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Study of the $K^{39}(d,d')$ Reaction*

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Elastic and inelastic scattering of 15-MeV deuterons from a natural potassium target was measured at ~12 scattering angles between 25 and 90°. Angular distributions corresponding to the following levels in K^{39} were obtained: 2.53, 2.82, 3.02, 3.60 MeV and to groups of unresolved levels at 3.88 and 3.94 MeV and at 4.08, 4.09, and 4.12 MeV. All distributions show a peak at small angles; all, except the one to the 2.53-MeV level, have almost identical shapes. The most strongly excited state is at 3.60 MeV with a peak cross section of 1.1 mb/sr at 34°. The data suggest that the 2.53-MeV level has positive parity, while all the other levels have negative parity and contain appreciable admixtures of a collective octupole vibrational state.

I. INTRODUCTION

THERE is strong evidence that inelastic scattering preferentially excites collective nuclear levels.[1] However, there are nuclei whose low-lying levels are expected to be mainly of the single-particle excitation type, e.g., nuclei near double closed shells. One may ask whether for these nuclei the inelastic scattering is different or whether the angular distributions and absolute cross sections are different from those of nuclei with collective levels. The present experiment was undertaken in order to answer this question. If the hypothesis of preferential collective excitation is correct, one must expect a smaller cross section for excitation of single-particle levels and perhaps a different angular distribution.

The calculations of Rost and Austern[2] in distorted wave Born approximation predict the same shape for the inelastic angular distributions of collective and single-particle states, and a larger cross section for the collective levels.

A similar question has been studied in the $Mg^{25}(d,d')$ reaction,[3] where it was found that collective excitations are ~10 times more probable than single-particle excitations. The angular distributions of the single-particle excitations, however, were not obtained. Also Mg^{25} has a large permanent deformation and it is not clear *a priori* that results obtained for an ellipsoidal nucleus hold also for a spherical nucleus. It would therefore be interesting to study inelastic scattering from a spherical nucleus with single-particle levels.

The ideal target for the study would be O^{17}, which has only one particle outside the double closed shell of O^{16}. The level structure of O^{17} is well understood and several single-particle levels are known (see, for example, Macfarlane and French[4]). However, the abundance of O^{17} in natural oxygen, and even in oxygen enriched in the heavy isotopes O^{17} and O^{18}, is so small that the experiment becomes very difficult. We therefore chose potassium for the target.

K^{39} is a single-hole nucleus, lacking only one proton to complete the $1d$–$2s$ double closed shells of Ca^{40}. It has an abundance of 93.1% in natural potassium (the remaining 6.9% are K^{41}, with 0.01% of K^{40}), and is, therefore, an inexpensive target. It has the disadvantage that its level structure is not well known; not even the spins and parities of the low-lying levels have been determined. Thus, the interpretation of the $K(d,d')$ experiment cannot yet be complete and must await the accumulation of more experimental data on the K^{39} levels.

Even theoretically, the level structure of K^{39} has not been studied. The ground state presumably consists mainly of a hole, $(d_{3/2})^{-1}$, in Ca^{40}, but it is difficult to make any guesses as to the structure of the excited states. There is some evidence that j–j coupling is not a bad approximation for the nuclei near calcium.[4–6] However, Mitler[7] found that the levels of Ca^{42} and Ca^{43} are not well represented by the shell model, even if the coupling is generalized from j–j to intermediate: Considerable admixtures of collective states, of core exictation states, and of higher configurations seem to occur.

II. EXPERIMENTAL

The University of Pittsburgh cyclotron produces a deuteron beam whose energy is approximately 15 MeV and whose intensity is about 1 μA. Details of the scattering system are discussed elsewhere.[8,9] Scattered particles were analyzed by a magnetic spectrometer and detected

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[1] B. L. Cohen, Phys. Rev. **116**, 426 (1959).
[2] E. Rost and N. Austern, Phys. Rev. **120**, 1375 (1960).
[3] A. G. Blair and E. W. Hamburger, Phys. Rev. **122**, 566 (1961).
[4] M. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).
[5] J. P. Elliot and A. M. Lane, in *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 39, p. 352.
[6] S. Goldstein and I. Talmi, Phys. Rev. **102**, 589 (1956); S. P. Pandya, *ibid*. **103**, 956 (1956).
[7] H. E. Mitler, Nuclear Phys. **23**, 200 (1961).
[8] R. S. Bender, E. M. Reilley, A. J. Allen, R. Ely, J. S. Arthur, and H. J. Hausman, Rev. Sci. Instr. **23**, 542 (1952).
[9] E. W. Hamburger, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

