energy $E2$ transitions should be excited to an appreciable extent even in the rare earth region [where higher $B(E2)$ values are found]. It should also be noted that lithium ions of 5 Mev should be capable of exciting with reasonably high yields most nuclei throughout the periodic table whose study with other projectiles has been previously reported in the literature.

ACKNOWLEDGMENTS

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Low-Lying Energy Levels in Sc^{41}†

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The reaction $Ca^{40}(d,n)Sc^{41}$ was studied at 4.15-Mev bombarding energy using nuclear emulsions as detectors. Four groups of neutrons were observed with Q values of -0.57, -2.43, -2.64, and -2.85 Mev. The observed angular distributions can be fitted with distirbution curves obtained from stripping analysis on the basis of $r_0=6.0$ fermi and $l_p=3$, 1, 1, 1, respectively. Two additional groups of questionable assignment were observed at $Q=-1.13$ and -1.41 Mev. Neutron groups from reactions on C^{12} and O^{16} were also observed and served to confirm the beam calibration as well as background and other correction methods.

THE mirror pair Ca^{41}–Sc^{41} is of interest from several points of view. To begin with, it is one of the highest mass doublets that can be investigated experimentally. Its study should, therefore, give an indication of how far one can push the ideas of charge symmetry that have been applied to lighter mass pairs so successfully. Further, the odd nucleon in each member of the pair should correspond to the beginning of the $f_{7/2}$ shell. The addition of this odd nucleon to the particularly stable 20-20 nucleon configuration of Ca^{40} might be expected to lead to a reasonably clean and uncomplicated level structure. The lowest lying states are most likely

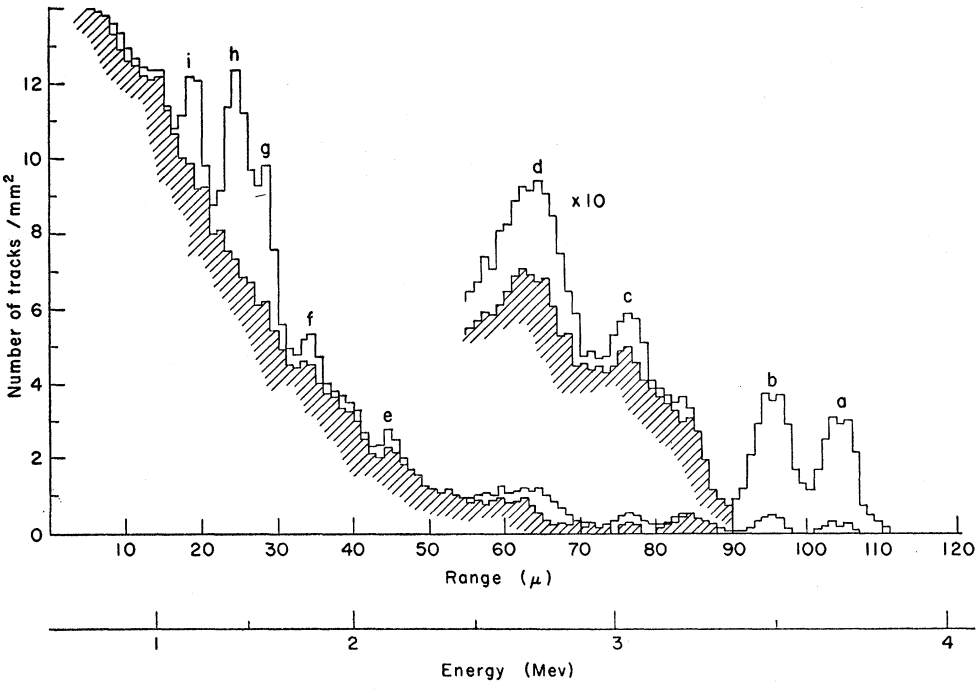

FIG. 1. Proton recoil spectrum for 35° laboratory angle. Shaded area illustrates background yield from separate background plate. Expanded portion indicates spectrum from additional scanning for tracks of 50 μ minimum length.

