INVITED PAPERS FROM THE TOPICAL CONFERENCE ON COMPOUND NUCLEAR STATES

Introductory Note

On 10–12 October 1963 the American Physical Society and the Oak Ridge National Laboratory sponsored a Topical Conference on Compound Nuclear States which took place in Gatlinburg, Tennessee. This conference was organized for the purpose of bringing together those interested in the recent progress in understanding the formation and decay of compound nuclear states as well as progress in describing nuclear reactions. Members of the Program Committee were as follows: J. L. Fowler, Chairman, Oak Ridge National Laboratory; L. C. Biedenharn, Duke University; Herman Feshbach, Massachusetts Institute of Technology; G. R. Satchler, Oak Ridge National Laboratory; T. A. Welton, Oak Ridge National Laboratory; and H. B. Willard, Oak Ridge National Laboratory.

On each of the three days of the conference there were morning and afternoon sessions. For the first five of these, various aspects of the subject were reviewed by invited experts. At each session contributed papers were presented, bearing more or less on the session subject. Abstracts of the contributed papers have been published in the *Bulletin of the American Physical Society* **9,** 163 (1964). At the time for submission of contributed papers, 6 September 1963, the authors had the option of providing along with their abstracts papers up to 600 words in length and which could include two figures. The longer papers were reproduced in a program that was distributed to attendees of the conference and are indicated in the author index of the *Bulletin*. Copies of the original conference program may be obtained through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C. for $0.50.

Although the attendance at the conference, 261 registrants, was rather larger than had been expected, the size of the meeting did not discourage discussion following the papers. This was largely due to the guidance of the session chairmen who not only encouraged the lively discussions of the papers, but who also led the discussions along relevant lines. These chairmen were as follows: T. A. Welton (substituting for E. P. Wigner), J. B. French, Rubby Sherr, Karl Wildermuth, Fay Ajzenberg-Selove, and L. C. Biedenharn.

A. H. Snell entertained the conference attendees with a very amusing afterdinner talk entitled "Physics with a Prayer."

Besides the invited papers, revised versions of which are published in this issue of *Reviews of Modern Physics*, papers were also presented by Erich Vogt, *Diffuse Boundary and the Compound Nucleus*, and by Michel Baranger, *Structure of Spherical or Deformed Nuclei at Low Energy*. The material by Vogt appears in *Reviews of Modern Physics* **34,** 723 (1962); that of Baranger is to be published in *Nuclear Physics*.

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Reduced Widths and Strength Functions*

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INTRODUCTION

My subject is reduced widths and strength functions. After having agreed to discuss this topic, I began to feel a little uneasy because general surveys of this subject have been given many times in the past and relatively little of what has happened since is new and of general enough interest to be included in a survey of this type. The theoretical developments of the type discussed at this meeting by Feshbach—work which has been done by Block, Feshbach, Lemmer, Shakin, and Weisskopf, and similar work reported at this meeting by McDonald—seem very interesting, but I certainly do not think it is appropriate for me to discuss them. I would therefore like to discuss a few relevant special topics which I judge to be of interest, and refrain from attempting to give a general survey starting from first principles.

REDUCED WIDTHS

Since the strength function is the average reduced width of nuclear levels, let me first start with a discussion of the widths of resonances. The generally

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

used R-matrix formalism separates the partial widths of a resonance into an inside factor and an outside factor, the outside component giving rise to a sharply energy-dependent penetrability and the inside one to a reduced width which reflects that part of the nuclear configuration that represents the channel in question. The extraction of these reduced widths is of considerable interest since, in addition to spins, parities, and energies, reduced widths are generally needed to establish the character of a given resonant state. I should point out that the same quantities that are called reduced widths in resonance reactions can also be obtained for bound states by studying stripping and pickup reactions, where it is fashionable these days to call them spectroscopic factors. Reduced widths can be obtained by many different experimental techniques and are of considerable importance in trying to understand nuclear structure.

