Scattering of Alpha Particles by Cr^{52}, Cr^{53}, and V^{51}†

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The scattering of various-energy alpha particles by Cr^{52} has been studied. The spins and parities of most of the Cr^{52} levels up to 7 MeV were either assigned or confirmed. The reduced transition probabilities $B(EI)\downarrow$ for several levels were determined with the aid of the Austern-Blair model. Similar measurements with 50-MeV alpha particles on Cr^{53} and V^{51} were made and some evidence is considered for the description of Cr^{53} as a Cr^{52} core coupled to an odd neutron.

I. INTRODUCTION

THE scattering of medium-energy alpha particles has been used as an effective tool for the study of nuclear spectroscopy in numerous cases. Since the alpha particles are strongly absorbed, the observed scattering to low-lying excited states results primarily from the surface of the nucleus. This makes the method particularly advantageous for the study of surface vibrational states. The most useful experimental information is the variation of the differential cross section as a function of the center-of-mass scattering angle. In general, these angular distributions obey the Blair phase rule[1] and give characteristic patterns indicative of the angular momentum transferred to the nucleus. For an even-even nucleus this is equivalent to a spin and parity assignment of the state excited. The two-phonon, 4+ states are an exception and do not give characteristic angular distributions at any particular incident energy. The relative phase of these distributions has been seen to vary with respect to that of the elastic as a function of the incident alpha energy.[2] Hence, one may not be able to make definite spin assignments without studying the scattering at several energies.

One of the most useful of the theoretical models for alpha scattering is that of Austern and Blair.[3]

The model uses the standard form for the elastic scattering amplitude

$$f_{\mathrm{el}}(\theta)=f_c(\theta)+(i/2k)\sum_{l=0}^{\infty} e^{i\sigma_l}(2l+1)(1-\eta_l)P_l(\cos\theta),$$

where $f_c(\theta)$ is the Coulomb amplitude, σ_l the Coulomb phase shift for the lth partial wave, η_l the complex amplitude of the lth outgoing partial wave, $P_l(\cos\theta)$ the Legendre polynomial of order l, and k the relative wave number. The form of η_l is parametrized to be

$$\eta_l=\epsilon+B\Delta\frac{d\epsilon}{dl}+i\left(A\Delta\frac{d\epsilon}{dl}+D\Delta^2\frac{d^2\epsilon}{dl^2}\right),$$

where

$$\epsilon=(1+e^{(L-l)/\Delta})^{-1}.$$

The parameters L, Δ, A, B, and D were determined by a least-squares fit to the experimental elastic cross sections with the aid of a search program due to Springer,[4] who along with Darriulat, suggested the form for η_l. In the Austern-Blair model the scattering amplitude for the excitation of a single phonon is given by

$$f_{IM_I};00=\{\tfrac{1}{2}i(2I+1)^{1/2}\sum_{ll'} i^{l-l'}(2l'+1)^{1/2}e^{i(\sigma_l+\sigma_{l'})}\times\langle l'I,00|l,0\rangle\langle l'I,{-M_I}M_I|l,0\rangle\times(\partial\eta_{\bar{l}}/\partial_{\bar{l}})Y_{l'}^{-M_I}(\theta,0)\}C_1(I),$$

where $\bar{l}$ equals $\frac{1}{2}(l+l')$. All of the terms enclosed in braces can either be calculated or determined from the fit to the elastic angular distribution. This quantity when squared $(d\sigma/d\Omega)=|f|^2$) may be compared to the experimental to obtain the matrix element, $C_1^2(I)$.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{exp}}\Big/\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{calc}}=C_1^2(I)=\frac{\delta^2(I)}{(2I+1)}.$$

In general we chose to determine the ratio at the second observed maximum in the angular distributions. From the values of $\delta^2(I)$ [$\equiv\beta_e(I)R_e$; R_e is the electromagnetic radius] the reduced transition probability can be determined.

$$B(EI)\downarrow=\left[\frac{3}{4\pi}ZR_e^I\right]^2\frac{\beta_e(I)}{2I+1}=\frac{(3/4\pi)^2Z^2R_e^{2I-2}\delta^2(I)}{2I+1}.$$

Specifically,

$$B(E2)\downarrow=1.643\times10^{-2}Z^2A^{2/3}\delta^2(2)\quad(\mathrm{F})^4/e^2,$$
$$B(E3)\downarrow=1.690\times10^{-2}Z^2A^{4/3}\delta^2(3)\quad(\mathrm{F})^6/e^2.$$

This paper presents a study of the levels of Cr^{52}

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[1] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[2] J. R. Meriwether, A. Bussière de Nercy, B. G. Harvey, and D. J. Horen, Phys. Letters **11**, 299 (1964).
[3] N. Austern and J. S. Blair, Ann. Phys. (N. Y.) **33**, 15 (1965).
[4] A. Springer, University of California Lawrence Radiation Laboratory Report No. UCRL-11681, 1965 (unpublished).

using an Austern-Blair analysis of our inelastic-scattering data.