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due to single particle excitation and as such should be amenable to interpretation on the basis of the shell model.

As is the case for most neutron-rich members of mirror pairs, the Ca^{41} level scheme is reasonably well known,[1] even to excitations where the simplest pictures may no longer apply. In particular, parity and angular moment assignments have been made for the more prominent low-lying states. The present work was undertaken to compare the details of the low-lying Sc^{41} levels to this previous rather extensive study of Ca^{41}.

Thin targets were deposited onto a gold backing foils, both by sedimentation from an alcohol slurry and evaporation from a tantalum boat. Naturally occurring $CaCO_3$ and CaI_2 and samples of $CaCO_3$ enriched in Ca^{42} [2] were used. The targets used ranged from 0.2 to 1.7 mg/cm², with a gold backing foil of 4.2 mg/cm². The evaporated targets in all cases seemed to consist largely of CaO with varying amounts of carbonate present. Evidence for this conclusion was the varying yield of the carbon reaction peaks. To guard against further contamination due to preparation, several blank targets were prepared, which were either subjected to evaporation from an empty tantalum boat or had the residue from grinding in an empty aluminum silicate mortar deposited on them.

These various targets were bombarded with a collimated beam of analyzed deuterons from the Yale cyclotron. In a typical run, of the order of one millicoulomb of beam charge would be integrated. The scattered deuterons and charged reaction products were stopped in a lead absorber ring lined with 67 mg/cm² of gold foil. The latter served to reduce the likelihood of secondary (d,n) reactions being initiated in the absorbing ring. The lead also reduced markedly the amount of soft gamma- and x-ray background.

The reaction neutrons were detected in 50μ Ilford C-2 emulsions situated at scattering angles from 0° back to 162.5°. The detectors were placed normal to the scattering plane and inclined at 5° to the radius, which is the nominal particle direction. For about one third of the plates exposed, an auxiliary radiator of Mylar foil (0.8 mg/cm²) was placed behind the absorber. The knock-on protons produced in this foil were collimated by appropriate slits and then detected in the plates. In the other plates the hydrogen in the emulsion proper was used for the production of recoils.

Between exposure and processing, the emulsions were allowed to fade for six hours to reduce the amount of background fog resulting from gamma rays. The emulsions were scanned at 1000× magnification by means of microprojection techniques previously described.[3] Only proton tracks ending in the emulsion and making an angle of no more than 10° with respect to the nominal neutron direction were accepted. A minimum of 2000 tracks per plate were read. A typical neutron spectrum is shown in Fig. 1; this particular one was chosen since it shows all the groups discussed below. To improve the counting statistics, additional areas were scanned on each plate, recording only tracks exceeding some minimum range, such as 50 μ in the case of Fig. 1.

Internal checks were obtained on the beam calibration and the detection geometry by the presence of carbon and oxygen in many of the targets. Both reactions could be compared with previous experiments[4] as to energy levels and angular distributions. The lower energy oxygen groups further served as a check on the subtraction of background. To prevent any ambiguities which might arise from differences in geometry and excitation, the $O^{16}(d,n)$ reaction was also investigated as a separate experiment (see below).

The ranges of the various particle groups observed are shown as a function of angle in Fig. 2. Comparison of these experimentally determined loci with parametric curves of the various probable reactions then serves to identify the target. Two groups (e) and (f) may be clearly assigned to oxygen and one (a) to carbon. The