I would like to comment on techniques of extracting reduced widths from resonance reactions. The R-matrix formalism is used generally in connection with the Wigner–Teichmann[1] estimate that the reduced width of a single-particle state should be $\hbar^2/mR$. The ratio of the experimental reduced widths to this Wigner limit is usually the quantity quoted by experimentalists as θ^2, which gives the reduced width as a fraction of the single-particle width.

An alternative way of calculating this fraction is to calculate the single-particle width explicitly for the scattering from a purely real well.[2] The scattering as a function of energy will show resonances. These, with the proper spins and parities, can be compared with experimental widths at the same energies. Calculations for what currently are considered "reasonable potentials" give values of θ^2 which are quite different from the usual Wigner limit calculated from the R-matrix formalism and the penetrability. With fast computers, it takes very little more effort to do a calculation in this way than it does to look up penetrabilities in the appropriate tables. The range of parameters that might be considered reasonable for such purposes is pretty well restricted for the more common particles, so that uncertainties are not very great.

GROSS STRUCTURE FROM FINE STRUCTURE

Next I would like to show some recent results closely related to the concept of strength function. In the study of (d, p) reactions to particular final states, the yield of a state is proportional to the neutron reduced width of this state, as I have mentioned before. In poor-resolution experiments one sees the envelope of these states, which is, in fact, the strength function or the energy-averaged reduced width of these states. The width over which the reduced width is spread is roughly equal to the imaginary potential W and it is usual to say in qualitative discussions of the optical model that the value of W tends to be smaller for bound states, approaching zero near the ground state as it merges into the shell model. Figure 1 shows some old poor-resolution (d, p) results in the mass-50 region.[3] There are two strong bumps in what turned out to be the p-wave strength function. These are roughly in the ratio of 2:1 in most of these nuclei and were thought to be the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ giant resonances. Cohen and others[4] have shown that these bumps are, in fact, split into many states and considerable question has arisen about the spins of some of them. In the last few months, some of us at Argonne have been measuring spins of these states by looking at $(d, p\gamma)$[5] and $(n, \gamma\gamma)$[6] angular correlations and have come up with a rather disturbing picture. Figure 2 shows the known p states in these nuclei with their relative strengths, and shows that in ^{55}Fe, for instance, the $J^\pi=\frac{3}{2}^-$ and $\frac{1}{2}^-$ are pretty well mixed up. The envelope for all p states still has the shape we have seen in the gross-structure experiments, but the spin identifications were incorrect. The spin–orbit splitting seems, in fact, to be quite negligible in comparison with the other interactions splitting up the p-wave strength. The calculated mean energy of the two p states and their widths are shown in Table I, where it is clear that, while the spin–orbit splitting is about 0.2 MeV, the width of the states if 2–3 MeV.

This seems rather disturbing. Attempts to predict these states in terms of the coupling of particles to vibrational states have not been too successful, nor have similar attempts based on simple shell-model configurations. If these features near the ground state are

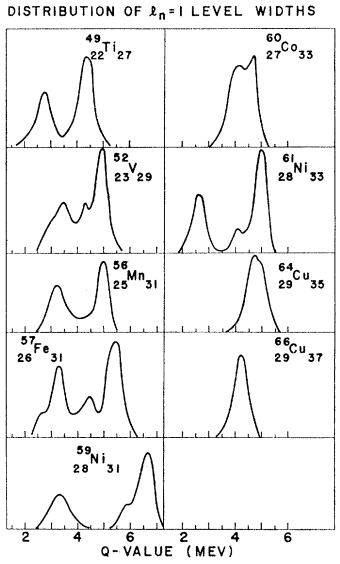

FIG. 1. Distribution of $l_n=1$ strength in (d, p) stripping reactions. The two strong peaks were originally identified as representing the $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$ single-particle strengths, but this identification was later shown to be incorrect.