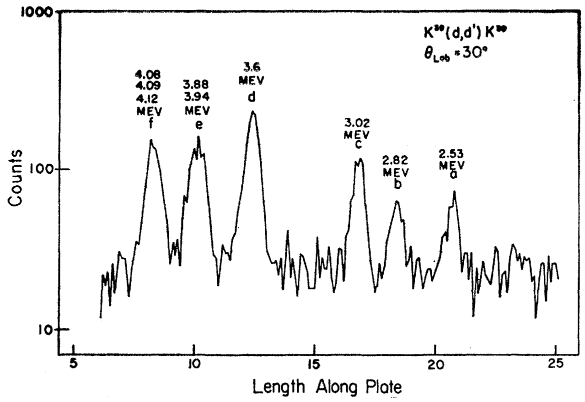

FIG. 1. Inelastic deuteron spectrum produced by a potassium target at $\theta_{lab}=30°$. No inelastic groups were identified at excitations below that of group *a* (2.53 MeV).

in nuclear emulsions (for the inelastic groups) or in a scintillation counter (for the elastic group). The targets were prepared by evaporation of the element on to gold foils of ~0.9 mg/cm², and were transferred to the scattering chamber without breaking the vacuum.[9] The figures show the results of two runs with different targets, indicated by circles and triangles, respectively. Exposures were made at approximately every 5°.

The energies of the levels observed in the present work have been measured with a precision of ±7 keV by means of the (p,p') reaction.[10] The results of the present work are less precise than, and consistent with, reference 10.

Absolute cross sections were not measured; however, it proved possible to obtain an estimate which is described below. The accuracy of the relative cross sections is best judged from the agreement between the two sets of data; it is usually ~±10%. At the smallest angle, $\theta=26°$, the error is ~±25%.

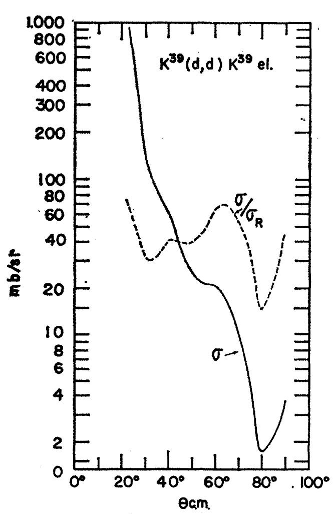

FIG. 2. Differential cross section σ for the elastic scattering of 15-MeV deuterons on potassium (solid curve). The dashed curve gives σ divided by the Rutherford cross section σ_R, arbitrarily normalized. The absolute cross-section scale is described in the text.

A typical spectrum, at 30°, is shown in Fig. 1. It was not possible to resolve the two levels at 3.88 and 3.94 MeV (group *e*) and the three levels at 4.08, 4.09, and 4.12 MeV (group *f*) found by Sperduto and Buechner.[10] The full width at half-maximum of the other peaks is ~80 keV.

Among the unresolved groups, the 3.88-MeV level is excited a little more strongly (by a factor ~2) than the 3.94-MeV level, while the 4.12-MeV level is excited about 3 times more strongly than the 4.08- and 4.09-MeV levels together.

III. RESULTS AND DISCUSSION

A. Elastic Scattering[11]

Figure 2 shows the differential cross section σ for the elastic scattering (full curve); the dashed curve gives σ divided by the Rutherford cross section σ_R.[11] The data may be compared to the distributions found for the neighboring elements Al^{27}, Ti^{48}, and Fe^{56} (the mass number of the most abundant isotope is given in each

