If one should perform an experiment in which the D-G interference term enters, then a more serious correction due to quadrupole phase shifts is to be expected, for the estimates above indicate an additional 36° lag between D and G waves. In the Cm^{242} problem the G wave is subject to the greatest phase shifts, since it is a weak group coupled to a relatively intense $l=2$ group. It should be emphasized that the above numerical values of the additional phase shifts apply only to case I. The phase shifts will be different for the different possible cases.

We can expect, regarding the noncentral interaction phase shifts, that (a) only the large collective $E2$ couplings will be of significance; (b) the shifts will be larger, the larger the intrinsic quadrupole moment; (c) the shifts will be largest for low-intensity groups coupled to high-intensity groups; and (d) the coupling may introduce phase shifts of either sign depending on the relative signs of the coupled partial waves in the classical turning-point region.

ACKNOWLEDGMENTS

We wish to acknowledge the invaluable help of Dr. Ben Segall and Dr. John Killeen in earlier work, published and unpublished, which laid the ground work for the present study. We wish to acknowledge the assistance of Mr. Michael Lowry for carrying out some of the IBM-650 programming.

PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Angular Distributions from Deuteron-Induced Reactions in Sodium*

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(Received October 30, 1957)

Angular distributions and absolute cross sections were obtained for a group of reactions induced by 14.8-Mev deuteron bombardment of Na^{23}. The ground state and the 1.341-Mev state of the $Na^{23}(d,p)Na^{24}$ reaction were fitted with Butler curves of $l_n=2$ and 0, respectively. The angular distributions of seven levels of the reaction $Na^{23}(d,d')Na^{23}$ were obtained. The Q values of these levels were measured to be -0.441, -2.073, -2.400, -2.689, -2.997, -3.689, -3.925, and -4.457 Mev all with an uncertainty of ± 0.040 Mev. The ground state and the first three excited states of Na^{22} were observed by the reaction $Na^{23}(d,t)Na^{22}$. It was possible to fit the angular distributions to all the Na^{22} states with $l_n=2$. The Q value of the $Na^{23}(d,t)Na^{22}$ ground state was measured to be $Q=-6.211\pm 0.040$ Mev.

I. INTRODUCTION

A STUDY has been made of some of the reaction particles resulting from the bombardment of Na^{23} with deuterons from the University of Pittsburgh cyclotron. The angular distributions of the (d,p), (d,d'), and (d,t) reactions have been measured. The angular momentum transfer and parity change for the (d,p) and (d,t) reactions were determined by fitting Butler-type curves to the observed angular distributions.

II. APPARATUS

The apparatus used has been previously described.[1] A collimated beam of 14.8-Mev deuterons was incident upon the target. The outgoing particles were magnetically analyzed and detected by a CsI crystal. The relative pulse heights for protons, deuterons, and tritons were approximately 1, $\frac{1}{2}$, and $\frac{1}{3}$, respectively. A system of aluminum foils in front of the crystal provided a

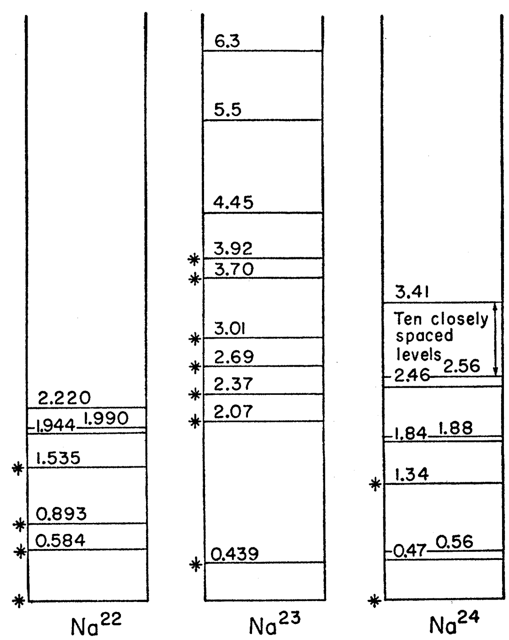

FIG. 1. Energy levels of Na^{22}, N^{23}, and Na^{24}. Asterisks denote levels studied in this work.