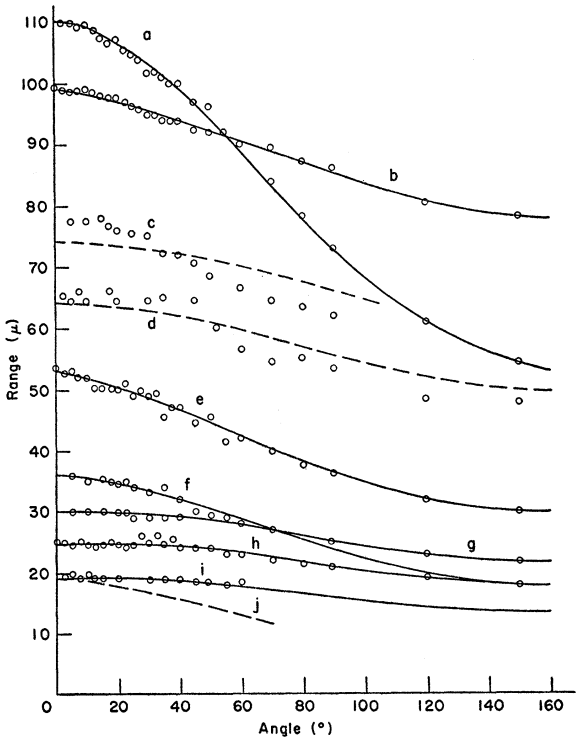

FIG. 2. Mean range of recoil groups *vs* laboratory angle. Curves are for expected range corresponding to average Q value *vs* laboratory angle. $C^{12}(d,n)N^{13}$—(a), (j): $Q=-0.24, -2.72$; $O^{16}(d,n)F^{17}$—(e), (f): $Q=-1.56, -2.09$; $Ca^{40}(d,n)Sc^{41}$—(b), (c), (d), (g), (h), (i): $Q=-0.57, -1.13, -1.41, -2.43, -2.64, -2.85$ Mev.

[1] C. K. Bockelman and W. W. Buechner, Phys. Rev. **107**, 1366 (1957).

[2] Separated isotopes were obtained from the Oak Ridge National Laboratory.

[3] H. S. Plendl and F. E. Steigert, Rev. Sci. Instr. **27**, 239 (1956).

[4] Middleton, El-Bedewi, and Tai, Proc. Phys. Soc. (London) **A66**, 95 (1953).

TABLE I. Summary of results.

Group	Target	Q(Mev)	Excitation (Mev)	l_p
(a)	C	−0.24		
(e)	O	−1.56		
(f)		−2.09		
(b)	Ca	−0.57	0.0	3
(c)	[a]	(−1.13)		
(d)	[a]	(−1.41)	(0.84)	
(g)		−2.43	1.86	1
(h)		−2.64	2.07	1
(i)		−2.85	2.28	(1)

[a] These groups most likely arise from $Si^{28}(d,n)P^{29}$ rather than $Ca^{40}(d,n)Sc^{41}$.

curves shown are for ranges expected for a beam energy of 4.15 Mev and assumed Q values of −0.24 Mev for $C^{12}(d,n)N^{13}$, and −1.56 and −2.09 Mev for $O^{16}(d,n)F^{17}$. These specific values represent a weighted average over data from all angles and should be assigned an uncertainty of ±0.05 Mev. They are all in good agreement with earlier results.[4] Except for the 2.37-Mev level in N^{13}, groups corresponding to more highly excited states in these two reactions are not expected to be seen because of energy limitations. The three observed groups then serve as an internal check upon the energy of the incident deuteron beam. A separate run, using a gaseous oxygen target, gave groups corresponding to −1.58 and −2.10±0.05 Mev.

The three groups labeled (*b*), (*g*), and (*h*) are identifiable with the $Ca^{40}(d,n)Sc^{41}$ reaction. They would correspond to Q values of −0.57, −2.43, and −2.64±0.05 Mev, respectively. While the mass of the target is not defined to better than about 10%, by this method, the absence of potassium and scandium from the samples used would suggest the heavier isotopes of calcium as the only possible source of interference. This conclusion was confirmed in a run with the enriched Ca^{42} target, where the Ca^{40} concentration was down by a factor of six. The yield of neutrons in these three groups was found to be down by about the same ratio.

A fourth group (*i*) of Q value −2.85±0.05 Mev may probably also be associated with the $Ca^{40}(d,n)$ reaction on the basis of comparison with the enriched target and background runs. However, because of the relatively higher background subtraction required, this group is only tenuously identified as to target mass, probably to no better than about 30%. There is, furthermore, a strong likelihood of confusion with neutrons leading to the aforementioned 2.37-Mev state in N^{13} at forward angles [group (*j*) in Fig. 2].

