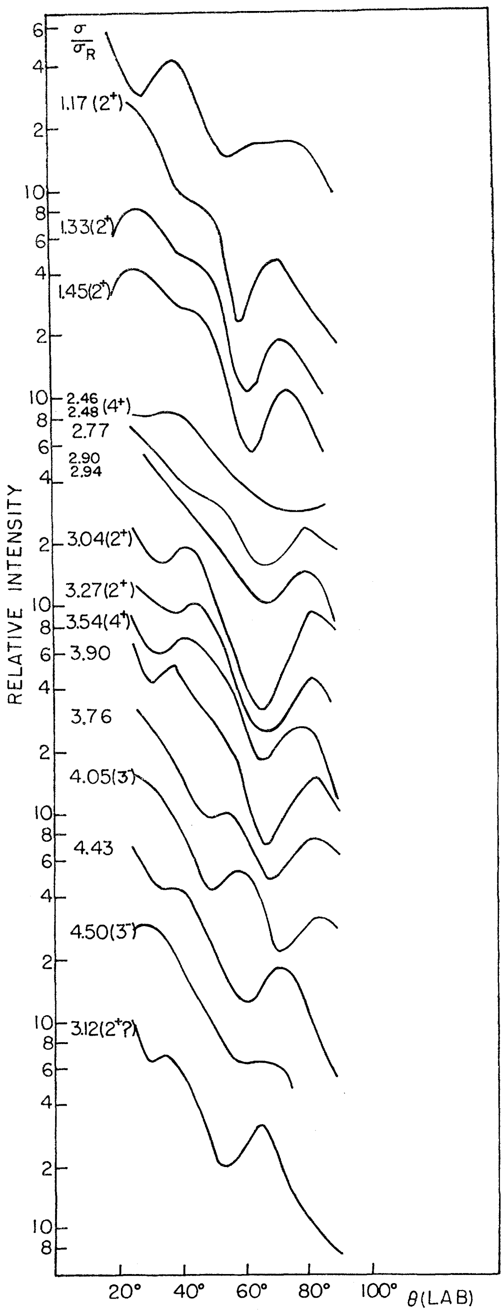

FIG. 3. Angular distributions of the elastic and inelastic deuteron groups from Ni. (See caption for Fig. 2.)

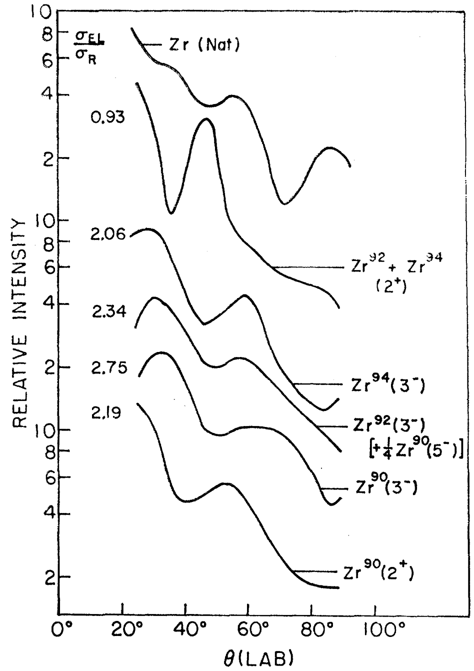

FIG. 4. Angular distributions of the elastic and inelastic deuteron groups from Zr. (See caption for Fig. 2.) The source isotopes for the different groups are indicated on the right of each angular distribution.

especially at angles beyond 50°. This is very difficult to understand, as these levels are believed to have nearly the same characteristics.

It is immediately clear from Fig. 3 that the Blair phase rule works very poorly here; class A angular distributions show some tendency to be out of phase with the elastic at small angles, but the breakdown is complete at large angles. Class B angular distributions are not in phase with the elastic, nor out of phase with the class A. Some of the levels of class C are known to be of even parity, but their angular distributions are considerably different from class A. Thus the phase rule is of little use; however it seems most probable that similar angular distributions lead to similar states. On this basis, all the levels of class C are very probably even parity.

With regard to the levels of class D:

(1) The 2.46–2.48 MeV levels are the two-phonon states discussed by Lemmer, Wall, and de-Shalit[8]; they predict angular distributions in phase with the elastic and decreasing relatively slowly with increasing angle. There are perhaps slight indications of these properties in Fig. 3, but in any case, the angular distributions are anomalous.

(2) The 2.90–2.94 MeV levels are weakly excited so that the experimental accuracy is poor. The angular distribution resembles that of class C, so that they probably are of even parity.

[8] R. H. Lemmer, A. de-Shalit, and N. S. Wall, Phys. Rev. 124, 1155 (1961).

(3) The 3.76-MeV state has an angular distribution quite similar to that from the 4.05-MeV state. It was found to be from Ni^{62} (see below) and has the cross section and energy expected for the 3^- collective state in that nucleus.

(4) The 3.12-MeV state of Ni^{60} and the 4.43-MeV state of Ni^{58} have angular distributions somewhat similar to class C, although definitely different. It would be surprising if these were negative parity states as they are below the 3^- collective levels. They are thus probably of positive parity. There is some evidence from other experiments to support this conclusion for the 3.12-MeV level.[9]

In summary, the data for the Ni isotopes indicates that the Blair phase rule is nearly useless in this region, but parity identifications are often possible by comparing with angular distributions from levels of known parity.

B. Zirconium and Tin Isotopes

Since one of the basic assumptions in derivations of the Blair phase rule is that the size of the incident particle be small compared to the radius of the target nucleus, one might hope that the phase rule is more useful in heavier nuclei. In this connection, we discuss the angular distributions in the Zr and Sn isotopes that were reported in reference 1. The principal new developments are that the levels in Zr have now been identified by use of separated isotope targets (see below), and the elastic scattering angular distributions are now available[7] for comparison.