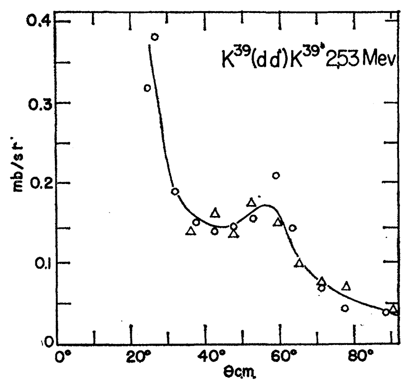

FIG. 3. Angular distribution for the $K^{39}(d,d')K^{39*}$ 2.53-MeV reaction. The circles and triangles correspond to two independent sets of data. The solid curve is freely drawn through the experimental points.

case) by Cindro and Wall,[12] also at 15 MeV; the comparison is best made to the σ/σ_R curve. The potassium data fit in well between the Al and Ti curves; the structure in the angular distribution is less pronounced than for Al and more similar to Ti. On the other hand, the positions of the peaks and valleys in the σ/σ_R curves shift slowly to smaller angles as the atomic weight increases, as one would expect from diffraction theory. All four σ/σ_R curves show a valley near 33°. The value of σ/σ_R at this minimum appear to change slowly from nucleus to nucleus, as shown in the following table:

Nucleus	Al^{27}	Ti^{48}	Fe^{56}
θ (min)	34°	32°	32°
σ/σ_R (min)	0.34	0.26	0.27

[11] The elastic scattering was measured in collaboration with C. A. Low. See C. A. Low, Master's thesis, University of Pittsburgh, 1961 (unpublished).

[12] N. Cindro and N. S. Wall, Phys. Rev. **119**, 1340 (1960).

Interpolating between these results of Cindro and Wall we conclude, that for K^{39}, we should expect $\sigma/\sigma_R \sim 0.3$ at the minimum at 32°. We shall adopt this value, thus establishing an absolute cross-section scale for the elastic scattering; the scale of Fig. 2 has been drawn under this assumption. From the systematics of elastic scattering data we estimate that this scale is correct within a factor of 1.4.

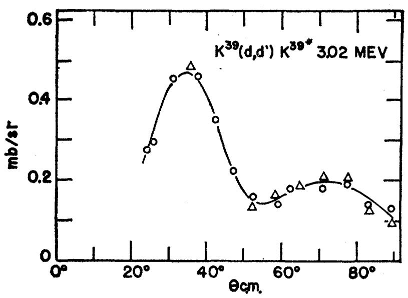

FIG. 5. Angular distribution for the $K^{39}(d,d')K^{39*}$ 3.02-MeV reaction.

B. Inelastic Scattering

The inelastic absolute cross sections were obtained by comparison with the elastic group at 34°, using the elastic absolute scale described above. We estimate that the inelastic absolute cross section scale is correct within a factor of 1.5.

The angular distributions are shown in Figs. 3 to 8. Figure 9 shows all distributions together on a semi-logarithmic scale. It is impressive how similar to one another all the distributions are, except the one to the 2.53-MeV level.

a. Significance of Absolute Cross Sections

The observed absolute cross sections for the different levels are appreciably smaller than the value expected for collective excitations. This can be seen from Table I, which shows the inelastic deuteron cross sections for nearby nuclei at 15 MeV. For each nucleus, the cross section of the most strongly excited level is given at the peak of the angular distribution, σ (peak), and at 60°, σ (60°). For V^{51} and Fe^{56}, only measurements at 60° are available.[13] Interpolating in the table we estimate that the most strongly excited state in K^{39} should have cross sections $\gtrsim 5$ mb/sr at the peak of the angular distribution and $\gtrsim 1.2$ mb/sr at 60°.

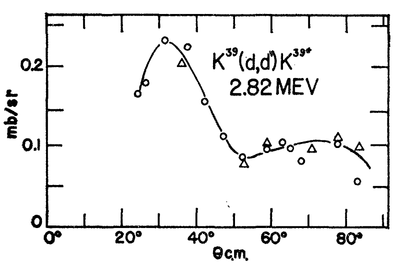

FIG. 4. Angular distribution for the $K^{39}(d,d')K^{39*}$ 2.82-MeV reaction.