[1] T. Teichmann and E. P. Wigner, Phys. Rev. **87**, 123 (1952).
[2] J. P. Schiffer, Nucl. Phys. **46**, 246 (1963).
[3] J. P. Schiffer, L. L. Lee, Jr., and B. Zeidman, Phys. Rev. **115**, 427 (1959).
[4] See, for instance, B. L. Cohen, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).
[5] D. S. Gemmell, L. L. Lee, Jr., A. Marinov, and J. P. Schiffer, Bull. Am. Phys. Soc. **8**, 523 (1963).
[6] R. E. Coté, H. E. Jackson, L. L. Lee, Jr., and J. P. Schiffer, Bull. Am. Phys. Soc. **7**, 551 (1962).

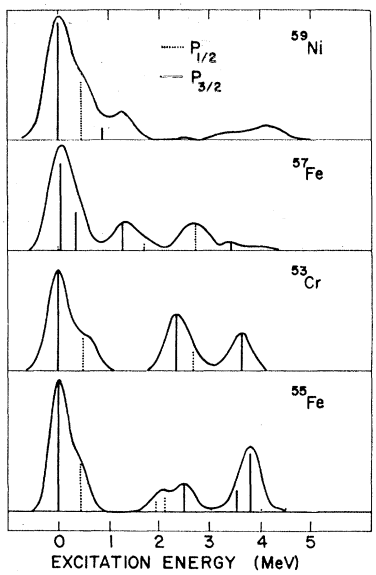

FIG. 2. Distribution of $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ strengths in various nuclei. The dotted lines represent $\frac{1}{2}$ states and the solid ones $\frac{3}{2}$ states; the heights of the lines are proportional to their reduced widths.

not understood, one might perhaps worry about how well simple one-particle excitations might explain the intermediate structure in the strength function at higher excitation energies. It is possible that since particles from dissimilar orbitals are involved, such interactions would tend to cause less splitting at the higher excitation energies.

TABLE I. Location and widths of $2p_{\frac{1}{2}}$ and $2p_{\frac{3}{2}}$ single-particle states in several nuclei.

Nucleus	Mean excitation energy (MeV) $P_{\frac{1}{2}}$	$P_{\frac{3}{2}}$	Halfwidth (MeV) $P_{\frac{1}{2}}$	$P_{\frac{3}{2}}$
^{53}Cr	1.21	1.40	0.9	1.4
^{55}Fe	1.39	1.53	1.1	1.7
^{57}Fe	0.51	2.07	0.80	0.59

PROTON RESONANCE WORK

Next, I would like to discuss some questions about such intermediate structure from a nonneutron point of view. Unfortunately, for historical reasons the subject of strength functions is regarded as the exclusive province of slow-neutron experiments. In this discussion I am making an attempt to emphasize other aspects of strength functions which tend to be ignored by experimentalists and theorists alike. Figure 3 shows some results on the excitation functions[7] of protons scattered elastically from ^{26}Mg. It is clear that a wealth of information can be obtained from such data; in this particular case, spins and parities have been assigned to 37 of these resonances and further work will