The Zr data are shown in Fig. 4. Of all the levels included, all but the 2.19-MeV level may be judged from cross-section information to be collective. For these strongly collective levels, it is clear that the phase rule works very well. The 2^+ groups are 180° out of phase with both the elastic scattering and the 3^- groups, and the latter are all rather accurately in phase.

The angular distribution of the 2.19-MeV group is most interesting; its phase is nearly midway between those of the 2^+ and 3^- groups. Since these angular distributions were measured using a natural zirconium target, one might suspect that this data is distorted by a level at essentially the same energy in Zr^{91}; however this is ruled out by intensity considerations. Furthermore, the analog level in Sr^{88} (1.83 MeV) was found[10] to have an essentially identical angular distribution. As these levels are rather weakly collective as evidenced by their high excitation energy and the fact that they are in semi-double-closed-shell nuclei, one is led to conclude that weakly collective levels do not obey the phase rule as well as the strongly collective levels. Similar conclusions may be drawn from the nickel data by the difference between class A and class C angular distributions.

[9] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council. (U. S. Government Printing Office, Washington, D. C., 1961).

[10] E. W. Hamburger (private communication).

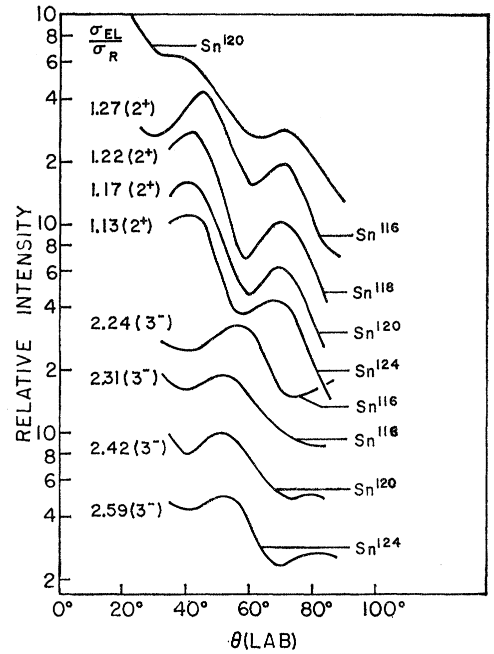

FIG. 5. Angular distributions of the elastic and inelastic deuteron groups from Sn. (See caption for Fig. 2.)

The data for the Sn isotopes is shown in Fig. 5; only the elastic and collective levels are included. It is clear that the phase rule works well in that the 2^+ and 3^- states give angular distributions which are essentially 180° out of phase, but the phase relationship with the elastic scattering angular distribution is not in accordance with the phase rule. The difficulty here may be that diffraction effects play a relatively minor role in the elastic angular distribution; this may also explain why the amplitude of the oscillations is so small.

From reference 1 (Figs. 12, 14), we see that the angular distributions for groups from noncollective levels in the Sn isotopes apparently do not have a simple phase relationship to those from the collective levels.

C. Conclusions

The most important conclusion from these angular distribution studies is that the phase rule is best fulfilled by the most collective levels. There are important differences between angular distributions from collective and noncollective levels of the same parity.

In most theoretical calculations, it is assumed that only that part of the wave function of a level which is collective contributes to the cross section for its excitation by direct-interaction inelastic scattering (DIIS). On this model, all angular distributions from states of a given spin and parity should be the same. The fact that this is not borne out experimentally might be interpreted to mean that some process other than excitation of collective modes can be important in DIIS. There is some evidence from reference 1, (the lack of correlation between cross sections for exciting given levels by

TABLE I. Level energies and parity assignments.

Zr^{90}

E(Mev) This paper	E(Mev) Reference 9	I(35°)/I(47°)	Parity This paper	Parity Reference 9	I(35°)
1.76	1.752	1.1	+	0^+	27
2.19	2.182	1.2	+	2^+	246
2.31	2.315	0.9	+	5^-	33
2.76	2.745	2.4	−		611
3.09	3.081	1.7	?	4^+	44
3.32	3.29	1.1	+		63
3.48		2.2	−		17
3.86		0.7	+		46
3.98		1.0	+		13
4.25		0.6	+		21
4.36		1.9	−		47

Zr^{91}

E(Mev) This paper	E(Mev) Reference 9	I(35°)/I(47°)	Parity This paper	Parity Reference 11	I(35°)
1.22	1.215	0.5	+	+	40
1.49	1.46	1.1	+		48
1.90	1.87	0.8	+		64
2.06	2.07	2.2	−	+	52
2.19	2.19	2.3	−		220
2.40		3.0	−		84
2.59	2.56	3.0	−	+	56
2.86	2.84	3.3	−		160
3.09	3.05	1.5	?	+	60
3.50	3.45	1.8	?		48

Zr^{92}

E(Mev) This paper	E(Mev) Reference 12	I(35°)/I(47°)	Parity This paper	Parity Reference 12	I(35°)
0.94	0.93	0.6	+	2^+	304
1.38	1.38	0.6	+	0^+	26
1.50	1.49	3.0	−	4^+	96
1.84	1.83	1.4	+	2^+	78
2.07	2.05	1.4	+	2^+	61
2.35	2.33	3.1	−	3^-	500
2.48		0.9	+		20
2.87		2.0	−		43
3.06		1.0	+		32
3.28		1.2	+		31
3.45		2.4	−		57
3.67		1.5	?		19
3.93		1.5	?		18
4.07		2.0	−		38