Two additional groups (*c*) and (*d*) are also seen on many plates. If attributable to the $Ca^{40}(d,n)$ reaction, they would have Q values of −1.13 and −1.41 Mev. But both appear above background only on runs using targets prepared by sedimentation. They further appear to shift with angle more in accordance with a target of mass 28 than mass 40. (The parametric curves in Fig. 2 for the heavier target.) Since they also show up in the background runs, although more weakly than might be hoped, it is highly probable that they are to be associated with either aluminum or silicon impurity introduced in preparation of the target material. Energetically they could be identified with the first and second excited states in the $Si^{28}(d,n)P^{29}$ reaction.[5] In this regard it should be noted that there is also an indication of the oxygen peaks in the background runs.

The fact that the 0.88-Mev gamma transition observed in $Ca^{40}(p,\gamma)Sc^{41}$ [6] would agree roughly with a first excited state in Sc^{41} at 0.84 Mev (Table I) is probably fortuitous. The reported gamma de-excitation is more likely due to a transition between higher states of excitation, e.g., an $M1$ transition from the recently observed 2.96-Mev ($\frac{1}{2}^-$) state[7] to the 2.07-Mev ($\frac{3}{2}^-$ or $\frac{1}{2}^-$) state observed in this work.

The angular distributions were obtained by a direct count of the number of tracks within a given group, normalized with respect to the area scanned. Wherever background was known to be present, the appropriate subtraction was made in accordance with the spectra from background plates. This was only important for the lower energies as indicated by the shaded portions of Fig. 1. As a check on the subtraction methods, the two $O^{16}(d,n)F^{17}$ impurity reaction peaks were compared to the results of the separate run on an oxygen target. The ground-state group involved only a background correction. Essentially identical distributions were obtained in both instances.

A second type of subtraction was necessitated by the crossing over of groups. As seen in Fig. 2, the $C^{12}(d,n)N^{13}$ ground state interferes with the $Ca^{40}(d,n)Sc^{41}$ ground state at 55° and 60°. Similarly, the first excited state of the oxygen reaction interferes with the first excited state of the calcium reaction in the region of 45°–90°, and with the second excited state beyond 120°. In each case of ambiguity, smooth extrapolations of yield *vs* angle were made through these regions of overlap, extrapolating from adjacent portions of the curves. The total yield was then proportionately divided in accordance with the extrapolations. In all cases the impurity contribution was quite small. The apportionment resulted in no obvious irregularities. Points so obtained are plotted as *x*'s in Fig. 3. The first excited state group in the oxygen reaction, which was subjected to corrections of this type as well as background subtraction, gave a distribution equivalent to that of the separate run.

Figure 3 shows the adjusted angular distributions in relative units, *viz.*, number of tracks/mm² of scanned emulsion. No correction has been made for the energy variation of the *n-p* cross section nor for the probability of the proton recoil leaving the emulsion. Except for the

[5] Calvert, Jaffe, and Marlin, Proc. Phys. Soc. (London) **A70**, 78 (1957).
[6] J. W. Butler (private communication).
[7] C. M. Class and R. H. Davis (private communication).

