measurement of $\mathcal{A}$ for polarized Co^{60} nuclei[5] and the numerous measurements[6] of the longitudinal polarization of beta rays show that $C'_{S,T}\approx -C_{S,T}$ and $C'_{V,A}\approx C_{V,A}$. With these restrictions on the interaction coefficients, the values of $\mathcal{A}$ and $\mathcal{B}$ show that the interaction is predominantly $V-A$. The other interaction combinations give greatly different values. Thus $S+T$ and $V+A$ give $\mathcal{A}=-1$ and $\mathcal{B}\approx 0$, and $S-T$ gives $\mathcal{A}\approx 0$ but $\mathcal{B}=-1$. It must be borne in mind, of course, that the limited accuracy of our data would not enable one to exclude small departures from assumptions (1) and (2) nor even fairly large violations of (3).

Recent experiments with positron emission in A^{35} and K capture in Eu^{152} have also shown that the Fermi interaction[7] is predominantly V and the Gamow-Teller interaction[7,8] is predominantly A. These results are in disagreement with the published analysis[9] of the He^6 experiment which indicate the presence of T.

The $V-A$ interaction is also in agreement with several recent treatments of the theory of beta decay.[10]

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

1 Burgy, Epstein, Krohn, Novey, Raboy, Ringo, and Telegdi, Phys. Rev. **107**, 1731 (1957).

2 This source of error of the result in reference 1 has been discussed earlier and the sign of the coefficient $\mathcal{B}$ and thus the $V-A$ coupling predominance inferred [V. E. Krohn, Bull. Am. Phys. Soc. Ser. II, 2, 340 (1957)].

3 Jackson, Treiman, and Wyld, Phys. Rev. **106**, 517 (1957).

4 L. Michel, Revs. Modern Phys. **29**, 223 (1957).

5 Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).

6 See, for example, Boehm, Novey, Barnes, and Stech, Phys. Rev. **108**, 1497 (1957), and the references contained therein.

7 Herrmannsfeldt, Maxson, Stähelin, and Allen, Phys. Rev. **107**, 641 (1957).

8 Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

9 B. M. Rustad and S. L. Ruby, Phys. Rev. **97**, 991 (1955); however, in a post-deadline paper presented at the 1958 Meeting of the American Physical Society in New York, these authors modified their original conclusions.

10 E. C. G. Sudarshan and R. E. Marshak, *Proceedings of the 1957 Padua-Venice Conference on Mesons and Recently Discovered Particles* (Nuovo cimento, to be published); Phys. Rev. **109**, 1860 (1958). R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958). J. J. Sakurai, Bull. Am. Phys. Soc. Ser. II, **3**, 10 (1958).

Beta Decay of the Pion

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LET us assume that the hypothesis of a universal (V,A) Fermi interaction, in the form suggested by Feynman and Gell-Mann,[1] will prove to be correct. Then baryons (and perhaps mesons) are coupled to electrons and neutrinos through a current, $j_\mu{}^A+j_\mu{}^V$, consisting of equal amounts of vector and axial vector parts. Feynman and Gell-Mann point out that if $\partial_\mu j_\mu{}^V=0$, then the close equality between the muon decay coupling constant and the Fermi part of the observed beta-decay constant can be understood. They further remark that if the difference (at present small experimentally) between the Fermi and Gamow-Teller beta-decay couplings should turn out to be zero, then $\partial_\mu j_\mu{}^A=0$ would be required for similar reasons. It is not known yet whether such a divergenceless axial vector can be constructed, but some preliminary attempts have been reported by Polkinghorne.[2]

This note is to remark that the relation $\partial_\mu j_\mu{}^A=0$, if it is true, has the additional consequence that $\pi\rightarrow e+\nu$ is forbidden. To see this, note that, if one neglects electromagnetic interactions, the amplitude for this decay must have the form

$$C(k^2)k_\mu l_\mu,$$

where

$$l_\mu=\bar{e}\gamma_\mu(1+\gamma_5)\nu,$$

and k_μ is the pion momentum. Thus, kinematically, only the component of the lepton current l_μ parallel to k_μ contributes to the decay. But in the fundamental interaction $j_\mu{}^A l_\mu$, this longitudinal component of l_μ gives no contribution, because $k_\mu j_\mu{}^A=0$. Thus the amplitude itself must be zero.