Zr^{94}

E(MeV) This paper	E(MeV) Reference 9	I(35°)/I(47°)	Parity This paper	Parity Reference 9	I(35°)
0.92	0.916	0.6	+	+	292
1.31	1.30	0.5	+		37
1.47	1.47	2.3	−		93
1.68	1.66	0.8	+		116
2.06	2.06	2.6	−		751
2.35	2.32	1.1	+		93
2.60		1.4	+		24
2.89		1.5	?		100
3.28					40
3.61		2.0	−		45
3.92		2.0	−		45

Zr^{96}

E(MeV) This paper	I(35°)/I(47°)	Parity This paper	I(35°)
1.73	0.6	+	220
1.87	2.4	−	1020
2.03	2.0	−	52
2.42	1.0	+	34
2.84	2.1	−	30
3.11	1.5	−	100
3.18	1.9	−	160
3.50	0.7	+	22
4.04	1.0	+	41
4.30	2.6	−	20

DIIS and stripping) that this other process is probably *not* excitation of single particles to higher particle states. The identification of this other process is therefore a problem of extreme interest and importance. The fact that the structure in the angular distributions of class C levels in Ni and the 2.19-MeV level in Zr is shifted to larger angles may indicate that this process takes place somewhat inside of the nuclear surface.

The probability for this other process is not grossly smaller than for the collective effect. The cross section for the 2.19-MeV level in Zr is only $\sim 25\%$ less than the cross section for the 0.9-MeV 2^+ levels in Zr^{92} and Zr^{94}. The 3^- collective levels in Ni are no more strongly excited than the strongest noncollective states. It should be pointed out, however, that collective effects are weaker in all cases studied here than in typical nuclei far from closed shells.

The rather poor performance of the phase rule in nickel indicates that further theoretical work on the inelastic deuteron scattering process would be desirable. Some method for treating the internal structure of the deuteron must be developed.

III. PARITY ASSIGNMENTS

Inasmuch as the phase rule works to some extent in Zr and Sn, one might hope to use it to determine parities of levels for which the parity is not known. In principle, one should measure angular distributions, but it is much simpler and almost as reliable within the limitation of the method to measure intensity ratios at two angles chosen such that the intensity ratio is very different for odd and even parity states. In the Zr region, Fig. 3 suggests that 35°/47° intensity ratio $\simeq 0.4$ for positive parity states and $\simeq 2.1$ for negative parity states. When this was used for a number of levels of known parities, it was found that most of the parities are correctly determined if the index is taken as

$$\begin{aligned} I(35°)/I(47°) &= 0.4 \text{ to } 1.4\text{—parity positive} \\ &= 1.4 \text{ to } 1.9\text{—parity uncertain} \quad (1) \\ &= 1.9 \text{ to } 3.1\text{—parity negative.} \end{aligned}$$

This index was then used for the Zr isotopes and Nb. In the Sn region, Fig. 4 suggests that 42° and 59° are suitable angles. The index finally chosen is

$$\begin{aligned} I(42°)/I(59°) &= 0.4 \text{ to } 1.6\text{—parity negative} \\ &= 1.6 \text{ to } 2.1\text{—parity uncertain} \quad (2) \\ &= 2.1 \text{ to } 4 \text{ —parity positive.} \end{aligned}$$

This index was then used for Rh, Pd, Cd, and In.

The parity assignments made by use of (1) and (2) are shown in Tables I–III.[11–13] In general, the agreement is reasonably good in cases where the parity is known. The principle exceptions are cases where members of the two-phonon triplet have ratios characteristic of negative parity; some of these are Pd^{104}—1.34 MeV, Pd^{106}—1.14 MeV, Pd^{108}—0.93, 1.05 MeV, and perhaps Zr^{92}—1.50 MeV and Zr^{94}—1.47 MeV. This is in accordance with the predictions of reference 8. On the other hand, at least one member of a two-phonon triplet—the 1.24-MeV level in Pd^{106}—has a ratio characteristic of positive parity. The situation for the two phonon states thus seems confused, but it is clear that as in the case of Ni, they do lead to exceptional angular distributions.

The other discrepancies with known data in Tables I–III are the 2.32-MeV 5^- state in Zr^{90}, and the 2.07- and 2.56-MeV states in Zr^{91}. It is only fair to point out, however, that the number of cases where parities are known is not large.

A notable feature of Tables I–III is the wide variation in the ratios. This reinforces the conclusion drawn above that angular distributions are not determined only by spins and parities.

It is difficult to evaluate the reliability of the parity determinations in Tables I–III. Certainly it would have been better to measure more complete angular distributions, but there would still be strong uncertainties in most cases if we may judge from the experience with angular distributions in Ni, Zr, and Sn discussed above. It was therefore not considered worth the great amount of extra effort needed to measure complete angular distributions. The parity assignments in Tables I–III are far from certain, and should be considered as indications rather than determinations.

IV. SURVEY OF ENERGY SPECTRA

In reference 1, a survey of energy spectra from (d,d') reactions in a large number of targets was presented. This data has proven useful for level identification, comparison with other inelastic scattering experiments, etc. We therefore present here an extension of that survey to many other elemental and isotopic targets. Curves through the data are shown in Figs. 6–10, and the energies of prominent levels are listed in Tables

[11] B. L. Cohen, Phys. Rev. **125**, 1358 (1962).
[12] Merle E. Bunker (private communication).
[13] B. L. Cohen and R. E. Price, Phys. Rev. **118**, 1582 (1960).