The most intense group in $K(d,d')$ corresponds to the 3.60 MeV level. Its cross sections are $\sigma(\text{peak}) = 1.2$ mb/sr and $\sigma(60°) = 0.47$ mb/sr. Even taking account of the large error in the absolute cross sections we conclude that the transition is much weaker, about 3 times weaker, than expected for a strong (collective) transition. This factor, ~ 3, is smaller than the factor 10 by which collective levels are favored over single-particle ones in the $Mg^{25}(d,d')$ reaction.[3] A possible explanation is that there are collective admixtures in the wave functions of the K^{39} states. Such an interpretation can be carried further. Figure 10 shows the cross section at the peak of the angular distributon as a function of the excitation energy. The data show a "giant resonance"-like behavior with a peak at 3.6 MeV. The cross section at 60°, also shown in Fig. 10 exhibits the same behavior. The data suggest that there is a collective state, strongly excited in inelastic scattering, fragmented among various levels near 3.6 MeV. In this connection we note also that the sum of the cross sections to the levels with excitation between 3.02 and 4.12 MeV is of the order of magnitude expected for strong transitions in this region: $\sum \sigma(\text{peak}) \sim 3$ mb/sr and $\sum \sigma(60°) \sim 1.3$ mb/sr.

b. Angular Distributions

The similarity of all the angular distributions, except to the 2.53-MeV level, further supports the hypothesis of a single collective oscillation fragmented among several levels.

The positions of the peaks and valleys in the angular distributions of inelastic scattering have been shown to depend on the parity of the final state[14,15] and on the

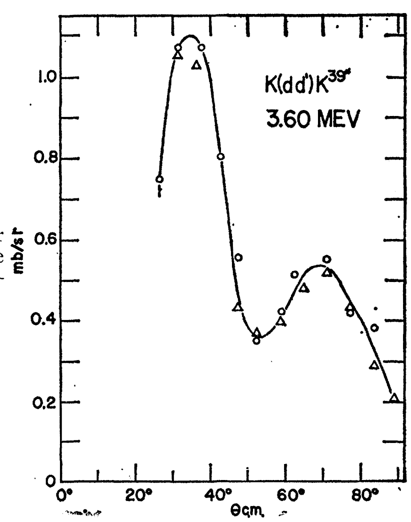

FIG. 6. Angular distribution for the $K^{39}(d,d')K^{39*}$ 3.60-MeV reaction.

[13] B. L. Cohen and R. E. Price 123, 283 (1961).

[14] J. S. Blair, Phys. Rev. 115, 928 (1959).

[15] D. K. McDaniels, J. S. Blair, S. W. Chen, and G. W. Farwell, Nuclear Phys. 17, 614 (1960).

number of vibrational or rotational quanta which are excited.[16] One may therefore hope to determine the parities of the excited levels of K^{39} from the angular distributions measured in the present experiment. The elastic scattering cross section (Fig. 2) shows only one well-defined valley at $\sim 80°$; not much can be said of its "phase"[14] from this valley only. The inelastic distributions to all the levels except the one at 2.53 MeV are in phase, i.e., have peaks and valleys at the same angles. The 2.53-MeV level, on the other hand, has a phase approximately opposite to the other levels; its major peak falls at $\theta \lesssim 25°$, where the other distributions have a valley, and its secondary peak occurs at $\theta \sim 58°$, where the other distributions again have a valley. We conclude (neglecting multiple phonon excitation[16]) that the parity of the 2.53-MeV level is opposite to that of all the other levels.

In order to determine the parities we compare the potassium distributions with other (d,d') distributions on nearby nuclei at similar energies (Mg^{24}, Mg^{25}, Mg^{26}, at 15 MeV,[3]; Ti^{48}, Fe^{56}, Ni^{58} at 11.8 MeV,[17]; Sr^{88} at 15 MeV,[18] and Zr at 15 MeV[13]). One finds[19] that all $0^+ \rightarrow 2^+$ transitions have their first peak at $\theta \lesssim 25°$ while the $0^+ \rightarrow 3^-$ transitions have a peak at $\theta \sim 32°$. Since the ground state of K^{39} has positive parity, this suggests that the 2.53-MeV level also has positive parity, while all the other levels studied in this work have negative parities.

It is possible that the "giant resonance" formed by the negative parity levels corresponds to the "anomalous" peak first observed by Cohen in (p,p') reactions.[20] The anomalous peak probably corresponds to a collective octupole vibraton of the nucleons, which in even-even nuclei will give rise to a 3^- level; in odd nuclei it will give rise to several levels of parity opposite to that of the intrinsic state (i.e., the ground state). The lightest nucleus in which the anomalous peak has been identified is Ti^{48},[15] where it occurs at an excitation of 3.6 MeV. Our "giant resonance" is therefore in the correct energy region to correspond to the octupole vibration.