The success of the Thankappan and True model[5] for the levels of Cu^{63} prompted us to study the levels of Cr^{53}. In terms of this model, Cr^{53} would be considered as an odd neutron in any one of three shell-model states—$p_{3/2}$, $p_{1/2}$, or $f_{5/2}$—coupled to the quadrupole vibration of the core, Cr^{52}. Although this model cannot take into account a proton hole in Cr^{52}, the levels of V^{51} were investigated experimentally in order to consider the possibility of such a coupling.

II. EXPERIMENTAL

The Berkeley 88-in. cyclotron was used to produce incident alpha particles of 23.5, 33, 50, and 75 MeV which were scattered from isotopically pure Cr^{52}, Cr^{53}, and V^{51} targets. The targets were thin, evaporated metal foils—between 200 and 400 $\mu g/cm^2$.

The beam-handling system and the scattering chamber have been described elsewhere.[6] The scattered alphas were detected in a unit consisting of four lithium-drifted silicon counters fixed at two (2.0) degree intervals. Thus the unit measured four energy spectra simultaneously at each position to which it was rotated. Pulses from the detectors were amplified by field-effect transistor preamplifiers[7] placed in the vacuum system. The pulses were further amplified[8] and then routed into quadrants of an ND-160, 4096-channel analyzer (one quadrant for each counter). After the accumulation of the energy spectra, the contents of the analyzer memory were transferred directly into the core of a PDP-5 computer.[9] All of the preliminary, and some of the final processing of the data was completed using the computer. For example, the spectra were permanently stored on magnetic tape, plotted, and those peaks that were completely resolved were integrated. The center-of-mass cross sections and scattering angles were then immediately calculated. Peaks in the spectra which were not experimentally resolved were separated using the IBM-7094 program, VFIT.[10,11]

III. RESULTS

Figure 1 shows the energy spectra taken at a laboratory angle of 50° obtained from the scattering of 50-MeV alpha particles from Cr^{52}. This angle was chosen because none of the alpha groups of interest are obscured by the groups due to the impurities, carbon and oxygen. Angular distributions for the principal alpha groups shown in Figs. 2–5. The solid curves are the Austern-Blair model[3] calculated angular distributions. The 2.97-MeV state, reported to be 2+ by van Patter,[12]