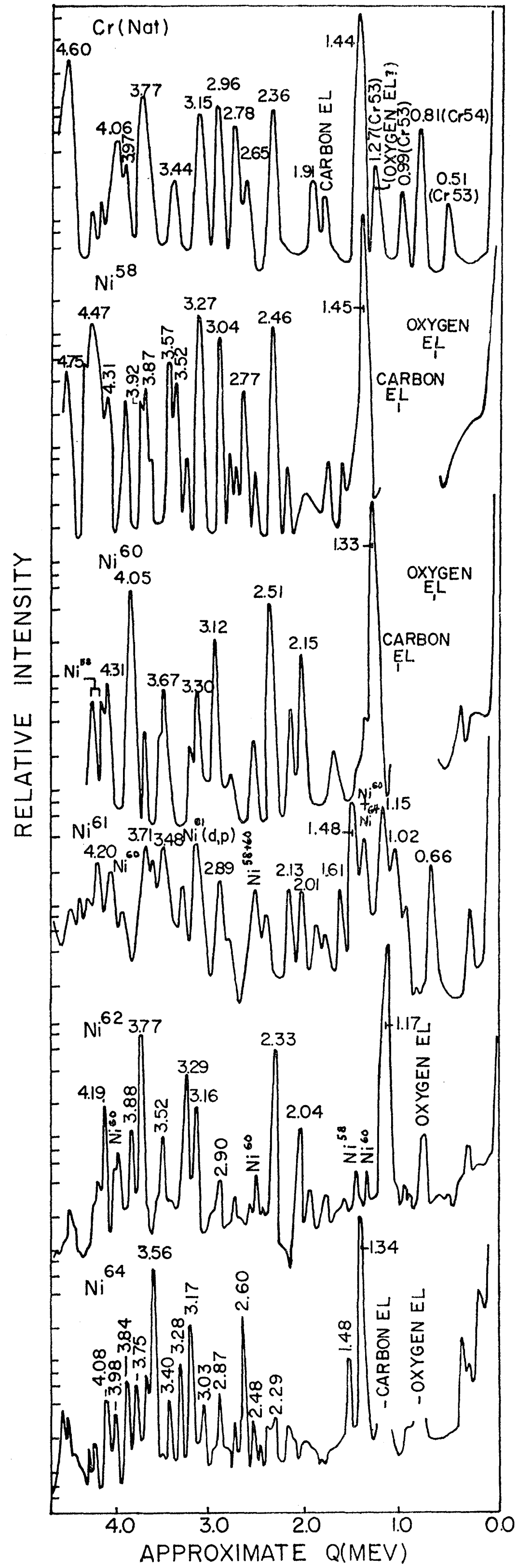

FIG. 6. Energy spectra of deuterons inelastically scattered from natural Cr, and Ni isotopes. Angles of observation are 60° for Cr and Ni^{61}, and 45° for Ni^{58}, Ni^{60}, Ni^{62}, and Ni^{64}. Spectra were obtained at two or more angles, so as to pick out peaks due to light element contamination of the target. Level assignments have been made only for peaks which appear definitely at all angles. Numbers on peaks are excitation energies in MeV; they are more accurate than the energy scale shown on the axis. Ordinate scale is logarithmic, but different curves are shifted arbitrarily.

TABLE II. Level energies and parity assignments.

Nb^{93} E(MeV) This paper	Nb^{93} E(MeV) Reference 9	$I(36°)/I(47°)$	Parity This paper	$I(47°)$	Rh^{103} E(MeV) This paper	Rh^{103} E(MeV) Reference 9	$I(42°)/I(59°)$	Parity This paper	Parity Reference 9	$I(42°)$	In^{115} E(MeV) This paper	In^{115} E(MeV) Reference 9	$I(42°)/I(59°)$	Parity This paper	Parity Reference 9	$I(42°)$
0.75	0.741	1.2	+	70	0.35	0.361	3.3	−	−	460	1.11	1.14	3.4	+		41
0.96	0.958	0.8	+	120	0.88		1.8	?		39	1.28	1.29	4.1	+	+	22
1.08	1.08	2.1	−	30	1.26	1.26	2.1	−		19	1.46	1.42	2.6	+	+	15
1.32	1.34	1.4	+	31	1.47		3.8	−		12	2.09	2.15	0.7	−		7
1.51	1.48	0.9	+	10	1.67	1.64	1.8	?		9	2.42	2.43	1.3	−		8
1.68	1.67	2.4	−	11	1.78		1.4	+		13						
1.96	1.92	0.9	+	12	1.99	2.02	1.4	+		21						
2.17		2.4	−	50	2.09		1.4	+		21						
2.51		1.8	?	20	2.29		1.8	?		14						
2.85		1.2	+	30	2.43	2.37	2.9	−		10						
					2.62		1.2	+		6						

IV–VI.[14–18] For all cases presented here, spectra were obtained at two or more angles so as to identify peaks due to light element contaminants. Levels listed in Tables were observed at each angle. Only levels which are quite certainly assigned are listed; there is good evidence from Figs. 6–10 for many additional levels.

Figure 6 shows the energy spectra at a single angle for (d,d') reactions in natural chromium, Ni^{58}, Ni^{60}, Ni^{61}, Ni^{62}, and Ni^{64}, and the energies of the levels found are listed and compared with other data in Table IV. Almost all levels except those in Ni^{64} and some in Ni^{62} were known previously, and the agreements in energies are satisfactory. However, the 1.91-MeV level in the chromium spectrum is too strongly excited to be from the known level in Cr^{50} or even from an unknown level in Cr^{53}; it is very probably from a level in Cr^{52}. The 3.90- and 4.47-MeV levels in Ni^{58} are clearly multiple; in the angular distribution work with natural nickel, the latter was resolved into a strong peak at 4.50 MeV and a much weaker one at 4.43 MeV. From energy and intensity systematics the 3.77- and 3.56-MeV levels in Ni^{62} and Ni^{64}, respectively, may be identified as the collective 3^- states. There is angular distribution evidence confirming this in Ni^{62} (see Fig. 3). In the five even-even isotopes, the 4^+ two-phonon level is about 8 times less strongly excited than the one phonon level. In Ni^{60}, where the 0^+, 2^+, 4^+ triplet is tentatively identified, the cross sections for exciting these are roughly proportional to $(2j+1)$ as might perhaps be expected; but this rule is by no means universal as will be noted below. In general, these spectra are characterized by several even-parity states excited about as strongly as the two-phonon states in the region up to the collective 3^- states.

