Measurements of $\vec{\mathrm{H}}\,\vec{\mathrm{D}}(\vec{\gamma}, \pi)$ and Implications for the Convergence of the Gerasimov-Drell-Hern Integral

S. Hoblit,[1,2,*] A. M. Sandorfi,[2,†] K. Ardashev,[1,3] C. Bade,[4] O. Bartalini,[5] M. Blecher,[6] A. Caracappa,[2] A. D'Angelo,[5] A. d'Angelo,[5] R. Di Salvo,[5] A. Fantini,[5] C. Gibson,[3] H. Glückler,[7] K. Hicks,[4] A. Honig,[8] T. Kageya,[6] M. Khandaker,[9] O. C. Kistner,[2] S. Kizilgul,[4] S. Kucuker,[1] A. Lehmann,[3] M. Lowry,[2] M. Lucas,[4] J. Mahon,[4] L. Miceli,[2] D. Moricciani,[5] B. Norum,[1] M. Pap,[7] B. Preedom,[3] H. Seyfarth,[7] C. Schaerf,[5] H. Ströher,[7] C. E. Thorn,[2] C. S. Whisnant,[10] K. Wang,[1] and X. Wei[2]

(LEGS-Spin Collaboration)

[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22901, USA*
[2]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Department of Physics, University of South Carolina, Columbia, South Carolina 29208, USA*
[4]*Department of Physics, Ohio University, Athens Ohio 45701, USA*
[5]*Università di Roma "Tor Vergata" and INFN-Sezione di Roma2, Rome, Italy*
[6]*Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[7]*Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*
[8]*Department of Physics, Syracuse University, Syracuse, New York 13210, USA*
[9]*Norfolk State University, Norfolk and Jefferson Lab, Newport News, Virginia 23606, USA*
[10]*James Madison University, Harrisonburg, Virginia 22807, USA*

(Received 25 July 2008; published 30 April 2009)

We report new measurements of inclusive π production from frozen-spin HD for polarized photon beams covering the $\Delta(1232)$ resonance. These provide data simultaneously on both H and D with nearly complete angular distributions of the spin-difference cross sections entering the Gerasimov-Drell-Hearn (GDH) sum rule. Recent results from Mainz and Bonn exceed the GDH prediction for the proton by 22 μb, suggesting as yet unmeasured high-energy components. Our π^0 data reveal a different angular dependence than assumed in Mainz analyses and integrate to a value that is 18 μb lower, suggesting a more rapid convergence. Our results for deuterium are somewhat lower than published data, considerably more precise, and generally lower than available calculations.

DOI: 10.1103/PhysRevLett.102.172002 PACS numbers: 13.60.Hb, 13.60.Le, 14.20.Gk, 25.20.Lj

In 1966, three sets of authors, Gerasimov [1], Drell and Hearn [2], and Hosoda and Yamamoto [3] independently derived a sum rule for the anomalous magnetic moment (κ) of spin $S = 1/2$ particles of mass m in terms of the energy-weighted difference between total photon reaction cross sections in entrance channel states with parallel (P) and antiparallel (A) photon and target spin alignments,

$$\int_{\omega_0}^{\infty} \frac{\sigma_P - \sigma_A}{\omega}\, d\omega = 4S\pi^2\alpha\left(\frac{\kappa}{m}\right)^2. \tag{1}$$

Recent literature has referred to this relation for $S = 1/2$ nucleons as the *GDH sum rule*. Hosoda and Yamamoto also showed that the same relation holds for spin $S = 1$ nuclei, such as the deuteron [4]. This expression follows from a dispersion relation for the forward elastic (Compton) amplitude [5], provided that the spin-flip Compton amplitude vanishes at high energy (ω) at least as fast as $1/\ln(\omega)$. Because of the latter requirement, this sum rule is not fundamental, in that no underlying theory falls if it is violated. Rather, convergence of the above integral to a different value would reveal an interesting property of a very high-energy process [6,7].

