# Comparison of the Reactions $A^{36}(d,p)A^{37}$ and $A^{36}(d,n)K^{37}$†

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The mirror reactions $A^{36}(d,p)A^{37}$ and $A^{36}(d,n)K^{37}$ have been studied at 3.85-Mev bombarding energy. In the first, $Q$ values of 6.55, 5.16, 4.92, 3.98, and 3.00 Mev were observed. The stripping distributions may be described in terms of $l_n$ values of 2, 0, 2, 2, and 2, respectively. In the second, $Q$ values of $-0.32$ and $-1.78$ Mev were observed. The former followed an $l_p=2$ angular distribution. The latter could be described by a sum of $l_p=0$ and $l_p=2$ distributions, suggesting an unresolved doublet.

## INTRODUCTION

THE comparison of the level structures of mirror nuclei is of some interest when considered in the light of the charge symmetry hypothesis of nuclear forces. While a number of such pairs have been investigated both experimentally and theoretically in the light-mass region, very little has been done among the heavier nuclei. The present study has been directed to obtaining such a comparison at mass 37. On the basis of the shell model[1] the odd nucleon involved in this case is expected to be represented as in a $d_{\frac{3}{2}}$ state. Since the core of eighteen protons and eighteen neutrons does not demonstrate any unusual stabilities, the low-lying excited states might be expected to represent both single-particle excitations and many-particle configurations. Nussbaum[2] has postulated the first excited state to be $f_{7/2}$. Considering the accessability of the recently closed $s_{\frac{1}{2}}$ (and conceivably even $d_{\frac{3}{2}}$) shell, however, even-parity levels are certainly not ruled out.

A comparison of the level structures of such a pair by means of equivalent or mirror reactions would, on the surface, appear to be an especially favorable technique. Unfortunately, there is some indication[3] that for incident energies below the Coulomb barrier, angular distributions may deviate markedly from the idealized situation and hence might be somewhat unreliable gauges of the parameters involved in the reaction. Hopefully, though, it is only diffusion of detail and not mislabeling that will be the end result.

The $A^{36}(d,p)A^{37}$ reaction has been investigated on several occasions in the past. Zucker[4] and Davison[5] have reported the $Q$ values and level spacings as obtained using aluminum absorption techniques. More recently Sukharevskii[6] has given preliminary information on the angular distribution of the ground-state proton group using nuclear emulsions. In addition nuclear emulsion experiments have given some data as to the level spacing in $A^{37}$ from the $Cl^{33}(p,n)A^{37}$ reaction.[7] While most of the data are consistent, a few discrepancies in the localization of the first excited state (or states) remain.[8] The $A^{36}(d,n)K^{37}$ reaction, has, on the other hand, not as yet been reported.

### Experimental Procedure

A sample of argon gas isotopically enriched to 96% $A^{36}$ and 4% $A^{40}$ was used in the present experiment. A small amount of nitrogen was also present. This last served as a convenient internal calibration on the experiment. No other contaminants were observed in the mass spectrographic analysis. The target gas was enclosed in a one-inch diameter cylinder by a nickel foil of 2.23 mg/cm². A pressure of 10 cm of mercury was maintained throughout the runs.

A magnetically analyzed beam of 4.05-Mev deuterons from the Yale cyclotron was used. Absorption in the nickel entrance foil and target gas reduced this to[9] 3.85±0.04 Mev at the scattering center. The elastic deuterons were stopped in 67.0 mg/cm² of high-purity gold foil. This permitted observation of protons at forward angles without interference except for contributions from Ni$(d,p)$ at 0°. No protons from $(d,p)$ reactions on impurities in the gold absorber were observed. The reaction protons were detected in 50 μ Ilford $C$-2 emulsions arranged at angles from 0° back to $152\frac{1}{2}$° in the scattering chamber previously described.[10] The only change made in the $(d,n)$ runs was to add a 434-mg/cm² tantalum absorbing foil to stop all charged particles. Preliminary to development all plates were faded several hours to reduce the gamma radiation fog. This was especially necessary for the $(d,n)$ runs.