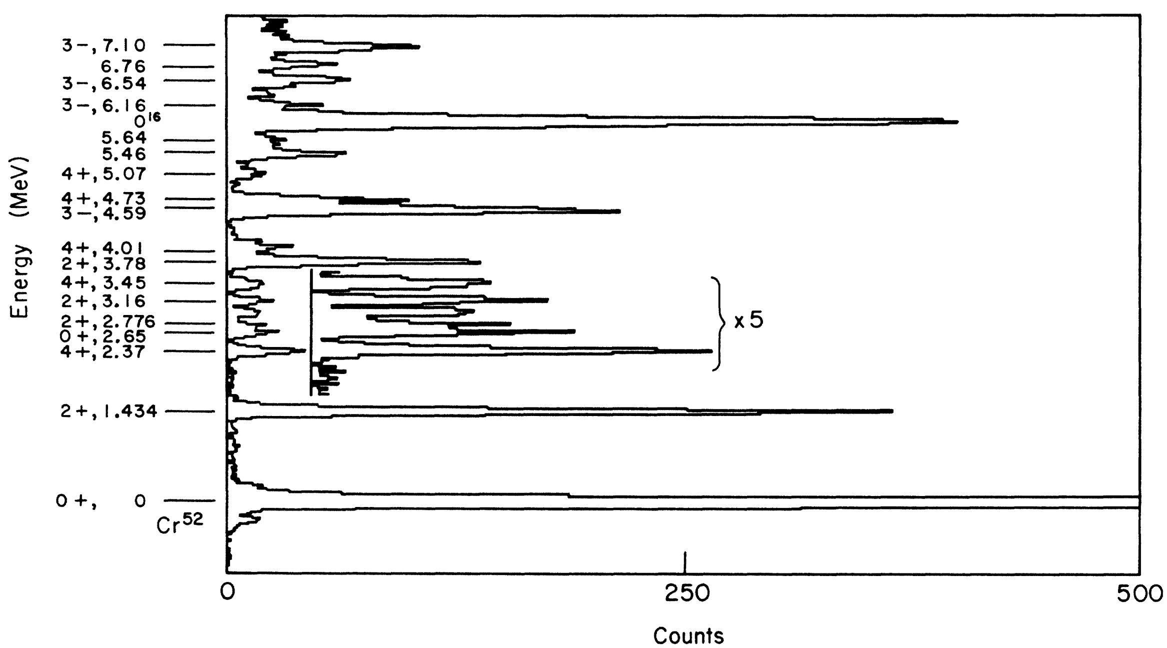

FIG. 1. Level scheme for Cr^{52} and an energy spectrum ($E_\alpha = 50$ MeV, $\theta_{lab} = 50°$) for $Cr^{52}(\alpha,\alpha')$.

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[6] B. G. Harvey, E. J.-M. Rivet, A. Springer, J. R. Meriwether, W. B. Jones, J. H. Elliot, and P. Darriulat, Nucl. Phys. **52**, 465 (1964).
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[9] Digital Equipment Corporation, 146 Main Street, Maynard, Massachusetts, 01754.
[10] D. L. Hendrie, Lawrence Radiation Laboratory (unpublished).
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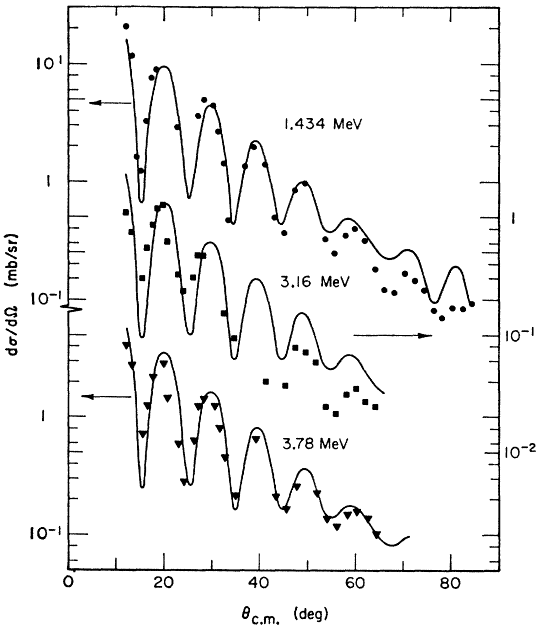

FIG. 2. Angular distributions ($E_\alpha=50$ MeV) for the 1.434-, 3.16-, and 3.78-MeV, 2+ states of Cr^{52}. The curves are the Austern-Blair calculation.

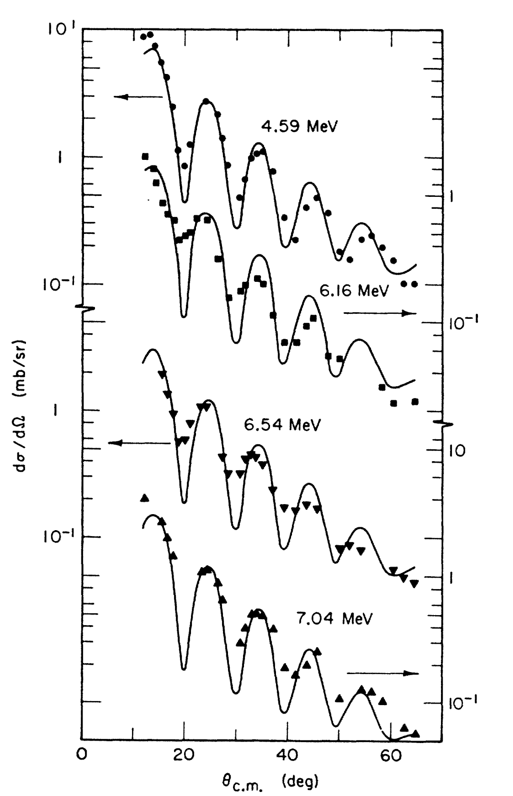

FIG. 3. Angular distributions ($E_\alpha=50$ MeV) for the 4.59-, 6.16-, 6.54-, and 7.10-MeV, 3− states of Cr^{52}. The curves are the Austern-Blair calculation.