In Ni^{61}, the 1.15- and 1.46-MeV levels are presumably the strongest one-phonon states. It is interesting to note that these levels are only very weakly excited in the Ni$^{60}(d,p)$ reactions. This is also the case with the two next-most strongly excited levels here, at 0.66 and 1.02 MeV. The level at 1.35 MeV in the Ni^{61} spectrum is probably due to Ni^{60} isotopic impurity.

The data for the zirconium isotopes is shown in Fig. 7 and Table I. For the even Zr isotopes, the 3^- collective levels can be identified easily, as they are by far the

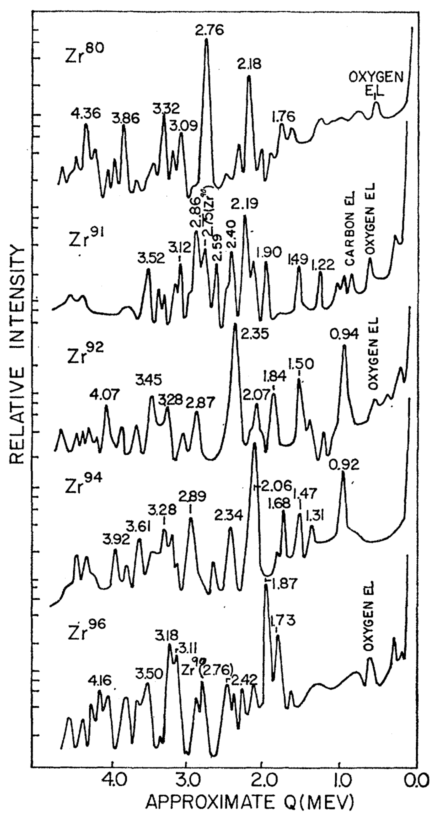

FIG. 7. Energy spectra of deuterons inelastically scattered from Zr isotopes at 35°. (See caption for Fig. 6.)

[14] K. Matsuda, Institute for Nuclear Study, University of Tokyo, Tokyo, Japan.

[15] Atomic Energy Commission Nuclear Level Schemes, $A=40$–90 (unpublished).

[16] B. L. Cohen, S. Mayo, and R. E. Price, Nuclear Phys. **20**, 360 (1960).

[17] P. Mukherjee and B. L. Cohen (to be published).

[18] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. **123**, 923 (1961).

TABLE III. Level energies and parity assignments.

Pd^{104}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 9	I(59°)
0.56	0.556	3.4	+	2^+	252
1.34	1.34	1.4	−		65
2.20		0.9	−		190
2.64		0.8	−		15
2.80		1.1	−		15
3.10		1.0	−		11
3.19		1.1	−		7
3.44		2.0	?		9

Pd^{106}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 9	I(59°)
0.52	0.513	5.4	+	2^+	540
1.14	1.125	1.2	−	2^+	100
1.24	1.22	4.0	+	4^+	30
1.95	1.92	1.1	−		22
2.09	2.09	0.9	−	3^-	307
2.29	2.28	1.6	−		21
2.41	2.46	1.0	−		19
2.51		1.4	−		25
2.68	2.68	1.5	−		15
2.77	2.78	1.4	−	5^-	36
3.11	3.06	1.5	−		8
3.26		1.1	−		16

Pd^{108}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 9	I(59°)
0.44	0.43	3.7	+	2^+	650
0.93	0.94	0.6	−	2^+	90
1.05	1.03	1.5	−	$0^+, 4^+$	42
1.44		1.6	−		20
1.63		2.8	+		12
1.77		1.9	?		8
2.03		0.7	−		245
2.38		1.4	−		16
2.55		0.8	−		23
2.96		0.9	−		17

Cd^{111}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 9	I(59°)
0.26	0.247	1.6	?	$5/2^+$	17
0.34	0.342	5.3	+	$3/2^+$	9
0.43	0.420				8
0.61	0.605	3.7	+	$5/2^+$	15
0.73	0.73				6
1.69	1.7				3
1.79					11
1.96		0.6	−		11

Cd^{113}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 13	I(59°)
0.30	0.300	3.5	+	$3/2^+$	16
0.58	0.582	4.2	+	$5/2^+$	48
0.69	0.675	3.8	+		9
1.16	1.18				6
1.76		5	+		10
2.01(?)					

Cd^{114}

E(MeV) This paper	E(MeV) Reference 9	I(42°)/I(59°)	Parity This paper	Parity Reference 9	I(59°)
0.56	0.56	4.0	+	2^+	150
1.15	1.15			+	5
1.21	1.21			+	15
1.28	1.28			+	12
1.37	1.37			+	9
1.86	1.86			+	4
1.98	1.96(?)	0.4	−		110
2.31	2.26	2.1	+	2^+	10
2.41	2.45	1.2	−		23
2.55	2.53	2.3	+	0^+	3
2.65	2.62	4.6	+	0^+	3
2.78	2.78	1.1	−		10
2.88	2.90	2.2	+	0^+	6
2.97	2.97	4.1	+		3
3.07	{3.00, 3.14}	1.4	−		7