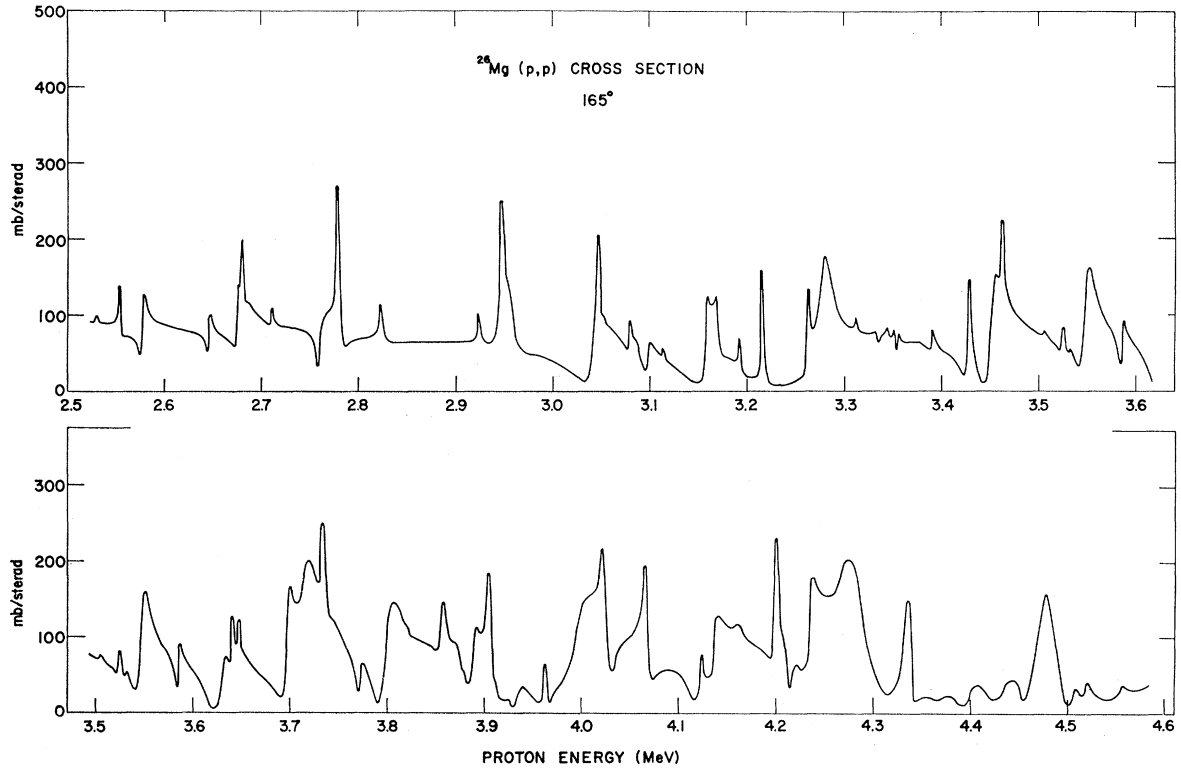

FIG. 3. Excitation function for protons scattered from ^{26}Mg. The data are those of Ref. 7.

[7] M. Mertz (private communication).

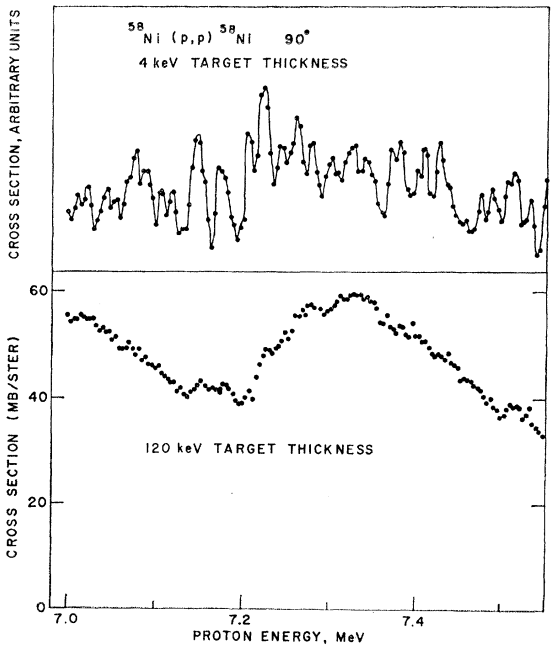

FIG. 4. Excitation function for the elastic scattering of protons from a thin and a thick target of ^{58}Ni under otherwise identical experimental conditions.