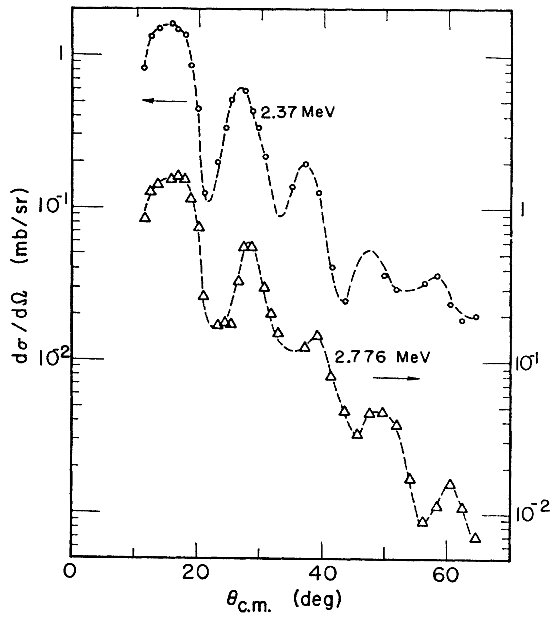

FIG. 4. Angular distributions ($E_\alpha=50$ MeV) for the 2.37- and 2.776-MeV, 4+ states of Cr^{52}. The curves are drawn through the points.

is very weak at most angles, and no angular distribution could be obtained. The same is true for the 2.65-MeV, 0+ state. The angular distributions for the 3.45-, 4.10-, 4.73-, and 5.07-MeV states are very similar to those for the 4+ states at 2.37 and 2.776 MeV. An assignment of 4+ is thus indicated. The states at 6.16, 6.54, and 7.10 MeV appear to be negative parity and probably are 3− states. This is in agreement with the electron-scattering data of Bellicard, *et al.*[13] Several

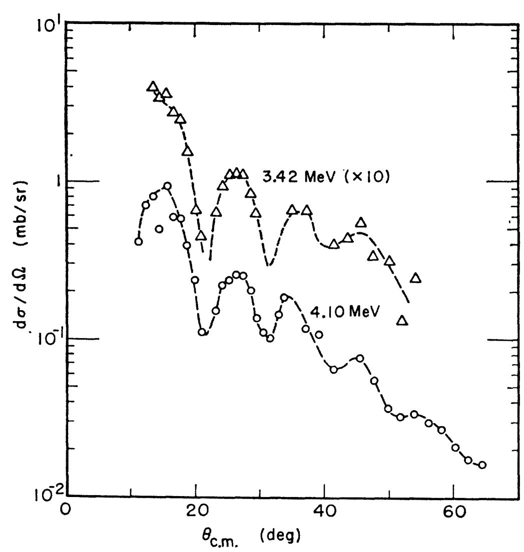

FIG. 5. Angular distribution ($E_\alpha=50$ MeV) for the 3.42- and 4.10-MeV states of Cr^{52}. The curves are drawn through the points.

[13] J. Bellicard, P. Barreau, and D. Blum, Nucl. Phys. **60**, 319 (1964).

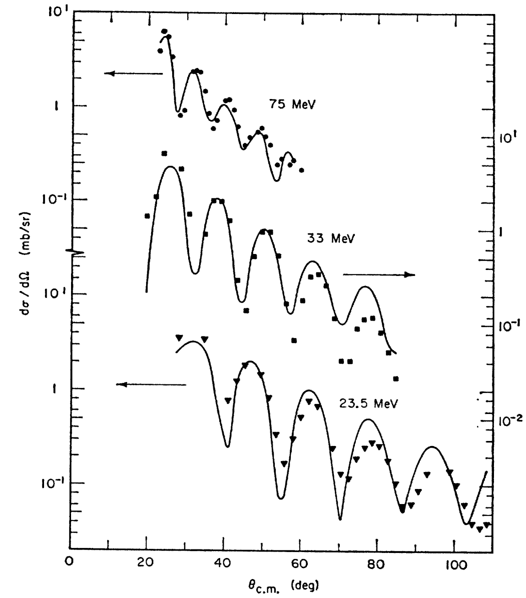

FIG. 6. Angular distributions for the 1.434-MeV, 2+ state for incident alphas of 75, 33, and 23.5 MeV. The curves are the Austern-Blair calculation.

TABLE I. $B(EI)\downarrow$ values obtained for Cr^{52}.