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[1] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, New York, 1955).
[2] R. H. Nussbaum, *Nuclear Levels in the Neighborhood of the* $1f_{7/2}$ *State* (Van Gorcum and Company, Amsterdam, 1954).
[3] J. P. Schiffer and L. L. Lee, Jr., Phys. Rev. **115**, 1705 (1959).
[4] A. Zucker and W. W. Watson, Phys. Rev. **80**, 966 (1950).
[5] P. W. Davison, J. O. Buchanan, and E. Pollard, Phys. Rev. **76**, 890 (1949).
[6] V. G. Sukharevskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1377 (1959) [translation: Soviet Phys.—JETP **36**(9), 981 (1959)].
[7] J. C. Grosskreutz and K. B. Mather, Phys. Rev. **77**, 580 (1950).
[8] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 730, 739 (1957).
[9] W. Whaling, *Handbuch der Physik* (Springer-Verlag, Berlin, 1958), Vol. 34.
[10] H. S. Plendl and F. E. Steigert, Phys. Rev. **116**, 1534 (1959).

Scanning of the emulsions was performed using microprojection at 500× magnification. No-gas runs were always taken with identical beam exposures to insure against erroneous data.

### $A^{36}(d,p)A^{37}$ Reaction

Range spectra of the reaction protons are shown in Figs. 1(a)–(c). These have been selected to illustrate

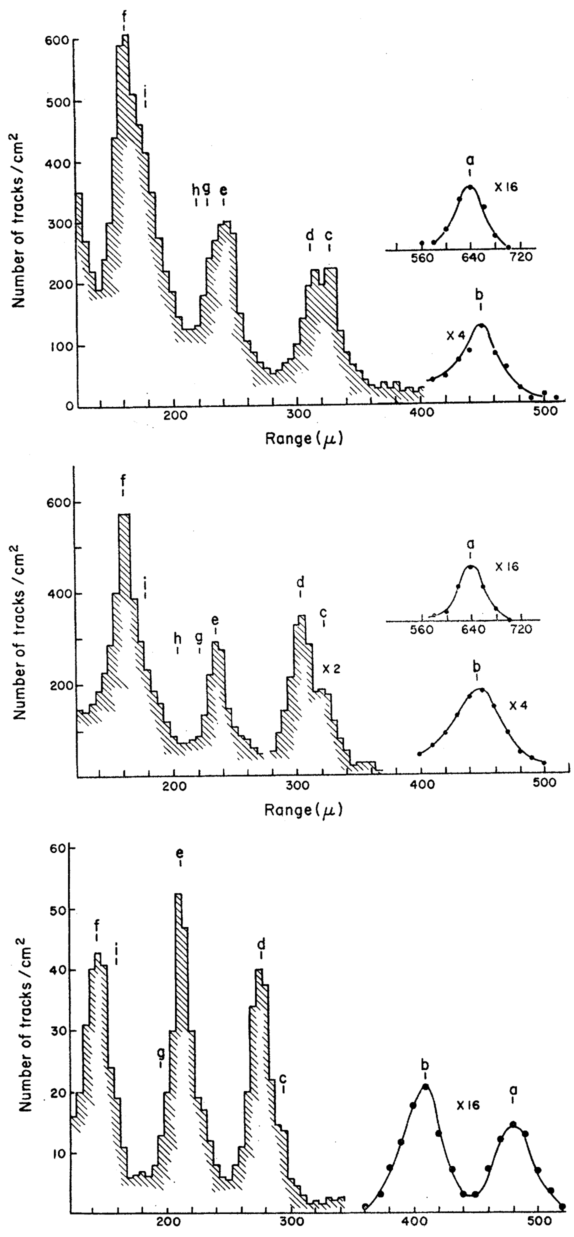


FIG. 1. Relative number of tracks as a function of range at (*a*) $12\frac{1}{2}°$, (*b*) $37\frac{1}{2}°$, (*c*) $132\frac{1}{2}°$ laboratory angle. Group *a* corresponds to the ground state of $N^{14}(d,p)N^{15}$. The groups *b*, *c*, *d*, *e*, and *f* correspond to the $A^{36}(d,p)A^{37}$ reaction as identified in Table I. Position *h* is where the first excited state of $N^{14}(d,p)N^{15}$ is expected. Positions *g* and *i* are where the ground and first excited states of $A^{40}(d,p)A^{41}$ are expected.