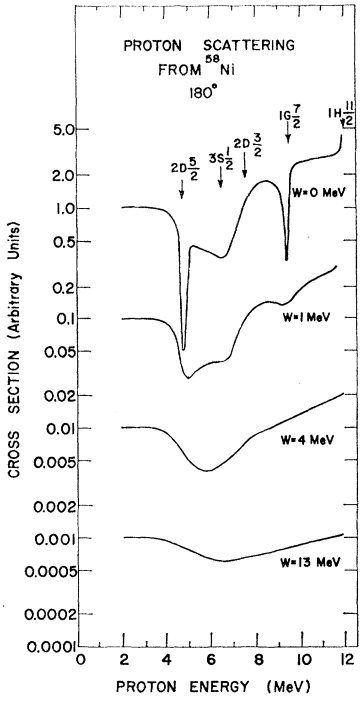

FIG. 5. The calculated excitation function for the elastic scattering of protons at 180° by a potential representing ^{58}Ni, with various values of the imaginary potential W. The resonances corresponding to various single-particle states are shown by arrows. The cross-section scales for successive curves are displaced by one decade.

allow many more to be assigned. Such information for a number of nuclei could be very valuable in testing some of the ideas about strength functions. Slow neutrons can provide such tests, but only with great difficulty. A simple 3.5-MeV Van de Graaff accelerator can be used to provide this type of data for nuclei ranging from mass 20 to 80 or more, but unfortunately, there has been little interest in such experiments in comparison with all the experimental effort and theo-

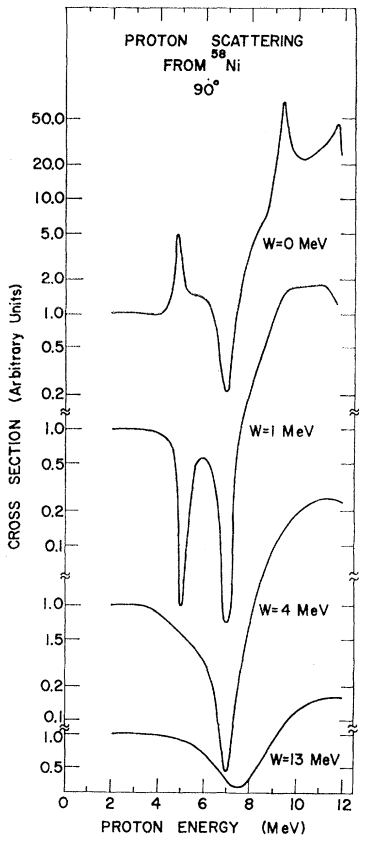

FIG. 6. The calculated excitation function for the elastic scattering of protons at 90° by a potential representing ^{58}Ni, with various values of the imaginary potential W. The resonances corresponding to various single-particle states are shown by arrows. The cross-section scales for successive curves are displaced by one decade.

retical conjecture that has gone into slow-neutron-induced resonance reactions and their interpretation.

GROSS STRUCTURE IN FLUCTUATIONS

Figure 4 shows the excitation function for the scattering of protons from ^{58}Ni with good and bad resolution. Even a qualitative inspection will show that the gross fluctuations must be due to some sort of nonrandom clusterings of strong levels.[8] It is clear that such structure must somehow be related to the intermediate

[8] L. L. Lee, Jr., and J. P. Schiffer, Phys. Letters **4**, 104 (1963).

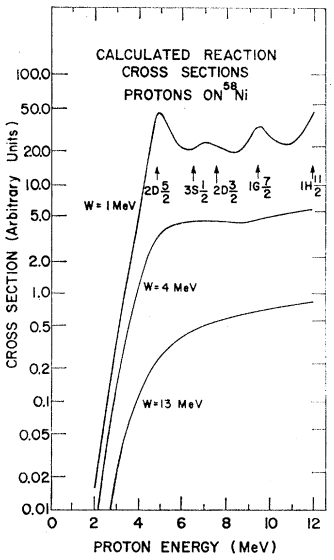

FIG. 7. Excitation curves for the reaction cross section. Other conditions were as described in Fig. 5.