Level (MeV)	$J\pi$	E_{IN} (MeV)	$\delta^2(I)$	$B(EI)\downarrow/e^2$ (F^{2I})
1.434	2+	23.5	0.44	57.9
		33	0.41	53.9
		44.4[a]	0.36	47.3
		50	0.41	53.9
		75	0.31	40.4
3.16	2+	23.5	0.055	7.23
		33	0.036	4.73
		44.4[a]	0.026	3.42
		50	0.042	5.52
3.78	2+	23.5	0.080	10.5
		33	0.090	11.8
		44.4[a]	0.13	17.1
		50	0.12	15.8
		75	0.11	14.4
4.59	3−	23.5	0.138	269
		33	0.153	298
		50	0.142	277
6.16	3−	50	0.034	64.7
6.54	3−	50	0.058	108.8
7.07	3−	50	0.057	108.5

[a] Data from Ref. 15—analysis, this work.

states between 4.9 and 7 MeV were too weakly excited to determine the angular distributions. The 5.46-MeV group was strong but gave a featureless angular distribution. This group probably represents more than one state.

Similar measurements were made using 23.5-, 33-, and 75-MeV alpha particles. Figure 6 shows the angular distribution and the theoretical curves for the 1.434-MeV quadrupole state at each energy.

The phase of the 2.37- and 2.776-MeV, 4+ states changes as a function of the incident energy as shown in Fig. 7. We previously observed this behavior for Ni^{58} and Ni^{62}.[2] The rate of change of the phase with energy for the two states is different, but at present we have no explanation to offer for this fact.

The reduced transition probabilities for a number of states were determined in the manner given in the Introduction. These are listed in Table I. It should be noted that the values are generally independent of energy, as they should be. The values we obtain are consistently lower, by a factor of 2 or more, than the electron-scattering data of Bellicard,[13] the Coulomb excitation work of McGowan,[14] or the Saclay group's[15] smooth cutoff analysis of their alpha scattering data. We have reanalyzed the Saclay data using the Austern-Blair (A-B) model and find a large reduction in the value of $B(E2)\downarrow$ obtained. These data along with Peterson's,[16] which is in agreement with ours, are given in Table II. It would probably be erroneous to attribute the above discrepancies to failures of the Austern-Blair model as there are many examples, in

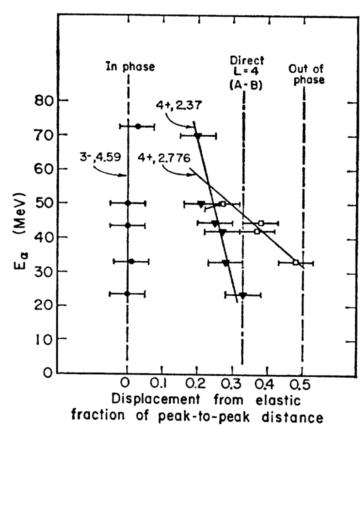

FIG. 7. The change of the phase of the 2.37- and 2.776-MeV, 2+ levels with incident energy. The 4.59-MeV data is for reference only. The 42- and 44-MeV data are taken from Refs. 16 and 15, respectively.

TABLE II. Comparison of various $B(E2)\downarrow$ values for the 1.434-MeV, 2+ state in Cr^{52}.

$B(E2)\downarrow$	Determination	Analysis	Reference
57.9	23.5 MeV (α,α')	A-B	a
53.9	33.0 MeV (α,α')	A-B	a
53.9	50.0 MeV (α,α')	A-B	a
46.0	75.0 MeV (α,α')	A-B	a
60.1	42.0 MeV (α,α')	A-B	16
102	44 MeV (α,α')	BSW[b]	15
47.3	44 MeV (α,α')	A-B	15[a]
103	150–180 MeV (e,e')	...	13
124	Coulomb excitation	...	14

[a] This work.
[b] Blair, Sharp, and Wilets.