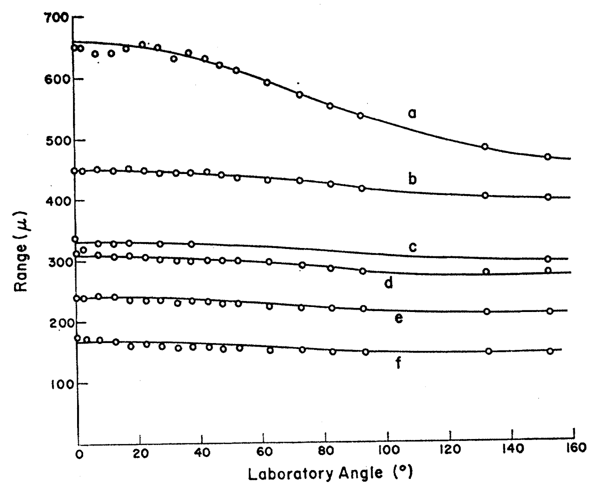


FIG. 2. Experimental range in the emulsion of the observed groups as a function of the laboratory angle. Solid lines correspond to the ranges predicted by the *Q* values listed in Table I [$A^{36}(d,n)A^{37}$].

best the evidence for the existence of a doublet as postulated by Davison[5] but not seen by Zucker.[4] Up to about 400 μ (shaded portion) the tracks have been plotted as a histogram in 5 μ intervals. Since this is certainly of the order of the straggling involved in the over-all range, no loss in detail is to be expected. From there to about 500 μ, intervals of 10 μ were used as the plotting unit. Beyond this, 20 μ intervals were used (inserts). These latter are actually somewhat larger than the straggling width and obviously introduced some artificial broadening. However, since no fine structure is either expected or seen in the vicinity of peaks *a* and *b*, the convenience of these units was given preference. To avoid confusion concerning the renormalizations required to plot these on the same relative yield axis, data in these latter regions have been indicated as points rather than histogram bars. At all angles additional scans were made recording only the scarcer long tracks. The scaling of the yield axis required in these cases in order to render reasonable detail is as indicated. Background, i.e., no gas, runs showed no particles except at 0°. They were ascribable to the Ni$(d,p)$ reactions and were simply subtracted out where they interfered. Integrated beam exposure was 38 microcoulombs.

The positions of the various lettered peaks (*a* through *f*) as a function of angle of observation are displayed in Fig. 2. Only peaks clearly observed are plotted as points. Range uncertainty is of the order of the circle diameter used. Where the presence of a group is only obvious from distortion in the shape of another group [as group *c* in Fig. 1(c)], its range has been considered as too poorly defined to plot. As a result of this arbitrary criterion, the position of group *c* has been omitted at many angles even though in some as in Fig. 1(c) at $132\frac{1}{2}°$, its probable position could be extracted from the data and is in agreement with the curves as drawn in

TABLE I. Reaction assignments and summary of data for the proton groups of Fig. 1.

| Group | Reaction | $Q$ (Mev) | $\Delta E$ (Mev) | $l_n$ | $r_0$ ($10^{-13}$ cm) |
|---|---|---|---|---|---|
| $a$ | $N^{14}(d,p)N^{15}$ | $8.62\pm0.06$ | 0 | 1 | 5 |
| $b$ | $A^{36}(d,p)A^{37}$ | $6.55\pm0.05$ | 0 | 2 | 6.5 |
| $c$ | | $5.16\pm0.06$ | $1.39\pm0.06$ | 0 | 6.5 |
| $d$ | | $4.92\pm0.06$ | $1.63\pm0.06$ | 2 | 6.5 |
| $e$ | | $3.98\pm0.05$ | $2.54\pm0.05$ | 2 | 7.0 |
| $f$ | | $3.00\pm0.05$ | $3.55\pm0.05$ | 2 | 7.0 |