The anomalous slowness of π_e decay could be thus explained. But the problem then becomes to explain why π_μ decay *is* seen. Obviously the muon would have to be exempted from at least one of the postulates of the Feynman–Gell-Mann scheme. Certainly the experimental situation on muon capture is not yet such as to prove much similarity to beta decay. Also, it is perhaps an advance to have the point of difficulty shifted from the electron to the (already mysterious) muon.

The author is indebted to T. W. B. Kibble and J. C. Polkinghorne for discussions out of which this note arose.

1 R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

2 J. C. Polkinghorne, Nuovo cimento (to be published).

Single-Particle Interpretation of Proton Spectra from (d,p) Reactions*

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WHEN the Butler formalism[1] for the deuteron stripping reaction is applied to a (d,p) reaction, it predicts that the amplitude with which a given state of the final nucleus is populated should be proportional to the neutron reduced width $\gamma_n{}^2$ of that state with respect to the ground state of the target nucleus. Utilizing this feature of (d,p) reactions, we have undertaken a study of average reduced neutron widths of bound states. This should be analogous to studies of the

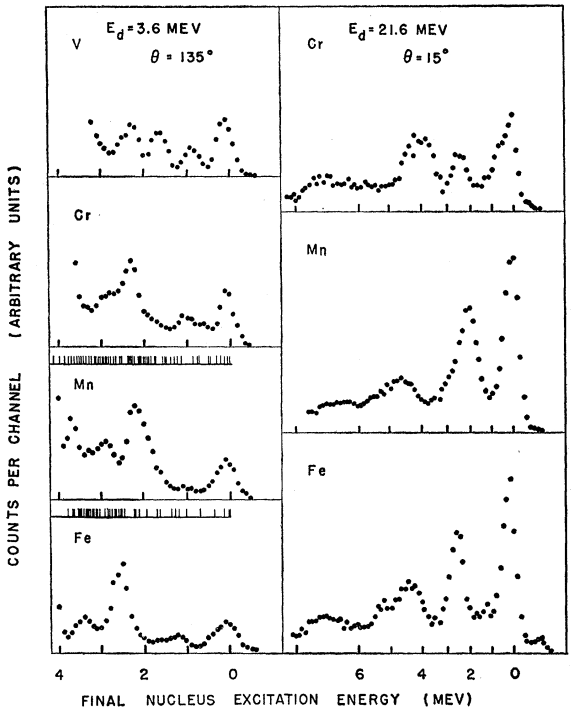

FIG. 1. The pulse-height spectra of protons from the (d,p) reaction as observed in a scintillation detector. The bombarding energies, angles of observation, target elements, and approximate energy scales are indicated on the figure. The known levels in Mn^{56} and Fe^{57} are given with the 3.6-Mev data.

neutron strength function γ^2/D for neutrons of positive energy in neutron scattering experiments.[2,3]

The optical model[3] for a neutron interacting with nuclei and the shell model[4] for the explanation of low-lying bound states of nuclei are both based on the single-particle states of a nucleon in an average potential. It has been pointed out by Lawson[5] that the choice of a suitable potential makes the positions of the single-particle states which are found as strength-function maxima in the optical model consistent with the single-particle states of the shell model.

Applying the arguments of Lane, Thomas, and Wigner[6] to this problem, one would expect the total reaction yields for the (d,p) process for each l value of the captured neutron to be determined by the single-particle widths of these states. If the situation for bound levels is similar to that for unbound ones, i.e., if the "intermediate coupling model" of reference 6 is applicable, then one might expect that maxima in the proton yield would be observed at proton energies which correspond to neutrons captured in a particular single-particle state by the target nucleus. These maxima could encompass many actual levels which can be produced in the final nucleus by incident neutrons with the proper l value. Thus each maximum would have the characteristic angular distribution predicted by the Butler theory for the orbital angular momentum of the captured neutron.[7]