* Work done at the Sarah Mellon Scaife Radiation Laboratory and assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at Atomic Power Division, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

[1] Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. 23, 542 (1952).

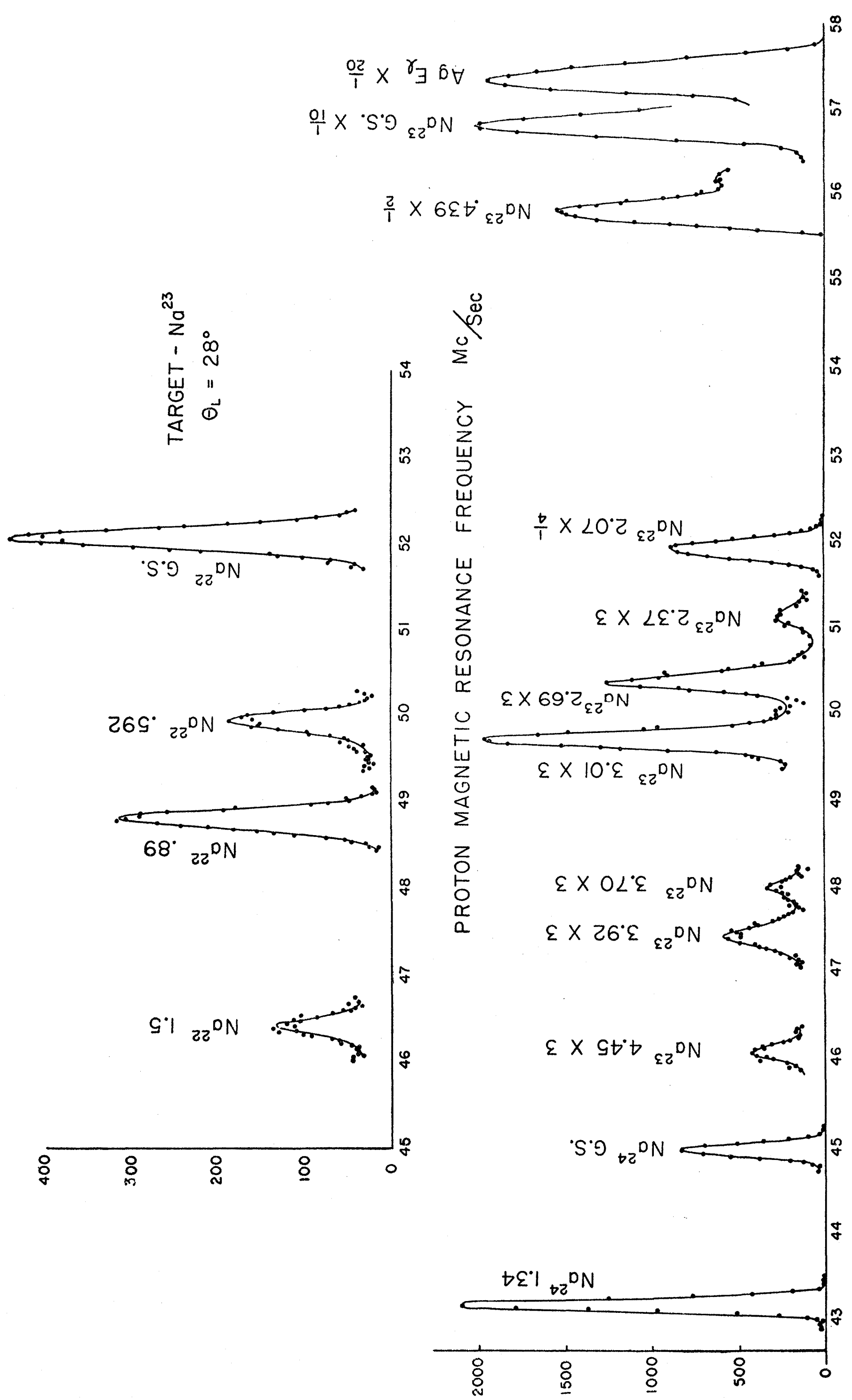

FIG. 2. Charged particle spectrum observed at 28° from a Na^{23} target bombarded by 14.8-Mev deuterons. The peaks are labeled by the state of the residual nucleus to which they belong.