Fig. 2. These curves represent the loci of ranges predicted on the assumption of an incident beam energy of 3.85 Mev, the reaction assignments as listed in the first two columns of Table I, and the $Q$ values (without the quoted errors) as enumerated in the third column. These $Q$ values were initially obtained making use of range-energy curves for protons in emulsion[11] and correcting back through the absorber foils utilizing the differential range data given by Whaling.[9]

The agreement between the drawn and the observed points serve to validate the target assignments to of the order of 10% in mass. Since this obviously does not exclude the possibility of contributions from $A^{40}(d,p)$, the expected positions for groups corresponding to the ground and first excited states of $A^{41}$ have been indicated, $g$ and $i$, respectively. Known higher states of excitation will not interfere with the present data. While such groups were not resolved, at some angles, as in Fig. 1(a), there is a noticeable asymmetry in the direction of their expected ranges. The location of the proton group from the first excited state of $N^{14}(d,p)$ is indicated as $h$. As is apparent from comparison of the three angles shown, this particular group will not cause any problems. In Fig. 1(c) it has passed off the scale to the left. The systematically low ranges manifested at the most forward angles for group $a$ should not be taken too seriously since this is the maximum range measurable in the emulsions subject to the geometry used.

The relative yield of each of the groups as a function of observation angle is displayed in Fig. 3. The letter in each case identifies the group in question. In all cases this was simply a count of the number of observed tracks associated with the peak, duly normalized for the area of emulsion scanned and the target volume visible. Where ambiquity due to asymmetry existed, a simple Gaussian centered on the peak and of half-width commensurate with straggling and a 1% local variation in absorber thickness was constructed and used. In no case did this result in discarding more than 10% of the tracks which might have been included on the basis of a straight count between equivalent range limits. The obvious exception to this is the treatment of the groups $c$ and $d$. In most cases, fortunately, group $c$ was only a small fraction of the total yield. However, forward of 20° it would appear to be about as intense as its usually dominant neighbor. For comparison, both the total number ascribable to both groups (crosses) and the fraction assigned to $d$ (circles) are shown in Fig. 3(d). Beyond 20° there was not enough distinction to justify plotting both. Considerably larger error bars have been drawn to these points in view of this problem of separation. The curves drawn are in each case the stripping distribution expected for the group and reaction in question assuming the values of $l_n$ and $r_0$ indicated. The standard Butler-Born approximation solutions[12] have been used throughout, even though the narrowness of some of the distributions would suggest application of a more refined analysis such as that of Nagasaki.[13]

These data have been summarized in Table I. As mentioned before, the assignment of reaction identity on the basis of known target constituency and range variation with angle is considered reasonably certain. The $Q$ values arrived at are essentially the same as those already in the literature. The only exception is the doublet at $c$ and $d$. Davison[5] reported such splitting on the basis of a slight peak asymmetry at 90° observation angle. Zucker,[6] on the other hand, under similar conditions did not see such structure. Similarly in the present experiment, there is no clear evidence for a doublet except forward of 50° and at the backward angles of 132½° and 152½°. There is, however, additional evidence

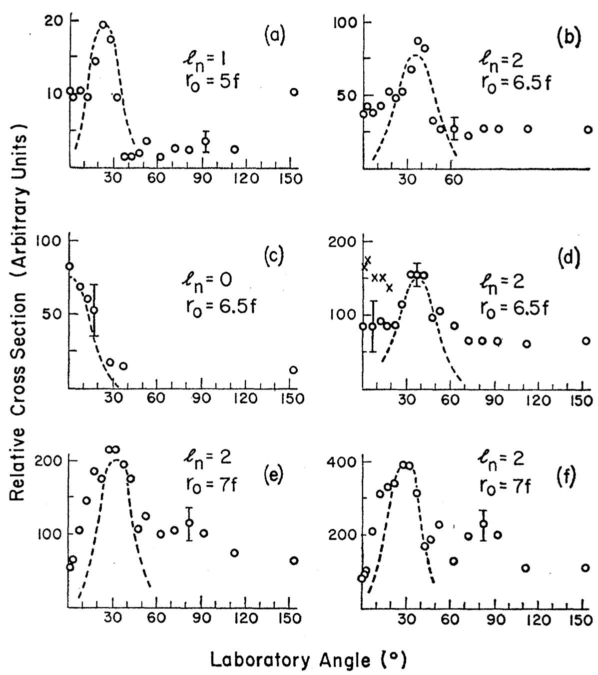


FIG. 3. Relative cross section as a function of angle. The letters correspond to the groups as identified in Table I. The curves shown are the theoretical stripping distributions for the $l_n$ and $r_0$ values indicated. The crosses in $d$ correspond to the sum of yields $c$ and $d$.