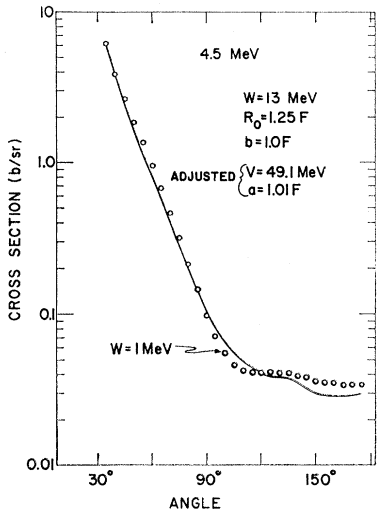

FIG. 8. Calculated angular distributions for 4.5-MeV protons scattered by ^{58}Ni. The points correspond to the calculation with $W=1$ MeV in Figs. 5 and 6. The line corresponds to a fit in which the original calculated curve is treated as "experimental data," W is kept fixed at 13 MeV, and only the well depth V and the diffuseness a of the real well are adjusted.

structure in the strength function. It would be very interesting to be able to assign this structure to particular configurations of the type discussed by Shakin, Feshbach *et al.*, but it is not at all clear how such assignments could be made. One possibility is to carefully study the presence and absence of particular bumps in various reaction channels. Another would be to study phase shifts of the scattering. It is pretty hopeless to study phase shifts with high resolution in this region of overlapping fine-structure resonances. On the other hand, it is not clear what information one would get if one obtained phase shifts from the poor-resolution data.

OPTICAL MODEL CALCULATIONS FOR p+^{58}Ni

Figure 5 is an attempt to show what the calculated scattering from ^{58}Ni is if one assumes an optical model with various values of the imaginary potential W. Figure 6 shows the same for a different angle and Fig. 7 shows the reaction cross section. The arrows mark the particular phase shifts resonating at a given energy—or, if you prefer, the particular strength-function maxima. The point I would like to make is that the usual type of experimental analysis tends to lose such effects. Confronted with such data, the optical model experts would merely assume that "the optical model parameters are changing with energy" and proceed to adjust all parameters to fit the data. Just to see if a fit could be obtained, I tried such a procedure. Keeping W fixed at 13 MeV and only adjusting the real well depth and the diffuseness, I tried to fit the rapidly changing originally calculated angular distributions for $W=1$ MeV in the vicinity of the $d_{\frac{5}{2}}$ state. Surprisingly good fits were obtained, as is shown in Figs. 8 and 9. The resultant parameters are given in Table II. It is clear that this procedure, which is the one that would usually be followed, would led to utterly nonsensical results; the sharp changing of parameters with energy in the optical model is without meaning. Yet all too often this is what is being done in the interpretation of experiments. It seems to me that essential information about the excitation functions is lost by using sharply energy-dependent parameters from an optical model as a means of forcing a fit to the experimental data. I do not know how meaningful it might be to attempt phase-shift analyses of such energy-averaged data, but it is clear that if such an analysis

TABLE II. Parameters for the "fitted" potentials of ^{58}Ni in the vicinity of the original $d_{\frac{5}{2}}$ resonance.

Proton energy (MeV)	Parameters of potential adjusted to fit "data" (W fixed at 13 MeV) V (MeV)	a (F)	Average deviation (%)	$d_{\frac{5}{2}}$ phase shift Original "data" ($V=56$ MeV) ($W=1$ MeV)	From fit
4.5	49.1	1.010	13	10.5°	4.6°
5.0	49.3	1.228	24	−29.5°	−1.0°
5.5	54.5	0.822	27	−22.6	−0.4°