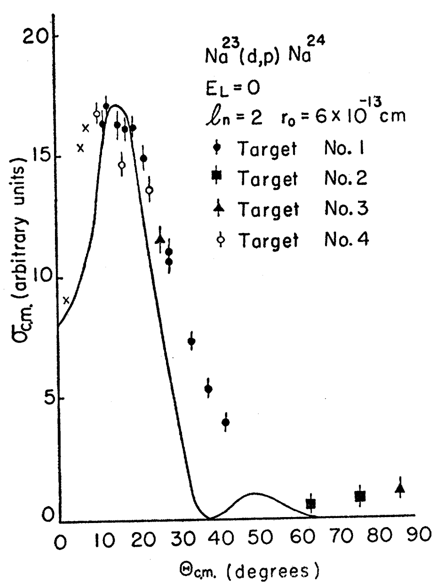

FIG. 3. Angular distribution of the $Na^{23}(d,p)Na^{24}$ ground state.

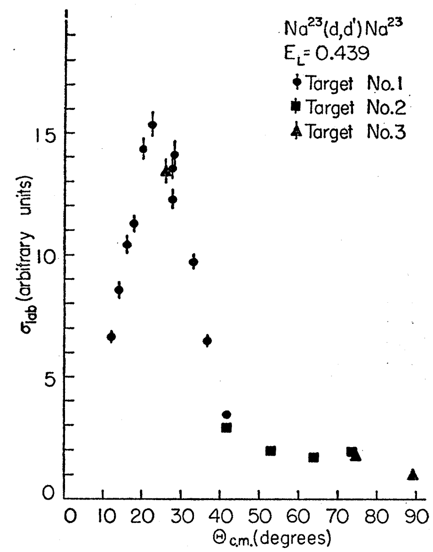

FIG. 5. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 0.439-Mev level.

method of shifting relative pulse heights. Since the pulse height differs for different types of particles, a multichannel analyzer was used to record simultaneously each type of particle. The necessary width of the individual channels depends on the resolution of the crystal. A resolution of four to six percent is expected[2] from a CsI(Tl) crystal. The crystals used in this work were CsI (unactivated) and had a resolution of ten to twelve percent. This increased channel widths and resulted in an increase in background per channel.

In addition to the background produced by charged particles there is a gamma-ray background present. This background is independent of the magnetic field and extends into the region of triton pulse heights as lower energy particles are focused. The increased channel widths aggravated this effect. (This gamma-ray background prevented the observation of levels in Na^{22} above 1.535-Mev excitation.)

III. TARGET PREPARATION

The target was made by evaporating purified sodium on a silver foil 0.01 mg/cm² thick in the scattering chamber. A survey run on silver showed it to contribute no structure. The thickness of the sodium targets used

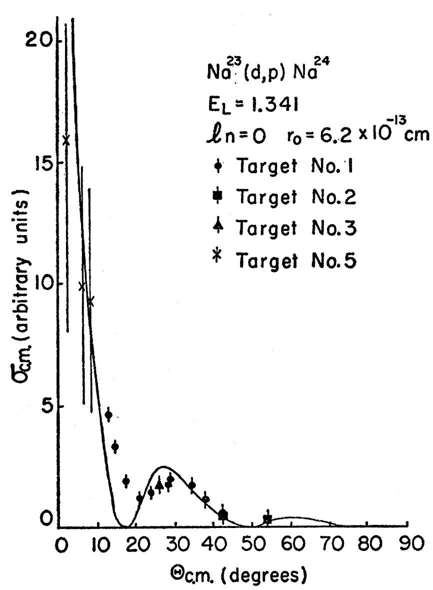

FIG. 4. Angular distribution of the $Na^{23}(d,p)Na^{24}$ 1.341-Mev level.

