and using an internal light chopper in the monochromator. These curves were recorded for all polarization positions of interest.

The light spot was checked for uniformity. Care was taken to minimize contact effects. Also, the amount of wave vector swept by the sample varies with light wavelength. Therefore, we divided our normalized curves by the appropriate change in light wave vector at each point.

We were interested in observing the effect of the cubic symmetry of the crystal upon the DDP. For this purpose we prepared samples in various crystallographic orientations. In Fig. 3 we show three sets of curves of the normalized change in the DDP plotted as a function of the energy of the incident photons. Solid and dashed lines denote different samples with the same crystallographic orientation. Polarization angles of 55 and 100° with respect to the quiescent position of the current direction in the sample are denoted by circles and triangles, respectively. In Fig. 4 we show three sets of curves of the normalized change in the DDP plotted as a function of the angle between the polarization and the quiescent position of the current direction in the sample for a photon energy of 0.685 eV. Squares, open circles, and full circles denote samples of different crystallogrphic orientations. The samples oscillated ±15° about their quiescent position. All data were taken at room temperature.

We have shown theoretically that DDP can occur in a homopolar cubic semiconductor, and have discovered such an effect experimentally. Our experimental curves for samples of different crystallographic orientations are sufficiently distinct to show the existence of a directional dependence of the photoconductivity. We assume that it is a bulk effect since it is large for low photon energies where light penetrates deeply into the sample. It remains to be determined whether the theoretical prediction of DDP in Eq. (3) and our experimental results are fully compatible.

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EVIDENCE FOR AN ISOTENSOR ELECTROMAGNETIC CURRENT*

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An unambiguous and model-independent test for the presence of isotensor terms in photopion production is suggested. On analyzing the available data, striking evidence for the presence of such a term is found.

Both the isospin and SU(3) transformation properties of the electromagnetic current are usually assumed to be identical to those of the charge $Q = I_3 + \frac{1}{2}Y$. In particular, under isospin transformations it transforms as the sum of an isoscalar and the third component of an isovector. The lack of experimental evidence for this assumption was first pointed out by Grishin et al.[1] and by Dombey and Kabir,[2] and it was subsequently suggested by one of us[3] that a study of the reaction $\gamma N \rightarrow \pi N$ in the region of the $\Delta(1236)$ resonance was a particularly useful way to investigate this problem. In this paper we wish to present evidence for appreciable effects in these reactions due to the presence of an isospin-2 term in the electromagnetic current, in contradiction to the above $|\Delta I| \leq 1$ rule.

If we abandon the usual assumption on the isospin composition of the electromagnetic current, then in addition to the usual isospin amplitudes for photoproduction, (1) an isoscalar amplitude A^0 leading to the $I = \frac{1}{2}$ final πN state and (2) isovector amplitudes A^1, A^3 leading to the $I = \frac{1}{2}, \frac{3}{2}$ final states, we have also (3) an isotensor amplitude A^2 leading to the $I = \frac{3}{2}$ final state. The amplitudes for the observable processes are

$$(3/\sqrt{2})A(\gamma p \rightarrow \pi^+ n) = 3A^0 + A^1 + (\tfrac{3}{5})^{1/2}A^2 - A^3, \quad (1a)$$

$$(3/\sqrt{2})A(\gamma n \rightarrow \pi^- p) = 3A^0 - A^1 + (\tfrac{3}{5})^{1/2}A^2 + A^3, \quad (1b)$$

$$3A(\gamma p \rightarrow \pi^0 p) = 3A^0 + A^1 - 2(\tfrac{3}{5})^{1/2}A^2 + 2A^3, \quad (1c)$$

$$3A(\gamma n \rightarrow \pi^0 n) = 3A^0 + A^1 + 2(\tfrac{3}{5})^{1/2}A^2 + 2A^3. \quad (1d)$$

In particular, it is easy to see that the $|\Delta I| \leq 1$ rule predicts

$$\Gamma(\Delta^+ \rightarrow p\gamma) = \Gamma(\Delta^0 \rightarrow n\gamma) \quad (2)$$

for the radiative widths, whereas in the presence of isospin-two terms this will not be so.