most strongly excited in the spectrum. The 2^+ states are the second most strongly excited, so that they are presumably somewhat collective; this includes the 2.19-MeV state in Zr^{90}, although evidence is cited above against its collective nature. There is also evidence[13] that the 2^+ state in Zr^{92} is almost pure $(d_{5/2})_2{}^2$, and thus not collective. In Zr^{91}, both the 3^- and 2^+ collective states are mixed among many levels, as expected, but the energies are about the same as in Zr^{90}. The 1.49- and 1.89-MeV states in Zr^{91} are not excited in $Zr^{90}(d,p)$ reactions,[11] but all of the others up to the 2.74-MeV state are known from that reaction and are strong single-particle states. The data for the Pd and Cd isotopes are shown in Fig. 8. In the even Pd isotopes the three most strongly excited levels (in decreasing order) are the collective 2^+, the collective 3^-, and the two phonon states. In Pd^{106} and Pd^{108}, the 2^+ states are the most strongly excited of the two-phonon triplet, whereas in Ni the 4^+ was the most strongly excited. The spectrum of all Pd isotopes is dominated by odd-parity levels above the 3^- collective state.

In all of the even Pd and Cd isotopes studied here, the 3^- collective state is a single nuclear state (within our resolution) in agreement with theory. In both Pd and Cd, the one-phonon states are excited about eight times more strongly than the two-phonon states; this ratio is the same as in Ni. In Cd^{114}, the 2^+ is the most strongly excited two-phonon state (as in Pd); the two-phonon 2^+ state is apparently shared among the 1.21- and 1.37-MeV states, with the former being stronger.

In Cd^{111}, the collective states (populated in Coulomb excitation) are the 0.34- and 0.61-MeV levels. It, therefore, is most surprising that the 0.26-MeV level for which the ground state γ-ray transition is 3000 times slower, is about as strongly excited as these in (d,d') reactions. This is a clear demonstration that collective effects are not the only important ones in inelastic scattering. The situation is somewhat more normal in Cd^{113}, where the most strongly excited low lying states are the 0.30-, 0.59-, and 0.68-MeV levels which are just those excited in Coulomb excitation. In both Cd^{111} and Cd^{113}, the collective 3^- states are easily recognizable.

The data for Sb, Ce, and Sm are shown in Fig. 9. All of these targets are natural isotopic mixtures, which makes assignments to isotopes very difficult. The spectrum from $_{51}Sb$ bears a resemblance to that from $_{49}In$.[1] Presumably the levels from 0.54 to 1.51 MeV are the 2^+ states (coupled to the odd proton) and the 2.13-

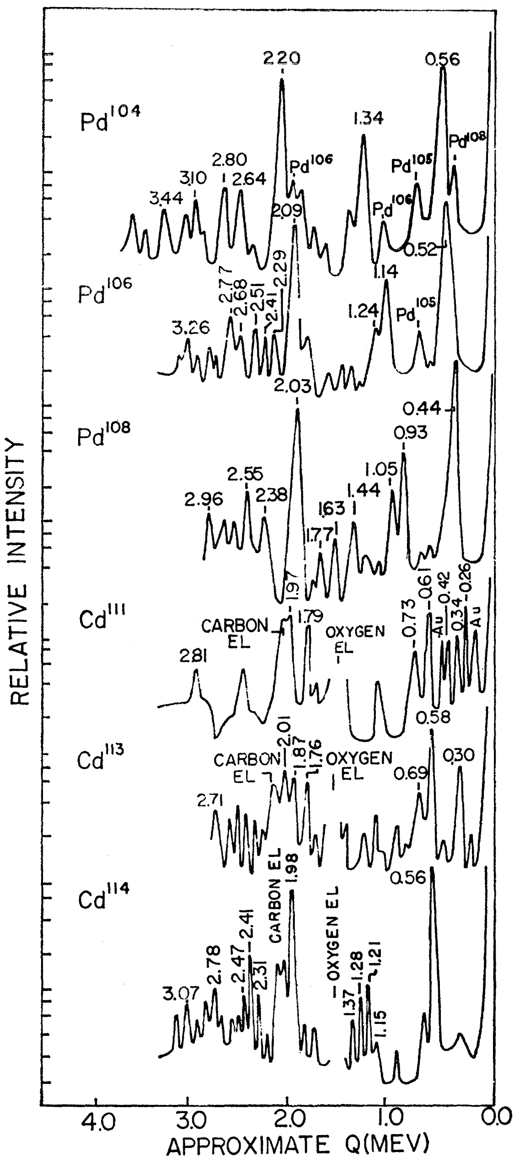

FIG. 8. Energy spectra of deuterons inelastically scattered from Pd and Cd isotopes at 59°. (See caption for Fig. 6.)

and 2.43-MeV groups are the 3^- states. Ce is 88% Ce^{140}, so that the strongest levels are from that isotope; the 1.60-MeV level is the 2^+ first excited state, and the 2.08-MeV level, which is rather strongly excited, is known to be 4^+.

From its energy and cross section, the 2.46-MeV level is presumed to be the collective 3^-. This may be the level excited in the beta decay of La^{140} which is assigned as spin 3 but parity uncertain.[9] Several of the known states of Ce^{142} can also be identified in the cerium spectrum.