For the proton and deuteron, the right-hand side of Eqn. (1) reduces to 204 and 0.7 μb, respectively. Recently, a collaboration from Mainz and Bonn has experimentally checked the GDH sum rule for the proton [8], and consistency with calculations for the deuteron over a limited energy range [9]. Their proton measurements spanned 0.2 to 2.9 GeV and yielded $254 \pm 5 \pm 12$ μb, exceeding the sum rule expectation. Multipole analyses such as SAID (scattering analysis interactive dial-in program) [10] or MAID (Mainz unitary isobar model for pion electroproduction) [11] agree that a contribution of -28 μb is expected from near threshold below 0.2 GeV. This would require an as yet unmeasured -22 μb from high energies to restore agreement with Eqn. (1), which is possible since some negative contributions have been suggested by Regge models [12,13].

We report here new measurements of inclusive π photo production from a polarized HD target with polarized photon energies covering the P_{33} Δ resonance. The experiments were performed at the Laser Electron Gamma Source (LEGS) at Brookhaven National Laboratory with tagged circular polarized γ rays between 190 and 420 MeV. The general characteristics of the LEGS beams are discussed in Ref. [14]. Here, the photon polarization averaged between 60% to 99% and was cycled between left and right circular states every few minutes.

The polarized target consisted of solid hydrogen-deuteride (HD), held in a frozen-spin state. The material was condensed in a variable temperature cryostat, where the NMR polarization monitoring system was calibrated at 2 K, transferred to a dilution refrigerator for polarization at $\sim$15 mK and 15 T, held there for typically three months to reach the frozen-spin state, and finally transferred to an In-Beam Cryostat (IBC) operating at 0.3 K, where a thin 0.9 T solenoid maintained the H and D orientations [15]. Data were collected during two periods in Fall 2004 and Spring 2005, the first emphasizing H polarization, with initial vector polarizations of $P_{\rm H} = 0.59$ and $P_{\rm D} = 0.07$, and the second using increased D polarization following a radio frequency (RF) transfer of spin between H and D, with $P_{\rm H} = 0.32$ and $P_{\rm D} = 0.33$. In the first of these, the deuteron tensor polarization was negligible, while in the Spring 2005 run, $P_{\rm D}^T \sim 7\%$. Midway through each period, the H polarization was flipped with an RF transition. This produced four distinct data blocks with differing target polarizations, during which the in-beam spin relaxation times for polarized H and D ranged from 7 to 15 months. The polarization was monitored frequently with a cross-coil NMR system within the IBC [16].

For these measurements, pions were detected in a large *Spin Asymmetry* (SASY) calorimeter. An array of 432 NaI(Tl) detectors, an XBOX, surrounded the target covering laboratory (Lab) angles from 45° to 135°. A cylindrical array of plastic neutron detectors was positioned between the XBOX and the IBC. A forward wall consisting of 31 cm of plastic scintillators, backed by an array of 176 Pb-glass crystals, detected reaction products at Lab angles between 10° and 40°. The configuration of these detectors was optimized for neutral pions, with either two decay photons detected in the XBOX or one in the XBOX and the other in the forward wall. This provided nearly complete coverage for π° detection.

Two-pion production is negligible throughout our energy range [17]. As a result, spectra at a fixed angle and tagged energy are dominated by two-body (from H) or quasi-two-body (from D) kinematics. The energy of reconstructed neutral pions is compared to the two-body expectation in Fig. 1 for one of 10 angle bins, 17 tagged energy bins, and 4 target polarization groups. The simulated response (blue curve) is in excellent agreement. The spin asymmetry is evident in the left and right panels, which show yields for parallel and antiparallel beam and target spin alignments. Charged pion spectra are very similar.

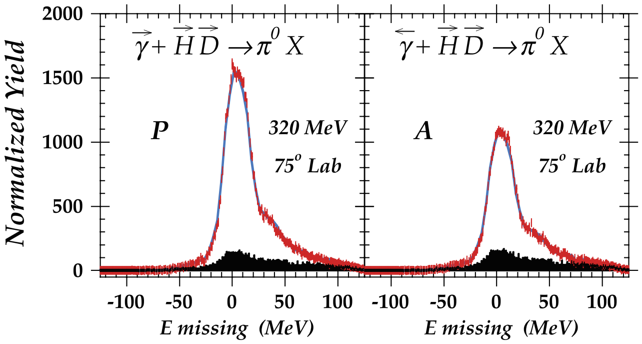

FIG. 1 (color). Differences between two-body kinematics and the measured π° energy are shown in red, for parallel (left) and antiparallel (right) beam and target spin alignments. Simulated energy differences are shown as the solid (blue) curves. Empty cell contributions are shaded in black.