[11] J. Rotblat, Nature **167**, 550 (1951).

[12] C. R. Lubitz, "Numerical Tables of Butler-Born Approximation Stripping Cross Sections," Randall Laboratory of Physics, University of Michigan, 1957 (unpublished).

[13] T. Honda and M. Nagasaki, Proc. Phys. Soc. (London) **74**, 517 (1959).

for such structure in neutron groups detained from $Cl^{37}(p,n)A^{37}$.[7] These would suggest levels at 1.40 and 1.65 Mev, in good agreement with those seen here.

Considering the quoted uncertainty in the incident beam energy, coupled with reasonable estimates as to the accuracy of the range-energy data, the probable error given in the table may appear somewhat optimistic. However, the excellent agreement between the value obtained for group *a* and that obtained by far more accurate measurements, while indeed fortuitous, would seem to indicate that the systematic errors which would be involved in assuming an incorrect beam energy and in using range-energy curves, while not necessarily negligible, are at least largely compensatory in the present experiment. In this sense the nitrogen impurity can be construed as providing an internal calibration of the energetics. The errors quoted are a reflection of this.

The values of $l_n$ and $r_0$ chosen for the nitrogen ground-state reaction (*a*) are in accord with expectation.[14] The values of $l_n$ necessary to fit the argon groups are likewise not too unreasonable considering that one is working with *s* and *d* nucleons. The absence of an identifiable *f* state ($l_n=3$) would appear somewhat strange, however. The values of $r_0$ necessary to fit groups *e* and *f* appear somewhat large, but this may well be only a reflection of a larger radius being involved for states of this excitation. In line with this, if one observes only the position of the maximum for the four $l_n=2$ distributions they appear to move systematically faster to smaller angles (i.e., larger radii) than accountable for simply by the change in excitation. These last two could indeed be fitted with $l_n=1$ distributions with $r_0$ values of the order of 3 fermis. This would appear to be an unreasonably small interaction radius. Likewise, to fit any of the peaks with $l_n=3$ would require quite large radii.

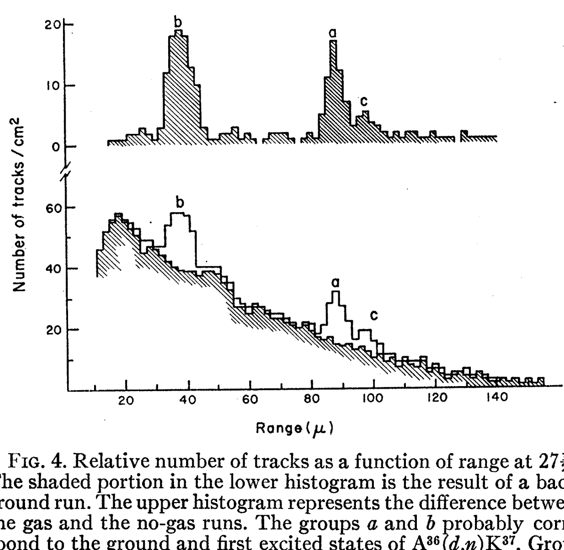


FIG. 4. Relative number of tracks as a function of range at $27\frac{1}{2}°$. The shaded portion in the lower histogram is the result of a background run. The upper histogram represents the difference between the gas and the no-gas runs. The groups *a* and *b* probably correspond to the ground and first excited states of $A^{36}(d,n)K^{37}$. Group *c* is identified with the first excited state doublet of $N^{14}(d,n)O^{15}$. The labels are as given in Table II.