Samarium has several isotopes including some with rotational and some with vibrational spectra. The 0.13-MeV level in Sm^{152} is the only rotational level encountered in this entire survey; it is very strongly

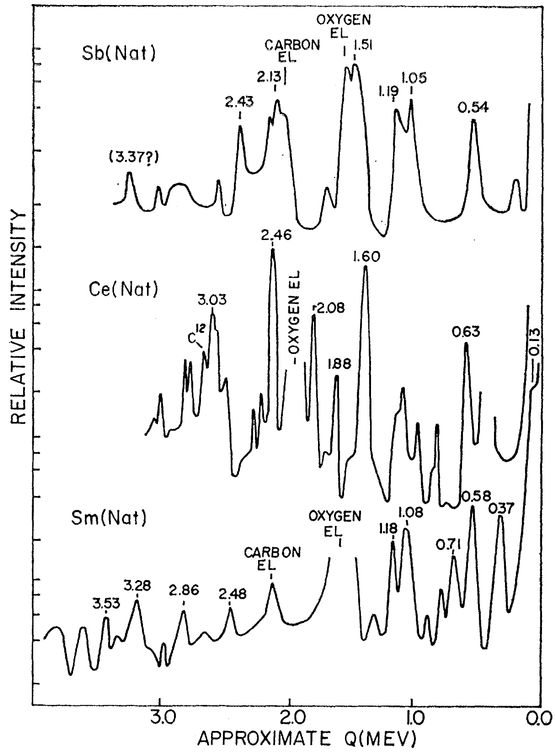

FIG. 9. Energy spectra of deuterons inelastically scattered from natural Ce at 75°, and Sb and Sm at 59°. The scale for Ce is different from the scale for Sb or Sm. (See caption for Fig. 6.)

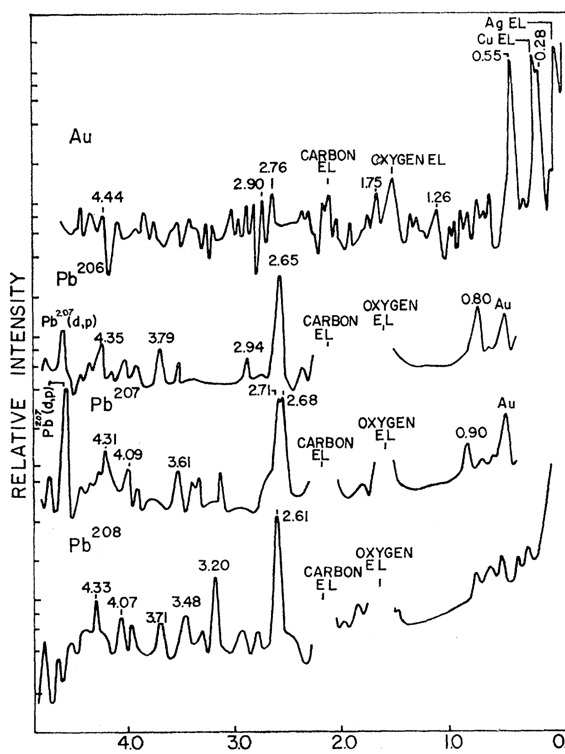

FIG. 10. Energy spectra of deuterons inelastically scattered from Au and Pb isotopes at 60°. (See caption for Fig. 6.)

TABLE IV. Level energies (MeV).

Cr (natural) This paper	Cr Reference 14	Cr References 9 and 15	Cr $I(60°)$	Ni^{58} This paper	Ni^{58} Reference 14	Ni^{58} Reference 9	Ni^{58} $I(45°)$	Ni^{60} This paper	Ni^{60} Reference 14	Ni^{60} Reference 9	Ni^{60} $I(45°)$	Ni^{61} This paper	Ni^{61} Reference 9	Ni^{61} $I(60°)$
0.51 (53)		0.54	7	1.45	1.449	1.452	600	1.33	1.333	1.333	657	0.28	0.284	13
0.81 (54)		0.842	40	2.46	2.459	2.458	60	2.16	2.158	2.159	27	0.66	0.660	36
0.99 (53)		0.97	10	2.77	2.780	2.772	15	2.29	2.287	2.285	9	0.92	0.915	14
1.27 (53)		1.29	19	3.04	3.045	3.025	49	2.52	2.503	2.504	82	1.02	1.019	51
1.44 (52)	1.438	1.433	428	3.27	3.260	3.260	80	2.64	2.640	2.624	3	1.15	1.137	125
1.91 (50)		1.90	12	3.52	3.526	3.528	19	3.14	3.110	3.120	39	1.46	1.460	140
2.36 (52)	2.371	2.368	61	3.57		3.592	30	3.31	3.280	3.316	12	1.61	1.616	20
2.65 (53)	2.662	2.66	12	3.87	3.906	3.898	16	3.38	3.390	3.391	2	1.75	1.735	6
2.78 (52)	2.768	2.767	44	3.90			13	3.70	3.670	3.670	13	1.82	1.812	8
2.96 (52)	2.963	2.97	65	4.10	4.103	4.106	13	3.75	3.726	3.732	4	2.01	2.007	18
3.15 (52)	3.162	3.161	55	4.47	4.45	4.5	65	3.92	3.920	3.886	5	2.13	2.127	19
3.44 (52)	3.432	3.46	14	4.75	4.75		24	4.07	4.038	4.038	113	2.57	2.599	12
3.77 (52)	3.767		81					4.33	4.31	4.31	15	2.89	2.890	26
3.97 (52)	3.926		17									3.13	3.112	45
4.06 (52)	4.03		29									3.48	3.488	53
4.60 (52)	4.56		166									3.65	3.643	40

Ni^{61} This paper	Ni^{61} Reference 9	Ni^{61} $I(60°)$	Ni^{62} This paper	Ni^{62} Reference 9	Ni^{62} $I(45°)$	Ni^{64} This paper	Ni^{64} Reference 9	Ni^{64} $I(45°)$
3.71	3.743	55	1.17	1.17	1170	1.34	1.34	845
3.95	3.924	11	2.04	2.05	29	1.48		15
4.07	4.078	20	2.33	2.34	162	2.29		9
4.20	4.184	38	2.90	2.90	8	2.49		6
4.77	4.756	10	3.16	3.17	48	2.60		110
			3.29	3.26	92	2.87		19
			3.52	3.52	24	3.03		13
			3.77		225	3.17		94
			3.88		27	3.28		40
			4.19		47	3.40		16
			4.24		5	3.56		320
						3.64		34
						3.75		23
						3.84		27
						3.98		12
						4.08		12

excited. There is no indication of a strongly excited 3^- level in Sm; this has previously been found to be the case in this mass region.