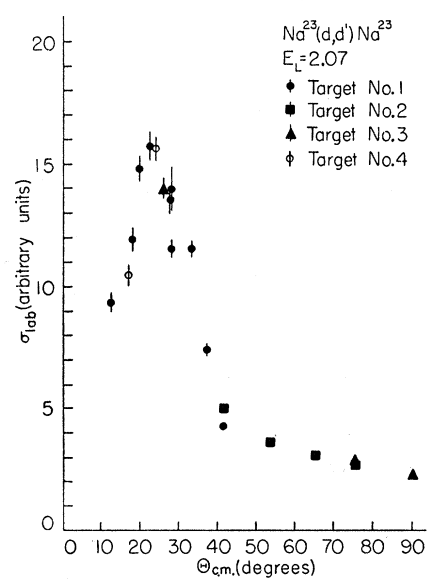

FIG. 6. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 2.07-Mev level.

[2] Levine, Bender, and McGruer, Phys. Rev. 97, 1249 (1955).

TABLE I. Summary of results obtained (g.s. = ground state).

Reaction	l_n	Spin (parity)	r_0 (10^{-13} cm)	Q (Mev)	$d\sigma(\theta)/d\Omega$ (mb/sterad)	$\theta_L{}^0$	Reduced width
$Na^{23}(d,p)Na^{24}$ g.s.	2	4^+	6.0		6.70 ± 1.95	13.9	0.039
$Na^{23}(d,p)Na^{24}$ 1.341 Mev	0	$1^+, 2^+$	6.2		18.1 ± 5.3	14.6	1.05, 0.63
$Na^{23}(d,d')Na^{23}$ 0.439 Mev					2.41 ± 0.70	24.6	
$Na^{23}(d,d')Na^{23}$ 2.07 Mev				-2.073 ± 0.040	12.4 ± 3.6	24.5	
$Na^{23}(d,d')Na^{23}$ 2.37 Mev				-2.400 ± 0.040	0.336 ± 0.098	24.6	
$Na^{23}(d,d')Na^{23}$ 2.69 Mev				-2.689 ± 0.040	2.69 ± 0.78	21.8	
$Na^{23}(d,d')Na^{23}$ 3.01 Mev				-2.997 ± 0.040	1.88 ± 0.55	24.7	
$Na^{23}(d,d')Na^{23}$ 3.70 Mev				-3.689 ± 0.040	0.328 ± 0.095	30.8	
$Na^{23}(d,d')Na^{23}$ 3.92 Mev				-3.925 ± 0.040	0.978 ± 0.295	30.9	
$Na^{23}(d,t)Na^{22}$ g.s.	2	3^+	7.0	-6.211 ± 0.040	2.41 ± 0.71	22.5	0.0135
$Na^{23}(d,t)Na^{22}$ 0.584 Mev	2	$0^+, 1^+, 2^+, 3^+, 4^+$	7.0		0.728 ± 0.213	22.9	0.00405
$Na^{23}(d,t)Na^{22}$ 0.893 Mev	2	$0^+, 1^+, 2^+, 3^+, 4^+$	6.5		1.33 ± 0.39	20.9	0.00813
$Na^{23}(d,t)Na^{22}$ 1.535 Mev	2	$0^+, 1^+, 2^+, 3^+, 4^+$	7.0		0.391 ± 0.117	19.6	0.00195

was $(6.2\pm1.6)\times10^{-4}$ cm. The thickness was determined from the variation of the half-width and counting rate of a level with successive evaporations. By extrapolation back to zero thickness the instrument half-width was measured. The increase in half-width is due to energy loss in the target, while the counting rate is a measure of the thickness. By using range-energy curves the thickness of the target could be found. Once one target was measured, the thickness of any other could be found by comparing the counting rate of a known level. As a check, a chemical determination was made yielding a value which agreed within the experimental uncertainty.