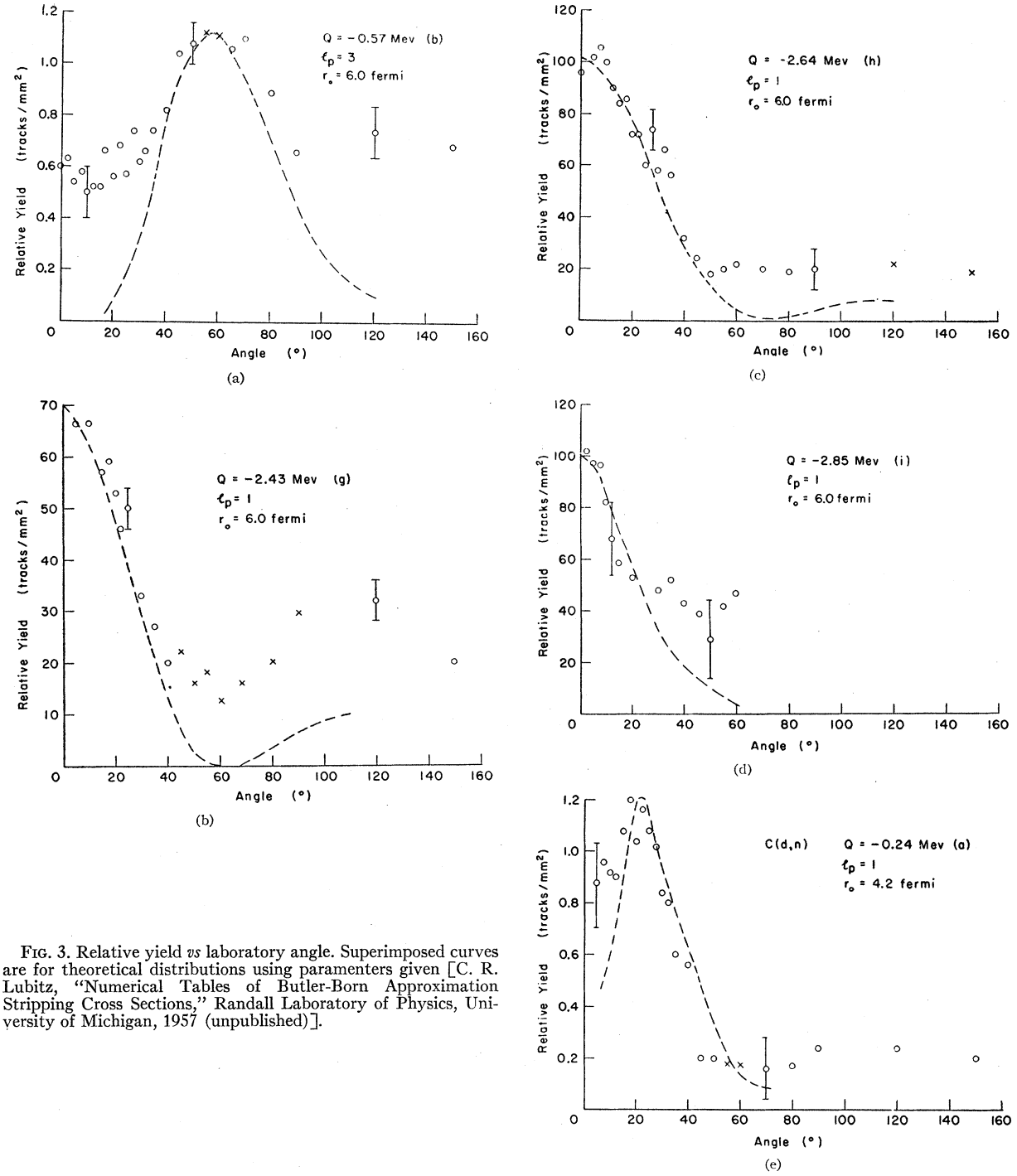

FIG. 3. Relative yield *vs* laboratory angle. Superimposed curves are for theoretical distributions using paramenters given [C. R. Lubitz, "Numerical Tables of Butler-Born Approximation Stripping Cross Sections," Randall Laboratory of Physics, University of Michigan, 1957 (unpublished)].

case of the carbon group, these corrections would not change the relative yield noticeably. The errors indicated are statistical, based upon the uncorrected yields. The carbon data, shown only for comparison purposes, is in good agreement with previous results.[4]

No attempt has been made to subtract possible carbon contributions from the yield curve for group (*i*) of Q value −2.85 Mev. This could lead to an erroneously high count at forward angles. Considering this, the angular distribution data shown for this group represents only a single run with a sedimented CaI_2 target. Group (*a*) in this run was down by about a factor of eight. The distribution so obtained did indeed show a systematic decrease in yield forward of 10°, but