The data for Au and the Pb isotopes are shown in Fig. 10. The Au spectrum is dominated by the two collective levels at 0.28 and 0.55 MeV, but levels are clearly resolved out to 3 MeV. It is difficult to speculate on which levels belong to the 3^- group, but there are many available possibilities.

The Pb spectra are dominated by the collective 3^- levels at about 2.6 MeV. The 5^- state in Pb^{208} at 3.20 MeV is also strongly excited, which may mean that it is collective. However, there is no analog level in the other isotopes. The 4.33-MeV 4^+ collective level[18] is

TABLE V. Level energies (MeV).

Sb (natural) This paper	Sb Reference 9	Sb $I(59°)$	Ce (natural) This paper	Ce Reference 9	Ce $I(75°)$	Sm (natural) This paper	Sm Reference 9	Sm $I(59°)$
0.54	0.54	9	0.63	0.63	11	0.13	0.12	280
1.05	1.042	13	1.60	1.60	40	0.37	0.37	37
1.19	1.20	11	2.08	2.08	17	0.58	0.56	42
1.51	1.504	25	2.46	2.41	56	0.71	0.69	15
2.13	2.160	11	2.66	2.65	2	0.80	0.78	7
2.43		7	2.93	2.92	4	1.08	1.09	27
			3.03		16	1.18	1.18	21
			3.14		7	2.48	2.4	4
			3.24		7	2.86	3.1	5
			3.32	3.30	7	3.28		7
						3.53		4

TABLE VI. Level energies (MeV).

Au			Pb^{206}			Pb^{207}			Pb^{208}			
This paper	Reference 9	$I(60°)$	This paper	Reference 16	$I(60°)$	This paper	Reference 9	$I(60°)$	This paper	Reference 17	Reference 18	$I(60°)$
0.28	0.279	160	0.80	0.81	80	0.57	0.570	94	2.61		2.62	240
0.55	0.548	210	2.65		230	0.90	0.894	33	3.20	3.19	3.20	44
1.26	1.22	10	2.94	2.95	29	2.68	2.71	138	3.48	3.47	3.48	11
1.64	1.68	18	3.58		25	2.71		128	3.71	3.73	3.71	9
1.75		12	3.79		33	3.61	3.61	16	3.97	4.01	3.96	8
2.22	2.20	10	4.35		35	4.09	4.10[a]	16	4.08			11
2.36		5				4.31	4.37	21	4.33	4.32	4.3	20
2.76		11							4.47			8
2.90		11							4.59	4.61		6
3.02	3.0	9							4.83	4.86		9
3.20		7										
3.84		5										
3.93		6										

[a] See reference 17.

somewhat more excited than neighboring levels, and there are analog levels in the other isotopes. The 0.80-MeV 2^+ state in Pb^{206} is rather strongly excited as expected from Coulomb excitation data.

TABLE VII. Corrections to previous survey of energy spectra.

	Reference 1	Corrected		Reference 1	Corrected
V	2.42	2.42	Nb	2.16	2.20
	3.91	4.00		2.81	2.91
Fe	2.66	2.67	Rh	2.10	2.17
	3.82	3.93	Pd	2.19	2.21
Co	2.18	2.20	Ag	2.17	2.22
	3.81	3.87		2.85	2.93
Cu	2.51	2.54	Cd	2.02	2.04
	3.81	3.87		3.85	3.96
Zn	2.71	2.74	In	2.49	2.49
	3.87	3.93	Te	2.07	2.09
Se	2.67	2.68		3.33	3.42
Ba	2.22	2.24	Sn^{116}	2.24	2.24
	2.83	2.90		3.92	3.99
	3.63	3.74	Sn^{117}	2.33	2.34
Pr	2.33	2.36		3.28	3.35
	3.04	3.11	Sn^{118}	2.31	2.31
Nd	1.21	1.21		3.65	3.73
	2.09	2.11	Sn^{119}	2.28	2.27
	3.51	3.60	Sn^{120}	2.42	2.43
Er	0.82	0.82		4.57	4.72
	2.25	2.29	Sn^{122}	2.48	2.50
Ta	2.03	2.02		4.43	4.58
	2.85	2.89	Sn^{124}	2.59	2.62
Pt	1.44	1.44		4.62	4.79
	2.17	2.19			
	3.29	3.39			
Y	2.54	2.61			
	3.79	3.85			
Zr	3.31	3.42			

V. CORRECTIONS TO SURVEY OF ENERGY SPECTRA IN REFERENCE 1

Since the publication of reference 1, a new and much improved energy calibration of the spectrograph system has been carried out. The energies of a few levels from each spectrum reported there have therefore been recalculated and are presented in Table VII.

The survey of spectra for reference 1 was cut short by an extended cyclotron breakdown, so that many of the spectra included in that survey were not measured at more than one angle. As a result, peaks from light element contaminants were inadvertently included in a few cases. The levels shown for the Sn isotopes at 1.48–1.57 MeV have been found to be due to oxygen in several of the isotopes. Similar levels in Ag, Cd, and Pr are also very probably due to oxygen.

ACKNOWLEDGMENTS

The authors are greatly indebted to N. Austern and H. McManus for helpful theoretical discussions, to J. DeFrancesco and W. Leonard for unsparing assistance in taking data, and to George Fodor of this laboratory and Frank Karasek of the Argonne National Laboratory for preparing the targets.