IV. EXPERIMENTAL RESULTS

Figure 1 shows the energy level diagrams for Na^{22}, Na^{23}, and Na^{24}.[3,4] The levels studied in this investigation are denoted by asterisks. All of these levels have been previously reported although those in Na^{22} had not been studied by the reaction $Na^{23}(d,t)Na^{22}$. Only the ground state and 1.34-Mev levels in Na^{24} were studied, the other levels being too closely spaced to be clearly resolved. The levels above 3.92 Mev in Na^{23} were obscured by a deuteron continuum arising from slit-edge scattering.

A search was made for the $Na^{23}(d,He^3)Ne^{22}$ ground state reaction at scattering angles of 13.7 degrees and 27.9 degrees in the laboratory system with negative results. This establishes the reaction as having a cross section less than ten percent that of the $Na^{23}(d,t)Na^{22}$ ground state.

Figure 2 shows the number of charged particles observed as a function of analyzing magnetic field at a laboratory angle of 28 degrees. The isotopic assignment of the levels was checked by measuring the variation of recoil energy with angle.

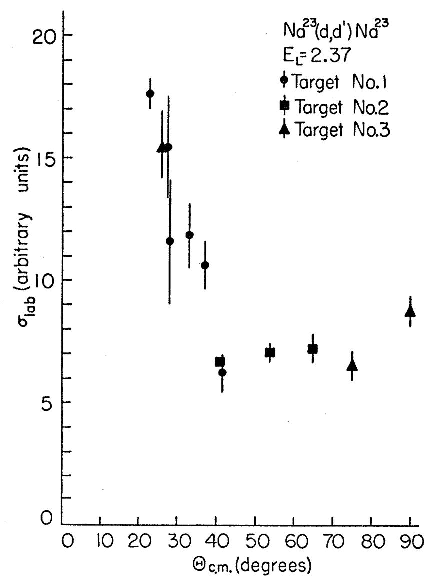

FIG. 7. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 2.37-Mev level.

[3] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[4] C. P. Browne and N. C. Cobb, Phys. Rev. **99**, 644 (A) (1955).

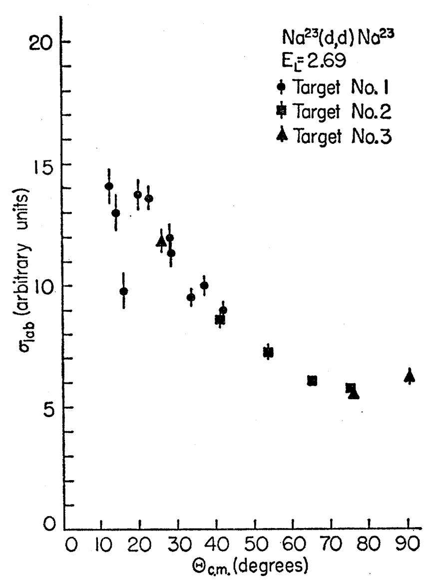

FIG. 8. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 2.69-Mev level.

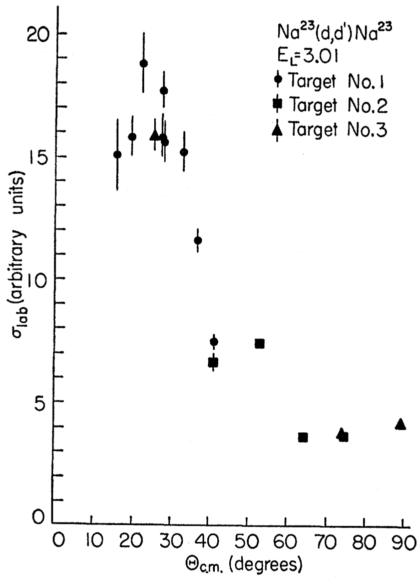

FIG. 9. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 3.01-Mev level.