The only unpolarizable nucleons in the target are found in a mesh of 50 μm Al wires used to conduct away heat during polarization and in pCTFE (C_2ClF_3) windows of the target cell. Their contributions are determined through empty cell measurements (black area in Fig. 1).

We discuss here inclusive π production, integrated over azimuthal angles, for which the differential cross section from polarized HD can be written as [15,18],

$$d\sigma(\theta, E_\gamma) = d\sigma_0^{\rm HD} - P_\gamma^c P_{\rm H} \hat{E}_{\rm H} - P_\gamma^c P_{\rm D}^V \hat{E}_{\rm D} + \sqrt{1/2} P_{\rm D}^T \hat{T}_{20}^0, \qquad (2)$$

where P_γ^c is the circular beam polarization, $P_{\rm H}$ is the hydrogen polarization, $P_{\rm D}^V$ and $P_{\rm D}^T$ are the deuteron vector and tensor polarizations, respectively, and a subscript zero (0) denotes an unpolarized cross section. Here, we have designated $\hat{E}_{\rm H} = d\sigma_0^{\rm H} E_{\rm H} = \frac{1}{2}[d\sigma^{\rm H}(A) - d\sigma^{\rm H}(P)]$, $\hat{E}_{\rm D}$ is the corresponding quantity for deuterium, and $\sqrt{1/2}\hat{T}_{20}^0 = \sqrt{1/2} d\sigma_0^{\rm D} T_{20}^0 = \frac{1}{2}[d\sigma^{\rm D}(A) + d\sigma^{\rm D}(P) - 2d\sigma_0^{\rm D}]$ is the deuteron tensor observable, following the convention of [18].

The data set consists of four distinct blocks with different target polarizations, each containing roughly equal amounts of data with right and left circular photon polarization. These eight data groups overdetermine the four observables of Eqn. (2). Fits varying $\hat{T}_{20}^0$ produced at most few percent changes in $d\sigma_0^{\rm HD}$, compared to fixing $\hat{T}_{20}^0$ to zero, and no perceptible changes to $\hat{E}_{\rm H}$ and $\hat{E}_{\rm D}$. Here, we focus on results of fits with $\hat{T}_{20}^0$ fixed to zero.

Sample angular distributions of the unpolarized cross section at the peak of the $\Delta(1232)$ are shown in Fig. 2 (solid circles). To compare with other available deuteron data, we have subtracted the well-known proton cross sections as parameterized by SAID(FA07k) [10]. Here, we show results for the Fall 2004 data for which the deuteron tensor polarization was negligible.

The normalization scale was checked by comparing $D(\gamma, \pi^0)X$ cross sections to data collected with the same detector array using a liquid-D_2 target of known length (open circles in Fig. 2). The Fall 2004 target was grown

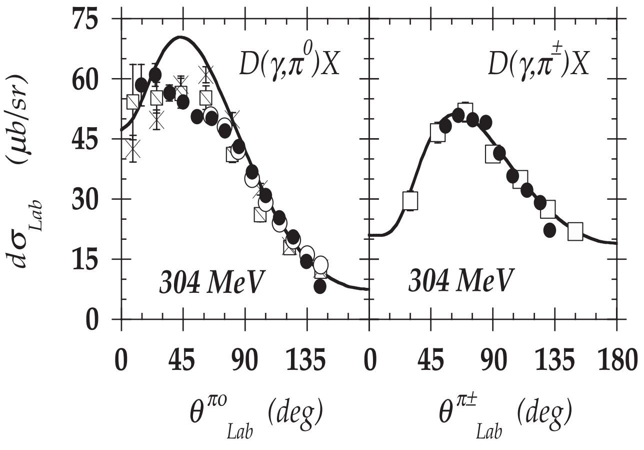

FIG. 2. Unpolarized cross sections (solid circles) for $D(\gamma, \pi^\circ)X$, left, and $D(\gamma, \pi^\pm)X$, right, at $E_\gamma = 304$ MeV, deduced by subtracting SAID(FA07k) predictions [10] for $p(\gamma, \pi)$ from fitted HD(γ, π) results. For π°, LEGS data from a liquid-D_2 target are shown as open circles; crosses and hatched boxes are from [17,20]. For the $\pi^\pm$ channel, open boxes are constructed from $\pi^- pp$ [21] and the π^-/π^+ ratio data of [22]. The curves are calculations from [18].