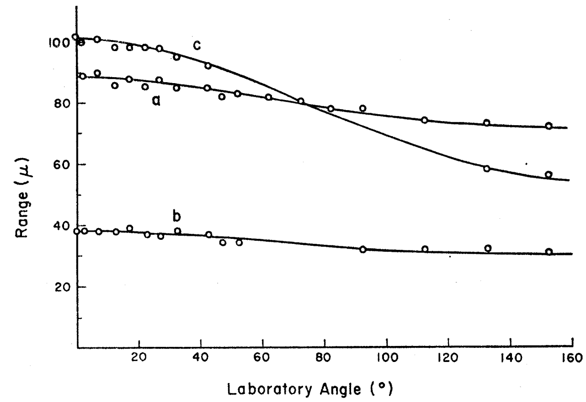


FIG. 5. Experimental range of observed groups as a function of laboratory angle. The solid lines correspond to the ranges predicted by the *Q* values listed in Table II [$A^{36}(d,n)K^{37}$].

## $A^{36}(d,n)k^{37}$

An example of the proton recoil range spectra obtained for the (*d,n*) runs is given in Fig. 4. Only tracks within 10° of the nominal reaction particle axis have been accepted. The lower histogram represents the data as obtained from two runs, one with a gas target (upper line) and a second for equivalent beam exposure but no gas (shaded area). Total integrated beam was 1200 $\mu$coul. Considering the small ranges involved, the plotting interval was chosen as 2 $\mu$. The straight arithmetic difference between the curves is shown in the upper histogram. Only rarely did negative values result and then only to the extent of a few tracks, well within counting statistics. Curiously enough even the background shows some structure coupled with the usual inverse range type of spectrum. A second background run eliminating the gas cell as well as the gas showed a somewhat lower background and no structure. Presumedly the difference was due to Ni(*d,n*) reactions in the cell windows.

Since the target gas contained several percent of both $A^{40}$ and $N^{14}$, the reactions $A^{40}(d,n)K^{41}$ and $N^{14}(d,n)O^{15}$, both having large *Q* values,[8,14] may also be expected to contribute. In general, only a few isolated tracks were observed outside the range region covered by Fig. 4. This is not too unusual considering the energy dependence of the *n-p* scattering cross section. Unfortunately the structure arising from the former reaction in the range region shown is unreported. The second reaction is only expected to contribute through its first state of excitation. The position expected for this closely spaced doublet is designated as *c* in the figure. Nowhere is this group strong. It is in fact lost inside group *a* between 45° and 100°. Its intensity is sufficiently small relative to *a* that its presence off center does not even appear to induce a shift in the maximum. This may be witnessed by the plot in Fig. 5 of the range corresponding to each

[14] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, 190, 198 (1959).

TABLE II. Reaction assignments and summary of data for the proton recoil groups of Fig. 4.

| Group | Reaction | $Q$ (Mev) | $\Delta E$ (Mev) | $l_p$ | $r_0$ ($10^{-13}$ cm) |
|---|---|---|---|---|---|
| *a* | $A^{36}(d,n)K^{37}$ | $-0.32\pm0.10$ | 0 | 2 | 6.5 |
| *b* | | $-1.78\pm0.10$ | $1.46\pm0.10$ | 0, 2 | 6.5 |
| *c* | $N^{14}(d,n)O^{15}$ | $-0.14\pm0.10$ | | | |

maximum as a function of angle. The low intensity of this nitrogen contribution in spite of the more favorable Coulomb barrier would seem to argue against the presence of very prominent groups from reactions on the $A^{40}$ fraction of the target gas.

The solid curves in Fig. 5 are expected ranges for the reaction and $Q$-value assignment made in the first three columns of Table II, assuming as before an incident beam of 3.85 Mev. As in the case of the $(d,p)$ data the quoted $Q$ values are an average over those individually obtained from the observed groups. The general agreement would tend to bear out the assignments. Again points are only shown for groups clearly observed above the background.