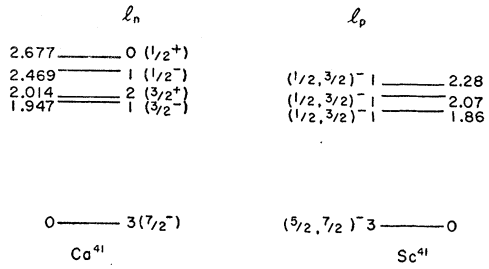

FIG. 4. Comparison of low-lying states in Sc^{41} with the more intense states of Ca^{41}.

still within the error bars indicated. If any appreciable fraction of the forward peak shown is attributable to carbon, then the interpretation as an $l_p=1$ distribution would be open to serious question.

The experimental results are summarized in Table I. Group (*a*) is assigned to the ground-state reaction $C^{12}(d,n)N^{13}$, and groups (*e*), (*f*) to the ground and first excited states of $O^{16}(d,n)F^{17}$. Groups (*b*), (*g*), (*h*), (*i*) are identified with the first four levels from $Ca^{40}(d,n)Sc^{41}$. Groups (*c*), (*d*) are very likely due to a silicon impurity, but are listed with the energies they would correspond to if they had originated in the calcium.

The level scheme of Sc^{41}, that these identifications would result in, is given in Fig. 4. This scheme is compared to the more intense low-lying states of Ca^{41} after isobaric correction. In this experiment no further attempt was made to specify the angular momentum unambiguously, so only the l_p values as determined from the respective stripping distributions are pertinent. Considering recent evidence of changes in distribution with bombarding energy, even these probably should be taken with some reservation. Nevertheless, the agreement among the low-lying levels appears to be quite reasonable.

If one considers the reaction cycle involving $Ca^{40}(d,p)Ca^{41}$ [1] and the Sc^{41}–Ca^{41} beta decay,[8] a ground-state Q value for $Ca^{40}(d,n)Sc^{41}$ of -0.60 ± 0.06 Mev would be suggested. This is in excellent agreement with the observed value of -0.57 ± 0.05 Mev. This latter value would indicate a mass difference for the Ca^{41}–Sc^{41} doublet of 5.92 ± 0.06 Mev. This may be compared with the isobaric (Coulomb and mass) correction of 6.12 Mev. The discrepancy of 0.20 Mev is quite in line with discrepancies observed in other mirror pairs.

ACKNOWLEDGMENTS

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[8] D. R. Elliot and L. D. P. King, Phys. Rev. **60**, 489 (1941).

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Resonance Fission Widths of U^{235} for Levels from 6 ev to 50 ev*

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The energy variation of the total and fission cross sections of U^{235} has been measured with the Nevis synchrocyclotron neutron velocity spectrometer. Fission widths for most of the levels up to 50 ev have been deduced from these measurements. The distribution of the 38 known fission widths shows that the number of channels available for the fission process is between one and four and is most probably two. If $\bar{\Gamma}_f$ is different for the two possible spin states of the compound nucleus, these cannot differ by more than an order of magnitude.

INTRODUCTION

THE wide variation of the fission widths of the neutron resonance levels in U^{235} has now definitely been established,[1–4] implying that the number of exit channels available for the fission process is small. The exact number of such channels, however, cannot be determined with any degree of accuracy from the available data for the following reasons: (1) The accuracy of the known fission widths is poor. (The range of the observed values of the fission widths for a particular resonance is frequently considerably larger than the stated errors of the measurements, which are fairly large in themselves). (2) The number of fission widths which have been determined is rather small. (3) The spin of the resonance level in the compound nucleus is unknown. (There are two possible spin states for the compound nucleus, and these may have

* This work was partially supported by the U. S. Atomic Energy Commission.

[1] V. L. Sailor, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nations, New York, 1956), Vol. 4, p. 199.

[2] W. W. Havens, Jr., and E. Melkonian, *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 99.

[3] F. J. Shore and V. L. Sailor, Phys. Rev. **112**, 191 (1958).

[4] E. Vogt, Phys. Rev. **112**, 203 (1958).