In the present experiment the spectrum of protons from a (d,p) reaction has been studied with deliberately poor resolution. We hoped to see whether any regularities in the gross features of the spectrum of protons emitted in (d,p) reactions could be found when several neighboring elements were studied and to see to what extent these regularities depended on bombarding energy. The spectra of protons emitted by targets of Cr, Mn, and Fe when bombarded by 21.6-Mev and 3.6-Mev deuterons are shown in Fig. 1. The high-energy spectra are certainly similar, with three peaks located near excitations of 0, 2.5, and 5 Mev in the final nucleus. At a deuteron energy of 3.6 Mev the spectrum could be studied only to about 4-Mev excitation since C and O surface contaminants became a serious problem above 4 Mev. Results from Cr, Mn, and Fe show the peaks for the ground state and the 2.5-Mev excited state, as in the higher energy results. Similar effects were obtained with 3.0-Mev deuterons. The Butler theory of deuteron stripping is known to fail at low energies where the Coulomb effects and the contribution from compound nucleus formation become appreciable.[8] One might, however, expect the arguments used for higher energies to be valid as long as most of the reaction proceeds by some process in which the neutron is captured directly into a state of the final nucleus.

A few angular distributions were measured at 21.6 Mev. Unfortunately the Butler theory predicts little difference in angular distributions for different l values at such a high bombarding energy; the angular distributions all tend to peak in the extreme forward direction. The experimental angular distributions appear to be similar for corresponding peaks in Cr, Mn, and Fe. It appears that an $l=1$ assignment would fit the proton group of highest energy consistent with the $2p_{3/2}$ ground state predicted by the shell model. It is also suggested that the second group at about 2.5-Mev excitation contains the $p_{1/2}$ width and the third group at 5 Mev might contain the combination of the $d_{3/2}$ and $d_{5/2}$ widths. The angular distributions tend to support these assignments although the evidence is by no means conclusive.

Preliminary results with targets of Ni, Cu, and Zn show different proton spectra. These can be attributed to the facts that in Ni^{60}, Cu, and Zn, an additional neutron can no longer be accommodated in the $2p_{3/2}$ state and that these elements contain more than one major isotope with Q values differing by one Mev or more. We plan to measure angular distributions more carefully, to look at higher excitation energies for the $3s$ state, to extend the measurements to more target elements, and perhaps to study the region of Ni, Cu, and Zn with separated isotopes. The gross structure found in the present experiment is similar to the "anomalous" inelastic scattering of protons found by Cohen[9] and to the inelastic deuteron scattering observed by Yntema and Zeidman.[10] This perhaps suggests that the effect found in inelastic scattering might be explained by a single-particle process similar to the one proposed here for the (d,p) reaction.

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

[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1952).
[2] H. H. Barschall, Phys. Rev. **86**, 431 (1952).
[3] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).
[4] M. G. Mayer, Phys. Rev. **75**, 1969 (1949).
[5] R. D. Lawson, Phys. Rev. **101**, 311 (1956).
[6] Lane, Thomas, and Wigner, Phys. Rev. **98**, 693 (1955).
[7] A suggestion similar to this has been made independently by A. M. Lane (private communication).
[8] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).
[9] B. L. Cohen, Phys. Rev. **105**, 1549 (1957).
[10] J. L. Yntema and B. Zeidman, Bull. Am. Phys. Soc. Ser. II, **3**, 56 (1958).

Time-Reversal Invariance in Nuclear Scattering

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WE report here some experimental tests of time-reversal invariance, or of parity conservation, or both, in high-energy nuclear scattering. The work was carried out because of the discovery of the failure of parity conservation in weak interactions.[1]

If parity conservation is assumed,[2] which recent experiments have shown to be a good approximation for strong interactions,[3] then one can show quite straightforwardly that time-reversal invariance requires the equality of P and e,[4,5] where P is the polarization produced in the scattering of unpolarized protons and e is the asymmetry produced when fully polarized protons are scattered. Furthermore, in the case of p-p scattering, it has been shown[6] that, at angles near 45° cm, $|P-e|$ is maximum and of the same order of magnitude as the ratio between the coefficients of the two parts of the scattering matrix which are noninvariant and invariant, respectively, under time reversal. It has been estimated that in strong interactions, present experimental data