The 2.53-MeV level, on the other hand, may correspond to the quadrupole vibration which gives rise to the first excited 2+ state of even–even nuclei. Yntema and Zeidman[21] and Cohen and Price[13] have identified levels analogous to the 2+ of neighboring even–even nuclei in the odd copper isotopes Cu^{63} and Cu^{65}. The 2.53-MeV level of K^{39} is approximately at the correct excitation energy to correspond to the 2+ state; thus in Ar^{38} the 2+ state occurs at 2.1 MeV.[22] However the systematics of (d,d') data[19] show that the 2+ quadrupole state is always strongly excited. In fact, it is the level which is most strongly excited. Since the 2.53-MeV level is excited rather weakly, we conclude that it can contain at most a small fraction of the quadrupole state; other fragments of the quadrupole state probably exist at excitation energies not examined in the present experiment, $E_x > 4.1$ MeV.

We conclude tentatively that the 2.53-MeV level has positive parity while the 2.82-MeV, 3.02-MeV, 3.60-MeV, and at least one of the 3.88-MeV and 3.94-MeV and of the 4.08-MeV, 4.09-MeV and 4.12-MeV levels have negative parity. It will be interesting to see these predictions are borne out by future experiments.

c. Comparison with the K^{39} (p,p') Reaction

There are two inelastic scattering experiments on K^{39} previously reported with which we can compare our data:

Tyrén and Maris[23] used 180-MeV protons and found only one strong inelastic group, at an excitation energy of 3.7 ± 0.4 MeV. This group almost certainly corresponds to the "giant resonance" found in the present

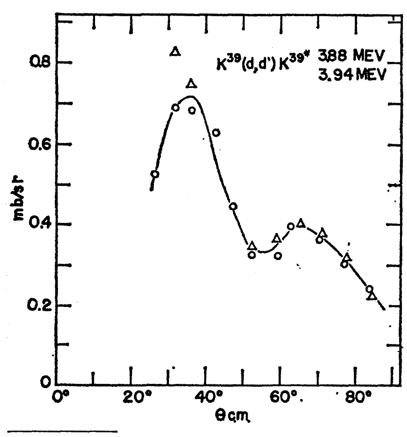

FIG. 7. Angular distribution for the $K^{39}(d,d')K^{39*}$ 3.88 and 3.94 MeV reaction.

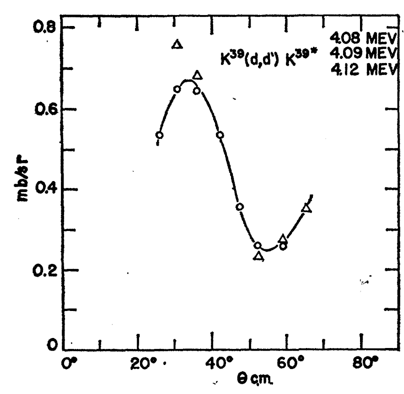

FIG. 8. Angular distribution for the $K^{39}(d,d')K^{39*}$ 4.08, 4.09, and 4.12 MeV reaction.

[16] R. H. Lemmer, A. de Shalit, and N. S. Wall, Phys. Rev. **124**, 1155 (1961).
[17] R. Jahr, K. D. Müller, W. Oswald, and U. Schmidt-Rohr, Z. Physik **161**, 509 (1961).
[18] R. K. Jolly, E. K. Lin, B. L. Cohen, and E. W. Hamburger (to be published).
[19] E. W. Hamburger (to be published).
[20] B. L. Cohen, Phys. Rev. **105**, 1549 (1957).
[21] J. L. Yntema and B. Zeidman, Phys. Rev. Letters **2**, 309 (1959).
[22] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).
[23] A. Tyrén and Th. A. J. Maris, Nuclear Phys. **6**, 446 (1958).