Let us now consider how an isotensor excitation of the Δ resonance can be detected in an unambiguous and model-independent way. This can be achieved by considering the difference of the total cross sections for Reactions (1a) and (1b),

$$\Delta(W) = \sigma_t(\gamma n \to \pi^- p) - \sigma_t(\gamma p \to \pi^+ n), \qquad (3)$$

as a function of energy. Following the notation of Chew et al.[4] (hereafter referred to as CGLN), we perform a partial-wave expansion of A^i. Thus $E_{l\pm}^i$ ($M_{l\pm}^i$) corresponds to an electric (magnetic) multipole transition to the πN final state with $J = l \pm \frac{1}{2}$. Noting that the only multipoles which can give rise to rapid energy variations in the resonance region are those leading to excitation of the resonance,[5] and separating off terms involving these from the other slowly varying terms, we have

$$\Delta(W) \propto \mathrm{Re}\{-(3\sqrt{5})M_{1+}^0(W)M_{1+}^3(W)^* + M_{1+}^1(W)M_{1+}^2(W)^* - M_{1+}^2(W)M_{1+}^3(W)^*\} + \text{slowly varying terms.} \qquad (4)$$

Assuming unitarity and T invariance, the Watson theorem[6] guarantees that the phases of the multipoles are given by the corresponding πN phase shifts. Hence, in contrast to the resonant $M_{1+}^{2,3}$ amplitudes, $M_{1+}^{0,1}$ will be real and slowly varying in this region. In the absence of any isotensor M_{1+}^2 transition, therefore, the only possible source of rapid energy variation in (4) is the first term, which will look like the real part of a resonance (and in fact with current estimates of M_{1+}^0 will be rather small). In particular there is no possibility of a dip or peak. On the other hand, if M_{1+}^2 is nonzero, by Watson's theorem the interference term $\mathrm{Re}M_{1+}^2M_{1+}^{3*}$ is necessarily either purely constructive or destructive and a dip or peak will necessarily result. Such a structure in $\Delta(W)$ is therefore a completely unambiguous sign of an isotensor term.

The above argument is simple and model independent, but qualitative. To make a more quantitative discussion, we must consider the theory of photoproduction in this region in a little more detail. In fact the conventional approach to this problem, initiated by CGLN[4] and developed with increasing refinement by several authors,[7] has proved remarkably successful in understanding the photoproduction data on protons, and clearly if this success is to be retained, the isotensor term can only be introduced in a rather restricted way. Let us consider how to do this. The above approach to this problem is based on the use of fixed momentum-transfer dispersion relations for the invariant amplitudes, from which a set of equations for the multipoles themselves can be projected. The absorptive parts in these relations are dominated by the terms shown in Fig. 1, where 1(c) is meant to signify only that the imaginary parts in the dispersion integrals are dominated by excitation of the resonance, and the only way in which isotensor terms can enter these diagrams is through the $\Delta N\gamma$ coupling, i.e., through a breakdown of Eq. (2). Writing resonance formulas for the resonance excitation amplitudes[8] ${}_NM_{1+}^3(W)$, defined by

$${}_pM_{1+}^3(W) = (\tfrac{2}{3})^{1/2}\{M_{1+}^3(W) - (\tfrac{3}{5})^{1/2}M_{1+}^2(W)\}, \qquad (5a)$$

$${}_nM_{1+}^3(W) = {}_pM_{1+}^3(W) + 2(\tfrac{2}{5})^{1/2}M_{1+}^2(W), \qquad (5b)$$

we obtain

$$(kq)^{1/2}{}_NM_{1+}^3(W) = \frac{[{}_N\Gamma_\gamma(k)\Gamma(q)]^{1/2}}{2(W_r - W) - i\Gamma(q)} = \left[\frac{{}_N\Gamma_\gamma(k)}{\Gamma(q)}\right]^{1/2} q f_{1+}^3(W), \qquad (6)$$

where k, q are the c.m. photon and pion momenta, and $f_{1+}^3(W)$ is the resonant πN scattering amplitude. Taking simple relativistic Breit-Wigner widths ${}_N\Gamma_\gamma(k) = \gamma_N k^3$, $\Gamma(q) = \gamma q^3$, the relation

$${}_NM_{1+}^3(W) = (\gamma_N/\gamma)^{1/2}(k/q)f_{1+}^{(3)} \qquad (7)$$

results. If we further take

$$(\gamma_p/\gamma)^{1/2} = \mu/2f \qquad (8)$$

for protons, the well-known CGLN static model[4] result is obtained, which is in excellent agree-