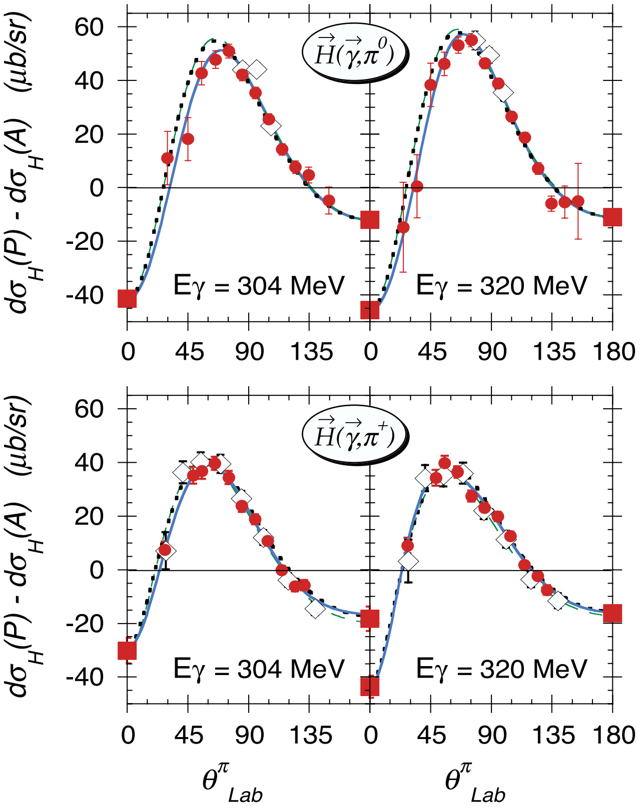

FIG. 3 (color). Angular dependence of the $[P - A]$ spin-difference cross section for polarized H at beam energies near the Δ peak. The data are solid (red) circles. Unpolarized limits (solid red squares) at 0° and 180° are the means of SAID [10] and MAID [11]. Open diamonds are from Mainz [19], interpolated to these energies. Predictions from SAID and MAID are dotted (black) and dashed (green) curves, respectively. Solid (blue) lines show Legendre fits to our data.

slowly and its length agreed with that expected from the known amount of HD gas. The Spring 2005 target was grown rapidly and its cross section scale was normalized to the Fall 2004 $D(\gamma, \pi^0)X$ by fitting to the interval $110° \le \theta^\pi_{\rm Lab} \le 150°$ where both our fits and the calculations of [18] agree that $\hat{T}^0_{20}$ is negligible.

Differential spin-difference cross sections, $[d\sigma^{\rm H}(P) - d\sigma^{\rm H}(A)] = -2\hat{E}_{\rm H}$, for polarized H are shown in Fig. 3 as solid circles for energies near the peak of the Δ. Since the pion has zero spin, at 0° and 180° the H spin difference reduces to $-2d\sigma^{\rm H}_0$. For these angles, the mean of SAID(FA07k) [10] and MAID(2007) [11] were used (solid squares). The Mainz H-Butanol results for π^+ are in very good agreement with our data, both here and at other energies. SAID and MAID multipole predictions, which include the Mainz data in their fits, reproduce the angular dependence of the π^+ spin difference. The Mainz π^0 differential spin-difference data are again in good agreement with our results, although they are limited to only a few backward angles [19]. However, forward of 80° Lab, our spin differences drop below the prediction of SAID and MAID. This trend occurs mainly near the Δ peak. At energies 40 MeV higher or lower, SAID and MAID π^0 predictions are quite close to our data.