The relative intensities of groups *a* and *b* as a function of angle are shown in Fig. 6. This, as before, amounts to a simple count of tracks in the difference spectrum adjusted for plate area scanned. No correction for *n*-*p* cross section variation has been made. The systematic distortion from this source will be small and not materially affect the yields indicated. Possible contributions from group *c* would further mean that the data shown in Fig. 6(a) would in reality be upper limits in the angular region 45° to 100°. Again this is not considered serious, since it is the maxima which are of primary interest. The curves drawn are the theoretical stripping distributions for the values of $l_p$ and $r_0$ indicated.[12] Two curves have been sketched for group *b*, since it is obvious that no single one would suffice to satisfy the data. It should be noted that the yield spectrum observed is quite similar to that witnessed for the sum over the doublet level in $A^{37}$ [crosses in Fig. 3(d)]. In both there is a sharp and significant minimum between the two maxima. Unfortunately, the techniques applied in the present experiment could not hope to resolve energetically a doublet of comparable spacing in $K^{37}$.

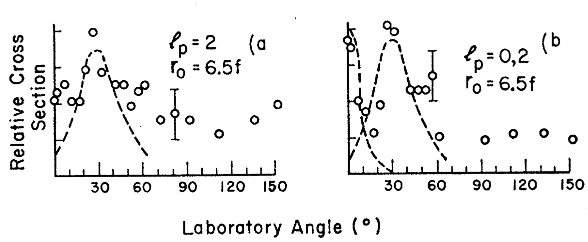


FIG. 6. Relative cross section as a function of angle. The letters correspond to the groups as identified in Table II. The curves shown are the theoretical stripping distributions for the values of $l_p$ and $r_0$ indicated.

The low intensity of group *c* did not justify assembly of an angular distribution.

The $(d,n)$ data are summarized in Table II. The nitrogen data is in agreement with previous work,[14] and may be considered as a nominal check on the energies involved. Because of the amount of background subtraction involved, the peak positions are not as confidently known as in the $(d,p)$ case. This is reflected in the considerably larger error estimates. There exists, at present, no energy level data to compare the $K^{37}$ levels to. The $l_p$ values used are not too unreasonable, however, considering the results of the $(d,p)$ analysis.

## Discussion

On the basis of a simple shell model construction for the mass 37 dyad, one would expect in each case a $d_{\frac{3}{2}}$ ground state. The low-lying excited states might then be formed by the promotion of the odd particle to an $f_{7/2}$ level or the creation of a hole in either of the recently filled $s_{\frac{1}{2}}$ and $d_{\frac{5}{2}}$ subshells. Since this odd nucleon is also

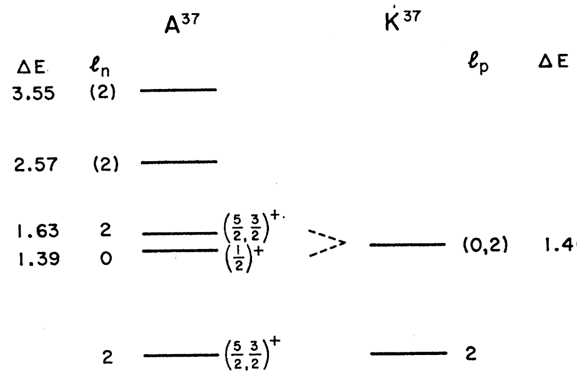


FIG. 7. Comparison of the proposed level structures of $A^{37}-K^{37}$ dyad. (Energies in Mev.) The level at 1.46 Mev in $K^{37}$ is probably a doublet not resolvable by the present experiment.

the third of four possible $d_{\frac{3}{2}}$ particles, even parity configurational states might alternatively be invoked. The data for the ground state and also for the first two excited states would appear to be compatible with this simple picture. The absence of a clearly labeled $l=3$ distribution is a little puzzling, however. One possible explanation of this last is suggested in the nature of the sequence of $l=2$ distributions in Fig. 3. None may really be described as classical stripping curves. In fact all exhibit a very large fraction of the total cross section which is best ascribed to processes other than stripping. Considering them in the order of excitation $(b,d,e,f)$ this fraction would appear to increase. The width of the forward angle peak also steadily increases from somewhat less than theoretically predicted to almost twice what is expected. The relative cross section at the backward angles is steadily increasing while that near zero degrees is falling off. Finally, but perhaps not as surprising, the radius parameter corresponding to the center of the over-all peak is monotonicly increasing. This steady shift of the center of gravity of the peaks to smaller angles would at least appear to rule out the likelihood of instrumental sources for the predominance of $l=2$ type maxima. Taking these incongruencies into account, one cannot help but question the validity of labeling at least the upper two states $(e,f)$ on the basis of their angular distribution. Further work is now underway to attempt to resolve the present confusion.