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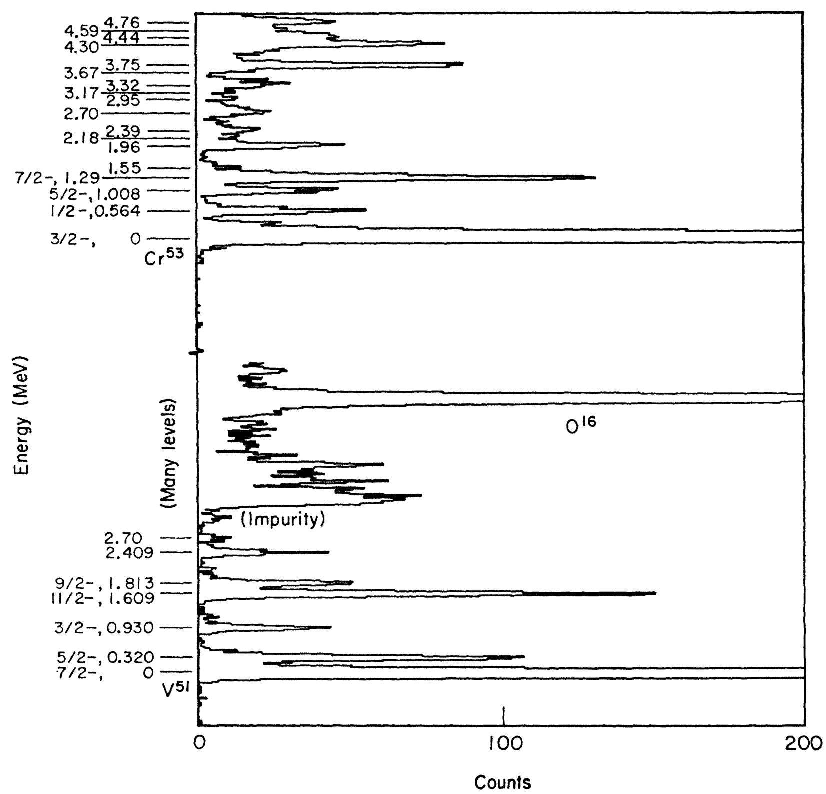

FIG. 8. Energy level schemes and energy spectra ($E_\alpha = 50$ MeV, $\theta_{lab} = 50°$) for Cr^{53} and V^{51}.

particular Ni^{62}, where the agreement of this method of analysis with electromagnetic methods is excellent.

Cr^{53}-V^{51}

The energy spectra for Cr^{53} and V^{51} are shown in Fig. 8. These were obtained from the scattering of 50-MeV alpha particles.

The angular distributions for the first three excited states of Cr^{53}, shown in Fig. 9, are very similar to the first 2+ state in Cr^{52}. This is indicative of the quadrupole nature of these states. In Cr^{53}, as in the case of Cu^{63},[17] there are three quadrupole states whose differential cross sections sum to that of the core state. Contrary to the copper case, the Cr^{53} levels do not have $B(E2)\downarrow$ values which are individually equal to that of the core state. These values are presented in Table III. They are calculated by use of the equation given at the bottom of the table. The weak-coupling model predicts that the values of δ^2 and of $B(E2)\downarrow$ should be the same for all members of the weak-coupled multiplet; Table III shows that this expectation is not realized for Cr^{53} or V^{51}. The deuteron-scattering experiments of Bock *et al.*[18] gave relative $B(E2)\downarrow$ values in good agreement with ours—i.e., the $\frac{1}{2}-$ level of Cr^{53} is excited 2-3 times as strongly as expected from the simple weak-coupling model and the $\frac{5}{2}-$ level is excited only one-half as strongly as expected.

TABLE III. Cr^{53} and V^{51} $B(E2)\downarrow$ values.

	Level (MeV)	$J\pi$	δ^2 [a]	$B(E2)\downarrow/e^2$ F^4
	0.564	$\frac{1}{2}-$	1.35	178
Cr^{53}	1.008	$\frac{5}{2}-$	0.27	35
	1.29	$\frac{7}{2}-$	0.53	69
	0.320	$\frac{5}{2}-$	0.56	67
V^{51}	0.930	$\frac{3}{2}-$	0.32	38
	1.609	$\frac{11}{2}-$	0.28	33
	1.813	$\frac{9}{2}-$	0.13	16
	2.409	"$\frac{7}{2}$"	0.14	17

[a] $\delta^2 = [(d\sigma/d\Omega)_{exp}/(d\sigma/d\Omega)_{calc} \times (2I+1)] \times [\Sigma_i (2J_i+1)/(2J+1)]$; I = (spin of core state) = 2; J_i = (spin of ith level of Cr^{53}) = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$; J = spin of Cr^{53} level.

Bock *et al.*[18] also calculated relative transition probabilities to several levels of Cr^{53} based on a modification of the simple weak-coupling core-excitation model. From the unified-model calculations of Ramavataram[19] and the shell-model calculations of Vervier[20] they obtained the amplitudes for the quadrupole component for each level of the multiplet. Since according to these calculations the $\frac{1}{2}-$ and $\frac{5}{2}-$ levels are appreciably mixed with single-particle components, they should

[17] B. G. Harvey, J. R. Meriwether, A. Bussière de Nercy, and D. J. Horen, Nucl. Phys. 70, 305 (1965).

[18] R. Bock, H. H. Duhm, R. Jahr, R. Santo, and R. Stock, Phys. Letters 19, 417 (1965).

[19] K. Ramavataram, Phys. Rev. 132, 2255 (1963).