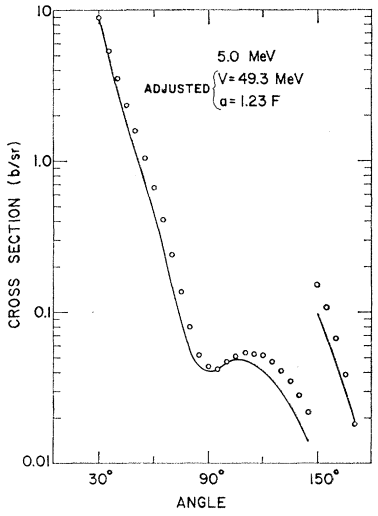

FIG. 9. Calculated angular distributions for 5.0-MeV protons scattered by ^{58}Ni. The points correspond to the calculation with $W=1$ MeV in Figs. 5 and 6. The line corresponds to a fit in which the original calculated curve is treated as "experimental data", W is kept fixed at 13 MeV, and only the well depth V and the diffuseness a of the real wel are adjusted.

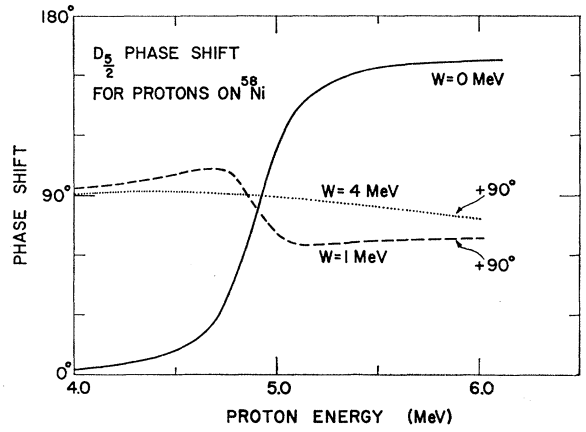

FIG. 10. The behavior of the calculated $d_{\frac{5}{2}}$ phase shift for protons scattered by ^{58}Ni in the energy region for which the calculations for Figs. 8 and 9 were made. The phase shifts for $W=1$ and 4 MeV are displaced by 90°.

could be made, quite detailed identification of the intermediate structure in the strength function would be possible. Such identifications would, of course, be of considerable interest. The calculated phase shifts for the above $d_{\frac{5}{2}}$ resonance are shown in Fig. 10; for a relatively small value of W, the anomaly in the phase shift is clearly discernible. If the gross fluctuations observed in the experimental data are, in fact, due to such effects, then they might be looked for in the experimental data. Figure 11 shows the corresponding transmission coefficients. Note the curious fact that the width of the

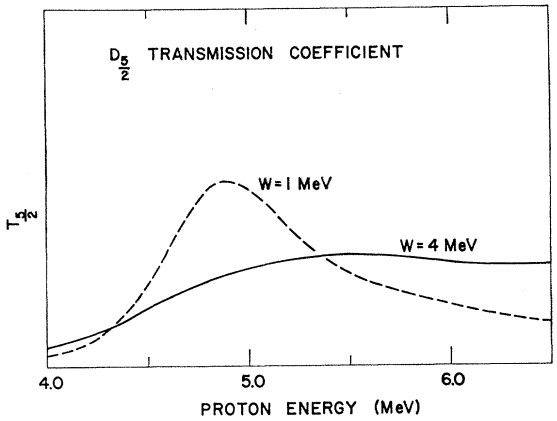

FIG. 11. The $d_{\frac{5}{2}}$ transmission coefficients for the calculated scattering of protons on ^{58}Ni.

resonance in the strength function seems to be closer to W than to the usually quoted value $2W$. This may possibly be associated with the fact that surface absorption was used rather than volume absorption. Table II gives the numerical values of the $d_{\frac{5}{2}}$ phase shift for both the originally calculated and the fitted curves. It is clear that the energy dependence of the $d_{\frac{5}{2}}$ phase shift, which was present in the original data, is lost in the fitting procedure.

In summary, I have tried to show that the concept of a smoothly varying strength function is only a rough approximation to the structure of real nuclei and that considerable detailed experimental effort is needed to get a better understanding of this.