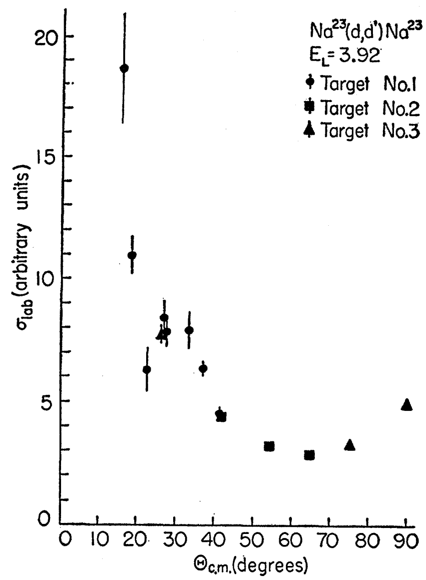

FIG. 11. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 3.92-Mev level.

A. $Na^{23}(d,p)Na^{24}$

The angular distributions for the two levels studied are shown in Figs. 3 and 4. The solid curve is that of the Butler stripping theory[5,6] for the value of l_n and r_0 specified. The value of r_0 was adjusted to give the best fit. This leads to the assignment of $J=0^+$, 1^+, 2^+, 3^+, or 4^+ to the ground state and $J=1^+$ or 2^+ for the 1.34-Mev state. These assignments are in agreement with previously reported values.[3]

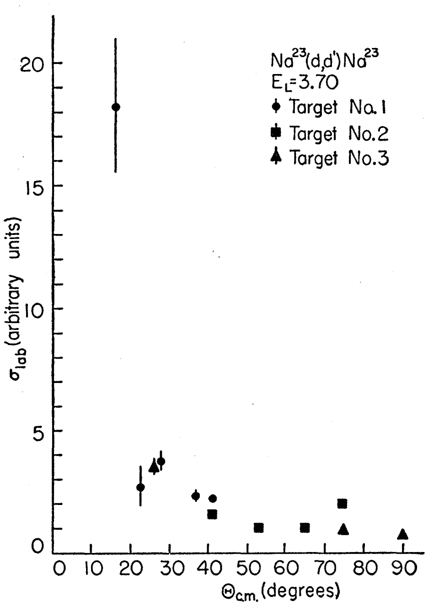

FIG. 10. Angular distribution of the $Na^{23}(d,d')Na^{23}$ 3.70-Mev level.

[5] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[6] R. Huby, *Progress in Nuclear Physics* (Butterworths-Springer, London, 1953), Vol. 3.

The stripping reduced widths have been calculated for these levels and are given in Table I. The calculation was made for the peak of the angular distribution of the ground state reaction. The possibility of two J values for the 1.34-Mev level leads to two possible values for the reduced width of this state. These values were calculated at 14 degrees. Since at this angle the fit to the Butler curve is poor, these values may be too large by a factor of four.

B. $Na^{23}(d,d')Na^{23}$

The angular distributions of the first seven excited states of Na^{23} are shown in Figs. 5 through 11. The

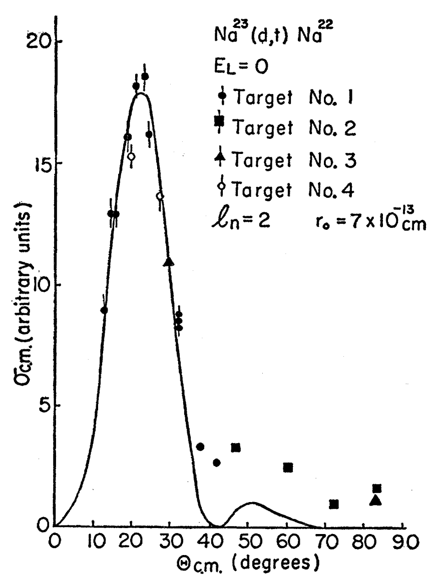

FIG. 12. Angular distribution of the $Na^{23}(d,t)Na^{22}$ ground state.