[20] J. Vervier, private communication quoted by Bock *et al.*, Ref. 18.

be less strongly excited than predicted by the unmodified weak-coupling model. Agreement with the experimental results for the $\frac{5}{2}-$ level was improved, but naturally the agreement was poorer for the $\frac{1}{2}-$ level. Preliminary calculations by Philpot and True[21] indicate that the $B(E2)\downarrow$ values may be explained by the model of Thankappan and True.[5]

The Cr^{53} group observed at an excitation of 1.96 MeV has an angular distribution that is indicative of a quadrupole excitation. Bock *et al.*[18] suggest that this level is the $\frac{5}{2}-$ level appearing in the calculation of Ramavataram[19] at 1.89 MeV and in the shell-model calculation of Maxwell and Parkinson[22] at 2.01 MeV. According to the calculations of Bock *et al.*[18] the level should be strongly collective and indeed it was strongly excited in their deuteron scattering experiment (about $\frac{1}{4}$ as strongly as the 1.29-MeV, $\frac{7}{2}-$ level) as well as in the present work, where the ratio of differential cross sections (1.96 MeV/1.29 MeV) was about $\frac{1}{5}$.

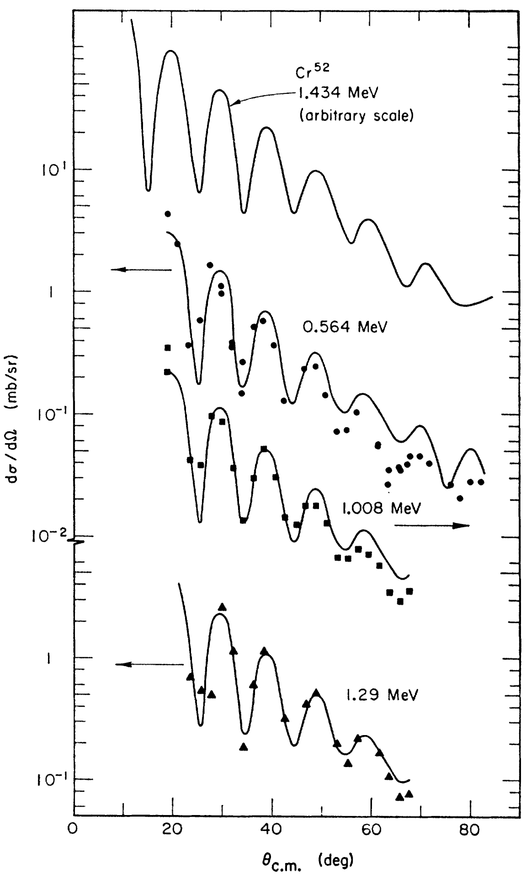

FIG. 9. Angular distributions for the 0.564-, 1.008-, and 1.29-MeV states of Cr^{53}. The curves are the Austern-Blair model calculation. The 1.434, 2+ level of Cr^{52} is shown for reference.