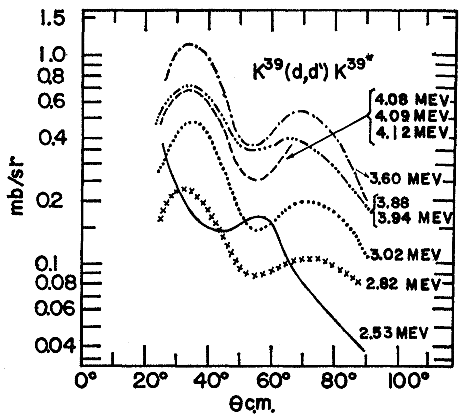

FIG. 9. The angular distributions of Figs. 3 to 8 shown together on a semilogarithmic scale. The lines correspond to the solid lines in Figs. 3 to 8.

experiment and whose fine structure Tyrén and Maris could not resolve.

Sperduto and Buechner[10] used 7.45-MeV protons with very good resolution. Figure 10 (lower part) shows the relative intensities with which the various K^{39} levels are excited, as a function of the excitation energy. The points are more irregular than in the upper portion of Fig. 10 [the (d,d') results], perhaps in part because of the better resolution. The most intense level is now at 3.94-MeV while the 3.60-MeV level is rather weakly excited. The comparison of the two parts of Fig. 10 indicates that the reaction mechanisms of (d,d') at 15 MeV and (p,p') at 7.45 MeV are different.

We note incidentally that the results discussed in the preceding two paragraphs show that the (p,p') reaction at ~7.5 MeV has a different mechanism than at high energies. Indeed, Cohen and Rubin[24] had already noticed that the intensity of the anomalous group in (p,p') decreases rapidly for incident energies below 15 MeV. Another way of verifying this change of reaction mechanism is to compare the 22-MeV (p,p') spectra of Cohen and co-workers with the ~7-MeV work of Buechner and his co-workers, for the same target nuclei. For example, cobalt and copper were studied by both groups.[24,25] The anomalous groups strongly excited at 22 MeV are weakly excited at the lower energies.

TABLE I. (d,d') cross sections at 15 MeV for nuclei near K^{39}.

Nucleus	Level (MeV)	σ (peak) (mb/sr)	σ (60°) (mb/sr)	Reference
Na^{23}	2.07	12.5	2.5	a
Mg^{24}	1.37	12	2.5	b
Mg^{25}	1.61	5.5	1	b
Mg^{26}	1.83	9	2	b
V^{51}	0.30	···	0.21	c
Fe^{56}	0.85	···	0.70	c
Sr^{88}	1.835	1.6	0.5	d
Zr^{92}	0.93	1.0[e]	0.2[e]	c

[a] W. F. Vogelsang and J. N. McGruer, Phys. Rev. **109**, 1663 (1958).
[b] See reference 3.
[c] See reference 13.
[d] See reference 18.
[e] Cross sections not corrected for isotopic abundance. Real cross sections can be up to four times larger.

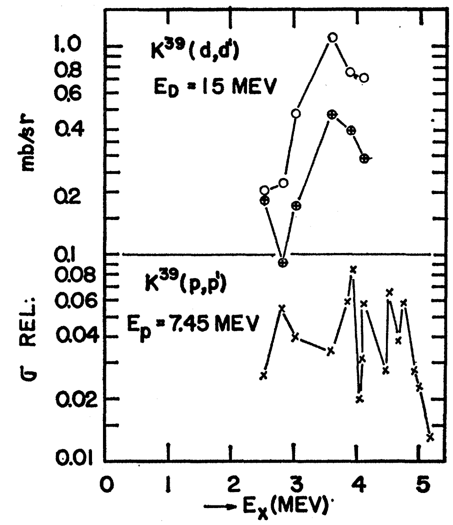

FIG. 10. Top: Cross sections for exciting various levels of K^{39} in the (d,d') reaction as a function of excitation energy E_x. The empty circles give the cross sections at the peak of the angular distributions while the crossed circles show the 60° cross section. Note that the points at $E_x=3.9$ and 4.1 MeV correspond to several unresolved levels. Bottom: Intensities of levels observed in the $K^{39}(p,p')$ reaction (reference 10) at 60° as a function of E_x.

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[24] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1958).
[25] M. Mazari, A. Sperduto, and W. W. Buechner, Phys. Rev. **107**, 365 (1957); M. Mazari, W. W. Buechner, and R. P. de Figueiredo, *ibid.* **108**, 373 (1957).