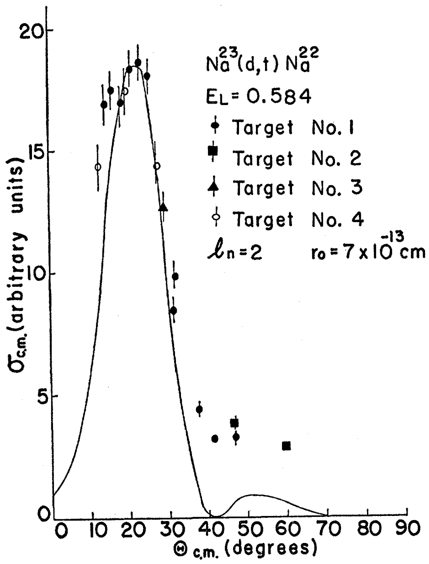

FIG. 13. Angular distribution of the $Na^{23}(d,t)Na^{22}$ 0.584-Mev level.

angular distribution of the Na^{23} ground state is not shown since it could not be separated from the silver ground state at angles less than 23 degrees.

C. $Na^{23}(d,t)Na^{22}$

Figures 12 through 15 show the angular distributions for the first four levels in Na^{22}. The solid curves are calculated from the pickup theory of Newns.[7] The value of l_n and r_0 were adjusted to give the best fit. All the distributions are best fitted with $l_n=2$, which leads to an assignment of $J=0^+$, 1^+, 2^+, 3^+, or 4^+ for all four levels. A value of $J=2^+$ for the ground state has been previously reported.[3]

The stripping reduced widths of these levels have been calculated using Irving's form for the triton internal wave function. The values were obtained in each case for the peak of the angular distribution. The results are given in Table I.

The Q value for the $Na^{23}(d,t)Na^{22}$ ground state was measured to be -6.211 ± 0.040 Mev. The Q values for the other states are in agreement with other work.[4]

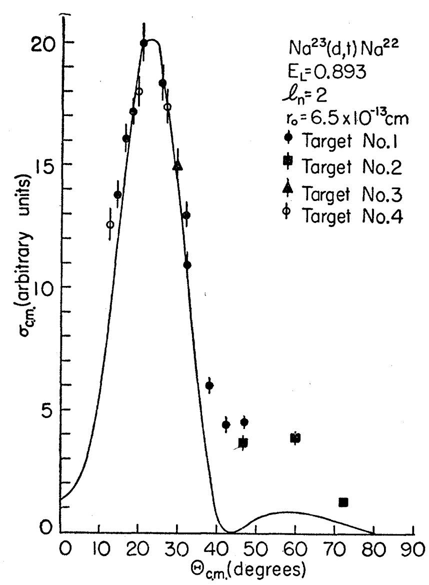

FIG. 14. Angular distribution of the $Na^{23}(d,t)Na^{22}$ 0.893-Mev level.

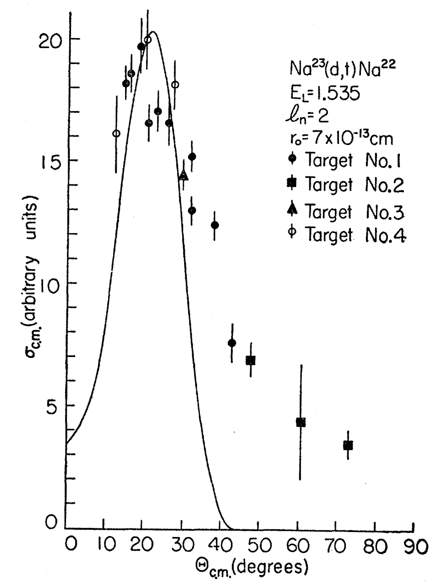

FIG. 15. Angular distribution of the $Na^{23}(d,t)Na^{22}$ 1.535-Mev level.

V. CONCLUSION

The results are summarized in Table I. The absolute cross sections obtained are uncertain to $\pm50\%$. Since the major source of uncertainty in the determination of the cross sections is the thickness of the target, relative cross sections are probably good to $\pm10\%$. The cross sections are given for the peak of the distributions wherever possible.

ACKNOWLEDGMENT

We wish to acknowledge the help received from Dr. A. J. Allen and Dr. R. S. Bender during the course of this project.

[7] H. C. Newns, Proc. Phys. Soc. (London) **A65**, 961 (1952).