The angular distributions of the π spin-difference cross sections have been fitted to a Legendre expansion (solid blue curves in Fig. 3). The integration of these distributions are shown as the open (red) crosses in Fig. 4. Our total spin difference for π^+ from polarized H (Fig. 4, top) is in excellent agreement with Mainz results [19], although limited to energies above 270 MeV by absorption in the neutron detectors surrounding the HD target. The π^0 spin-difference is lower than the Mainz results in the region of the Δ peak (Fig. 4, second panel from top), reflecting the differences in the angular distributions.

Another method of obtaining total cross sections is to simply count pions in the full detector. This technique was used in Mainz experiments. All quasi-4π detectors have efficiencies that vary with angle, which must be corrected using simulations. However, it is important to use accurate angular distributions to distribute events in such simulations to avoid biasing results, particularly when cross sections vary rapidly with angle. Counting neutral pions in the SASY detector, with efficiencies corrected by simulation using measured angular distributions, results in the solid (red) circles of Fig. 4. This agrees with direct integration of the angular distributions, and has smaller uncertainties since it avoids propagating errors from multiple background subtractions.

Systematic uncertainties on the cross section scale associated with target length, flux normalizations, and possible geometrical errors in simulation are estimated at 3.5%. Photon beam polarizations are known to 1%. Uncer-

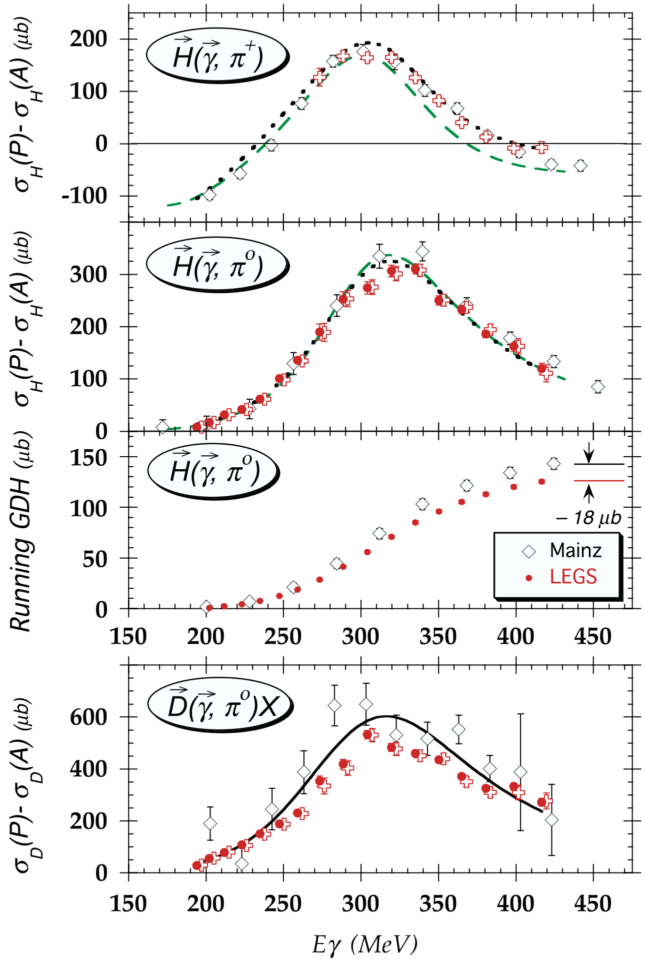

FIG. 4 (color). Total π^+ and π° spin-difference cross sections for polarized H (top two panels) and for π° production from polarized D (bottom). Open (red) crosses result from an angle integration of the differential spin difference (π° crosses are shifted by +3 MeV for clarity). Solid (red) circles result from counting π's in the detector, using the measured angular dependences in a simulation to correct for varying efficiencies. Mainz results, using the latter method, are shown as open diamonds [9,19]. The π° contribution to the running GDH(p) is plotted in the second to bottom panel against the upper limit of integration. Black and green curves in the upper panels are from SAID and MAID, as in Fig. 2. Solid black curve in the bottom panel is from [18].

tainties in target polarization vary between data groups, depending upon potential nonhomogeneities following RF manipulations and on transfer losses between cryostats. Error propagation has been studied with Monte Carlo and result in a 5.1% uncertainty in the integrated spin difference. The total systematic uncertainty in GDH(p) is then 6.3%.