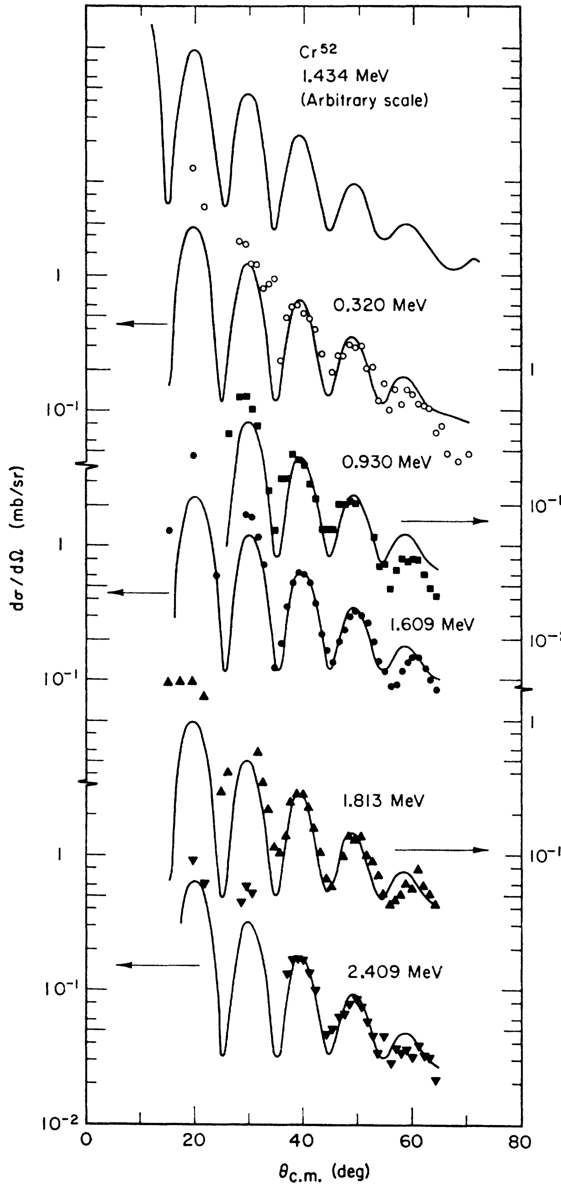

FIG. 10. Angular distribution for the low-lying V^{51} levels. The curves are the Austern-Blair model calculation; the 1.434, 2+ level of Cr^{52} is shown for reference.

The lifetime of $(4\pm2)\times10^{-15}$ sec[23] for the 2.32-MeV, $\frac{3}{2}-$ state of Cr^{53} corresponds to an enhancement of 200 Weisskopf units for an $E2$ transition to the ground state, and corresponds to about 0.6 Weisskopf units for an $M1$ transition. Our very small cross section to this level confirms the $M1$ nature of the transition assumed by Ramavataram[19] and others, since any observable $E2$ mixing would imply some enhancement for this decay mode.

In V^{51} the first five states appear to have strong

[21] J. Philpot and W. W. True (private communication).

[22] James R. Maxwell and W. C. Parkinson, Phys. Rev. **135**, B82 (1964).

[23] E. C. Booth and K. A. Wright, Bull. Am. Phys. Soc. **8**, 85 (1963).

quadrupole angular distributions although we are not in disagreement with the $l=4$ contributions, predicted by the shell model.[24] In addition, the sum of their differential cross sections equals that of the first 2+ in Cr^{52}. As seen in Table III their $B(E2)\downarrow$ values are not equal to the Cr^{52} state.

It is interesting to note that the sum rule predicted by the weak-coupling model[25] holds even though the coupling is not weak and none of the other predictions are realized.

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Limits for Lepton-Conserving and Lepton-Nonconserving Double Beta Decay in Ca^{48}†

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A search has been made for double beta decay in Ca^{48} using a new technique which involves the use of CaF_2 crystals as scintillation detectors. These crystals, enriched in either Ca^{48} or Ca^{40}, were used to detect ionizing particles originating within the crystals. The advantages of this technique are (1) a 4π geometry for a source without self-absorption and (2) good resolution which is independent of the relative angular and energy distribution of the two electrons. A lower limit of 2×10^{20} yr is placed on the lepton-nonconserving double beta decay without neutrinos. The determination of a lower limit for the Dirac-type double beta decay (with emission of two neutrinos) is complicated by impurities in the Ca^{48} used. By resorting to the usual coincidence type of search for double beta decay, which makes the effect of the impurities negligible, we established a lower limit of 5×10^{18} yr for this process. This is comparable with the lower limit of the theoretical estimates.

INTRODUCTION

PHENOMENOLOGICALLY, double beta decay[1] is concerned with a search for two possible reactions:

$$(A,Z)\rightarrow(A,Z+2)+2e^-, \tag{1}$$

$$(A,Z)\rightarrow(A,Z+2)+2e^-+2\bar{\nu}. \tag{2}$$

It has been emphasized, especially by Pauli[2] and Greuling and Whitten,[3] that the existence or nonexistence of reaction (1) is probably the most sensitive test for lepton conservation. Both reactions are expected to take place as the result of a second-order effect due to the same nucleon-lepton (weak) interaction which gives rise to the usual single beta decay.[4] It has been pointed out,[5] however, that reaction (1) could also conceivably take place in the first order if there existed certain lepton-nonconserving interactions. Prior to 1957, when only parity-conserving interactions were considered in beta decay theory, the double beta decay process was regarded as a possible means of determining whether the Majorana or Dirac description of the neutrino was the correct one. Both of the above reactions are allowed by the Majorana theory, but only reaction (2) can take place in the Dirac theory. In the particular case of Ca^{48}, which appears to be one of the most favorable nuclei to study, these theories predicted[4] a half-life of $3\times10^{15\pm2}$ yr for reaction (1) and $1\times10^{21\pm2}$ yr for reaction (2). Further, the two reactions are distinguished by the fact that the sum of the two electron energies in reaction (1) is constant and equal to the transition energy while it varies continuously in reaction (2) up to the same energy as its limit. Many searches were made in this period for double beta decay and several early apparently positive results were later disproved except one obtained by an indirect chemical method.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

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