A level comparison between the two nuclides is made in Fig. 7. If one is willing to accept the comparison of Figs. 6(b) and 3(d) as a reasonable indication of a doublet, the $K^{37}$ nucleus would appear to have a structure quite similar to that of $A^{37}$. Such a splitting, if of the order of 200 kev, could easily be hidden in the data. As may be seen in Fig. 4, group $b$ is consistently broader than $a$, certainly suggestive of such structure. Further, if the two subgroups were of about equal intensity at zero degrees, as in the $A^{37}$ case, this would only result in a systematic shift in the apparent $Q$ for their center of gravity of half the amount of the separation. Unfortunately, the counting statistics were not sufficiently good to allow reliable detection of such a systematic variation.

From the difference of the ground-state $Q$ values one obtains a value for the Coulomb energy difference at mass 37 of $6.87\pm0.15$ Mev. This would compare quite favorably with the value of $6.95\pm0.07$ Mev[15] extracted from the positron decay energetics of $A^{37}$.

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[15] R. Wallace and J. A. Welch, Phys. Rev. **117**, 1297 (1960).

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# Measurement of the Annihilation-in-Flight Cross Section at 0° for 8.5-Mev Positrons*

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The differential cross section at 0° for the annihilation in flight of 8.5-Mev positrons has been measured. The positrons were created in a thick Ta target which was bombarded by 20-Mev electrons from a linear accelerator. They were directed onto a Be target where annihilation occurred, and the annihilation photons were measured by use of a thick-crystal spectrometer. The measured value for the cross section is $1.3\pm0.2$ barns/steradian per electron, which is in agreement with theory.

## INTRODUCTION

A HIGH-CURRENT 22-Mev electron linear accelerator has been used at the Lawrence Radiation Laboratory to produce beams of nearly monoenergetic photons in the approximate energy range of 5 to 15 Mev.[1] The photons were obtained from the annihilation-in-flight of fast positrons; thus, it was considered desirable to check the differential cross section for this process in the energy range of interest. Differential cross sections for annihilation in flight of positrons have been previously examined at 1.0, 2.2, and 3.3 Mev,[2] and total cross sections have been measured at 50, 100, and 200 Mev.[3] The measurements reported below are those for the differential cross section at 0° for 8.5-Mev positrons, and were obtained by the use of techniques quite different from those previously employed.

In this report only the two-quantum annihilation process will be considered, since the one- and three-quantum processes are negligible at this energy for

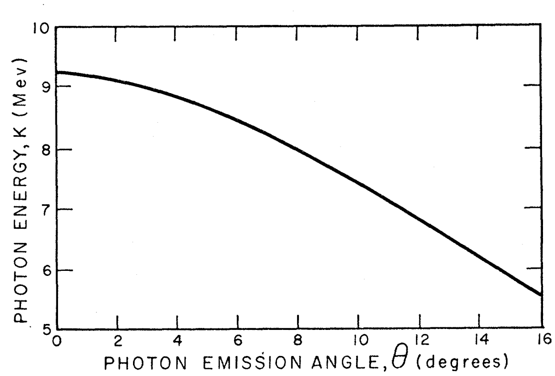


FIG. 1. Photon energy vs angle for annihilation in flight of 8.5-Mev kinetic energy positrons.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] C. P. Jupiter, N. E. Hansen, R. E. Shafer, and S. C. Fultz, University of California Radiation Laboratory Report UCRL-6044, 1960 (to be published).

[2] H. W. Kendall and M. Deutsch, Phys. Rev. **101**, 20 (1956).

[3] S. A. Colgate and F. C. Gilbert, Phys. Rev. **89**, 790 (1953).