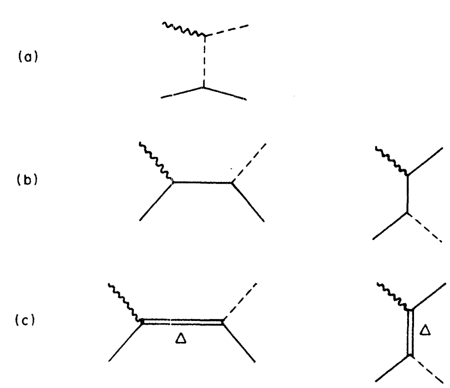

FIG. 1. The principal contributions to the low-energy absorptive parts.

ment with the data in the resonance region.[9] However, in the presence of isotensor terms, Eq. (2) is no longer valid, and to measure the breakdown of the $|\Delta I| \leq 1$ rule we introduce the parameter x, where[10]

$$ {}_nM_{1+}{}^3(W) = (1+x)\,{}_pM_{1+}{}^3(W). \qquad (9)$$

Now, in order to obtain the other multipoles, we need only evaluate the dispersion relations using the above results in the absorptive parts. The results will of course now be a function of x. However, by explicit evaluation we find that for the range of x we shall need to consider ($x \sim -0.2$), the changes in the other multipoles from the normal case ($x = 0$) are essentially negligible (of the order 1 %) and can be ignored. Thus in summary we find (1) the ambiguity introduced is essentially entirely in ${}_nM_{1+}{}^3(W)$, (2) results essentially identical to those of the conventional model for photoproduction on protons are reproduced, even in the presence of a quite large isotensor term, and therefore, (3) the presence or absence of such a term can only be determined by a study of the neutron data.

Before doing this, we briefly comment on the values of the multipoles used. All multipoles except $M_{1-}{}^{0,1}$ and ${}_nM_{1+}{}^3(W)$ were taken from the evaluation of Berends, Donnachie, and Weaver[7] in which the small contributions to the dispersion integrals from multipoles other than $M_{1+}{}^3$ are also included. ${}_nM_{1+}{}^3(W)$ is then given by Eq. (9). The $M_{1-}{}^{0,1}$ multipoles are taken from Born-plus-$M_{1+}{}^3$ calculation of Donnachie and Shaw.[9] These latter multipoles constitute the main uncertainty in the theory, since appreciable inelasticity in the p_{11} waves causes a breakdown of the Watson theorem, and in discussions of the details of differential cross sections and polarization measurements $M_{1-}{}^{0,1}$ must be fixed by the data.[11] However, since they make only a small contribution to the total cross section compared to the effects we consider below, this is not serious here.

Let us now compare our model with the data. In Fig. 2 we plot the predicted total cross sections for $\gamma n \to \pi^- p$ for the values $x = 0, -0.2$. The data are taken from two sources. (1) In the threshold region the theoretical predictions, which depend very little on x, are in excellent agreement with both the π^+ differential cross section[7,8] and with the experimental ratios of π^- to π^+ production obtained from deuterium measurements.[12] The points shown here have been estimated from these data. (2) Results of the Bonn experiment on deuterium which covers the range 0.2 to 1.5 GeV photon laboratory energy.[13] As can be seen, the value $x = -0.2$ is clearly favored. The differential cross-section data have also been examined, but at the present level of accuracy add little further information.

As we have said, the model is identical with the usual one for π^+ production, and in particular agrees very well with the total cross-section data.[14] In Fig. 3 we have plotted the quantity $\Delta(W)$ defined in Eq. (3) using the same data as above. The characteristic dip which results in a model-independent way from the presence of isotensor resonance excitations as shown above is clearly evident in both our model and the data.

We thus conclude that the striking evidence for isotensor terms already apparent in the rather

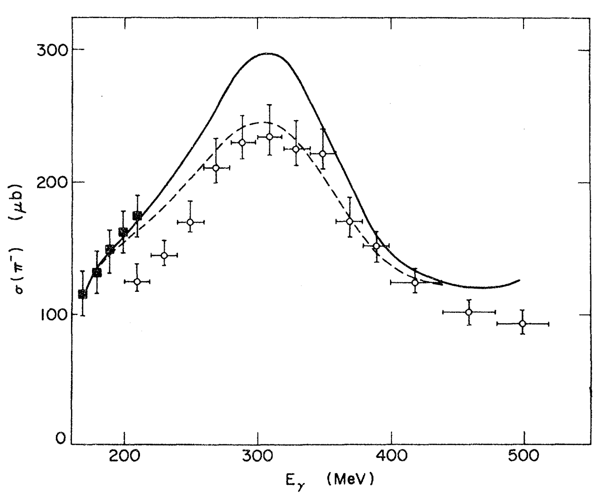

FIG. 2. The total cross section for Reaction (1b) as a function of energy. Solid line $x = 0$ (no isotensor), dashed line $x = -0.2$.