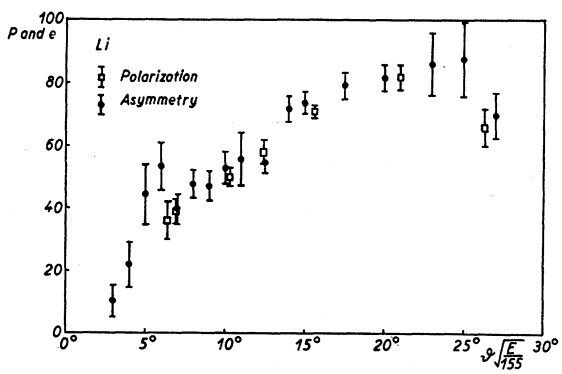

FIG. 1. Asymmetry (energy 155 Mev, angular resolution 0.6°) and polarization (energy 180 Mev, angular resolution 0.6°) for lithium.

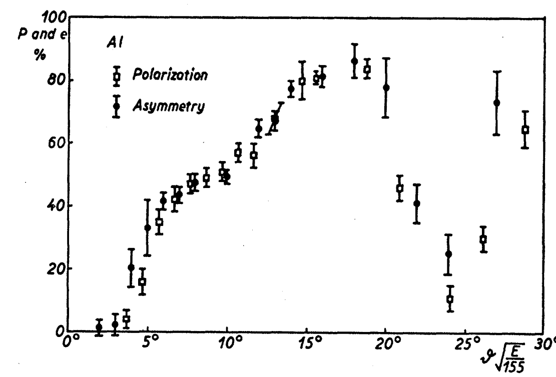

FIG. 2. Asymmetry (energy 155 Mev, angular resolution 0.5° for $\vartheta \geqslant 6°$; 0.9° elsewhere) and polarization (below 15°; energy 156 Mev, angular resolution 1.0°; above 15°; energy 175 Mev, angular resolution 1.3°) for aluminum.

set an upper limit of 10–20% to the relative strength of forces which are noninvariant with respect to time reversal.[7]

We have compared e and P for hydrogen, lithium, beryllium, and aluminum, chosen for their high spin-to-mass ratios, since a failure of $e=P$ in spin-zero nuclei would necessarily violate parity conservation.[5] No measurements of P have previously been performed for these elements. Values of e are available near our energy only for hydrogen. We have measured P for hydrogen, P and e separately for lithium and aluminum, and e/P for beryllium and aluminum, using the unpolarized 185-Mev external beam of the Uppsala synchrocyclotron. All the measurements of e and e/P were made with the range equipment of Alphonce, Johansson, and Tibell,[8] and those of P with the analyzer magnet setup described by Hillman, Johansson, and Tyrén.[9]

The values of e/P for beryllium and aluminum were determined in the standard double-scattering arrangement at one angle only, 14.2° in the lab system, by interchanging first and second targets, one of which was always carbon. All targets were 15 Mev thick, and a first-order correction was made for the energy degradation by having the second scattering take place at $(177.5/162.5)^{\frac{1}{2}}\times 14.2° = 14.8°$. In one case the measured asymmetry is $\epsilon_1 = P_C e_\nu$ and in the other $\epsilon_2 = P_\nu e_C$, where ν stands for either Be or Al. However, carbon has spin zero, so if parity is conserved $e_C = P_C$, and so $\epsilon_1/\epsilon_2 = e_\nu/P_\nu$.

The values of P for hydrogen were measured with polyethylene, but the good energy resolution of the magnet used meant that the subtraction was less than 10%. In the cases of lithium and aluminum, some inelastically scattered particles were included in both the e and, to a lesser extent, the P experiment, but the spectra measured by Tyrén and Maris[10] indicate that these contributions may be not more than a few percent, at least at the smaller angles.

The results for lithium and aluminum are given in Figs. 1 and 2. The errors shown are statistical standard