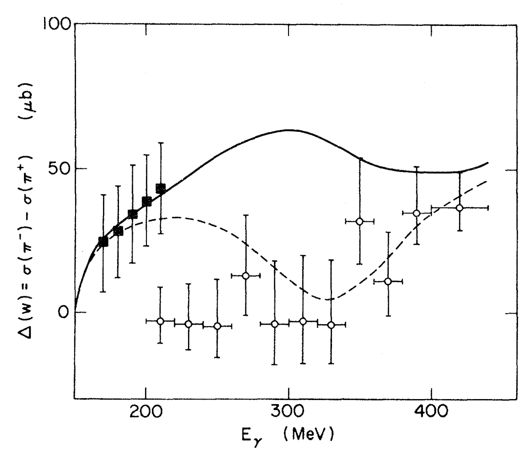

FIG. 3. The difference of the total cross sections for Reactions (1a) and (1b) as a function of energy. Solid line $x = 0$ (no isotensor), dashed line $x = -0.2$.

meager data at present available makes even more clear the need for further experimental investigation of this area, the importance of which with regard to ideas on symmetry breaking is clear. We have two remarks in this respect. Firstly, the above results lead to very large effects in Reaction (1d) in the resonance region. For example, at 330 MeV the total cross section is predicted to be 276 μb for $x=0$, 179 μb for $x=-0.2$. Secondly, as stressed in Ref. (3) a study of the inverse reaction

$$\pi^- + p \to \gamma + n$$

completely avoids any of the uncertainties associated with the use of a deuterium target. Such an experiment has already been reported[15] at a somewhat higher energy [E_γ(lab) = 520 MeV] and agrees with the results from the Bonn experiment[13] quoted above at this energy. It is of great importance to carry out such measurements over the region of the first resonance.

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[4]G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957).

[5]We have neglected the electric-quadrupole excitation E_{1+}, which is experimentally extremely small on protons. If it were not small, it could be separated off also, the argument going through completely unchanged.

[6]K. M. Watson, Phys. Rev. 95, 228 (1954).

[7]For a recent and detailed discussion, see F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. B4, 54 (1968).

[8]We assume resonance excitation through the magnetic-dipole rather than the electric-quadrupole transition. As noted above in Refs. 5 and 7, this is experimentally well verified on protons. We assume it so on neutrons also.

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[10]It might be thought that the success of the static model, and more elaborate calculations of ${}_pM_{1+}{}^3(W)$, preclude the possibility of these, since they are ignored. This is in fact not so, since the homogenous part of the equation for $M_{1+}{}^3$ is essentially the same as the equation for $M_{1+}{}^2(W)$, and solutions of the type (9) are also possible. For a discussion of this, see A. I. Sanda and G. Shaw, to be published.

[11]Sanda and Shaw, see Ref. 10.

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INERT HADRON REACTION FOR THE DETERMINATION OF THE POMERANCHUK TRAJECTORY SLOPE*

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A reaction with no expected secondary Regge poles ($\gamma p \to \varphi p$) is suggested as a means for direct experimental study of the Pomeranchuk exchange amplitude. From existing data on this reaction, we find a Pomeranchuk trajectory slope of $\alpha_P'(0) \simeq \frac{1}{2}$.

One of the most puzzling aspects of hadronic particle physics is the nature of the Pomeranchuk singularity.[1] Phenomenological studies of the Pomeranchuk exchange amplitude in common elastic scattering processes are unfortunately hampered by the occurrence of important secondary trajectory contributions. Consequently, the following three important questions concerning the Pomeranchukon are at least partially unanswered:

(1) Is the Pomeranchuk trajectory flat or sloping?

(2) What role do Regge cuts play in the Pomeranchuk amplitude?

(3) What is the dynamical origin of the Pomeranchuk contribution? (Is the Pomeranchuk built from background as semilocal duality models would suggest?)

Unambiguous answers to the preceding questions are unlikely to be forthcoming from studies of the common elastic scattering processes $\pi^\pm p$, $K^\pm p$, $\bar{p}p$, and pp. The purpose of this Letter is to point out the existence of an inert reaction in which all three channels are presumed to be de-