The π^0 contribution to the running GDH integral for the proton is plotted against the upper limit of integration in Fig. 4 (third panel from top). From 200 to 420 MeV, our integrated result is 125.4 ± 1.7(stat.) ± 7.9(syst.) μb. Integration of the Mainz data over the same interval gives 142.9 ± 5.4(stat.) ± 6.8(syst.) μb [19]. This difference of −17.5 μb appears to originate from a limited energy range. Applying this correction to the full Mainz+Bonn result, together with the −28 μb contribution from energies below 0.2 GeV, would bring their GDH(p) total down to 208 ± 6(stat.) ± 14(syst.) μb, where we have combined the systematic uncertainties from both experiments in quadrature. This is to be compared with 204 μb for the right side of Eqn. (1) and removes the need for additional canceling contributions.

The integrated spin difference for π° production from the deuteron is shown in the bottom panel of Fig. 4. These are somewhat lower than the Mainz results of [9] and considerably more precise. The calculation of [18] is shown as the solid curve. While certainly in proximity to the data, further theoretical work will be needed to address the discrepancies which are largest in the π° channel (see Fig. 2 as well).

In summary, while our π^+ data from polarized H agree with Mainz, near the peak of the Δ our measured angular distributions of π° spin differences fall faster at forward angles than the distributions assumed in Mainz analyses in lieu of direct measurements. Consequently, our π° contribution to Eqn. (1) is 18 μb less than the Mainz result and suggests that any remaining high-energy Regge tails must be quite small. Our results for polarized D are lower than Mainz data and have considerably smaller uncertainties. The data are also lower than recent deuteron calculations and point to the need for additional theoretical work to understand the GDH(D) convergence.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-98-CH10886, by the Istituto Nazionale di Fisica Nucleare, Italy, and by the U.S. National Science Foundation. We are indebted to Mr. F. Lincoln for his technical assistance. We thank Doctors C. Commeaux, J.-P. Didelez, and G. Rouillé for their collaboration during the early stages of HD target development. One of us (A. M. S.) would like to thank Doctors A. Fix and H. Arenhövel for supplying their deuteron calculations.

---

[*] Corresponding author: hoblit@bnl.gov
[†] Corresponding author: sandorfi@jlab.org

[1] S. B. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966).
[2] S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, 908 (1966).
[3] M. Hosoda and K. Yamamoto, Prog. Theor. Phys. **36**, 425 (1966).
[4] M. Hosoda and K. Yamamoto, Prog. Theor. Phys. **36**, 426 (1966).
[5] M. Gell-Mann, M. L. Goldberger, and W. E. Thirring, Phys. Rev. **95**, 1612 (1954).
[6] H. Abarbanel and M. Goldberger, Phys. Rev. **165**, 1594 (1968).
[7] L. N. Chang *et al.*, Phys. Lett. B **329**, 514 (1994).

[8] H. Dutz *et al.*, Phys. Rev. Lett. **93**, 032003 (2004).
[9] J. Ahrens *et al.*, Phys. Rev. Lett. **97**, 202303 (2006).
[10] R. A. Arndt *et al.*, Phys. Rev. C **66**, 055213 (2002).
[11] D. Drechsel *et al.*, Nucl. Phys. **A645**, 145 (1999).
[12] S. Simula *et al.*, Phys. Rev. D **65**, 034017 (2002).
[13] K. Helbing, Prog. Part. Nucl. Phys. **50**, 451 (2003).
[14] G. Blanpied *et al.*, Phys. Rev. C **64**, 025203 (2001).
[15] A. M. Sandorfi *et al.*, in *Proc. NSTAR 2005: Physics of Excited Nucleons*, edited by S. Capstick, V. Crede, and P. M. Eugenio (World Scientific, New Jersey, 2006).
[16] C. Thorn and A. Caracappa, AIP Conf. Proc. **980**, 397 (2008).
[17] B. Krusche *et al.*, Eur. Phys. J. A **6**, 309 (1999).
[18] A. Fix and H. Arenhovel, Phys. Rev. C **72**, 064005 (2005).
[19] J. Ahrens *et al.*, Eur. Phys. J. A **21**, 323 (2004).
[20] U. Siodlaczek *et al.*, Eur. Phys. J. A **10**, 365 (2001).
[21] P. Benz *et al.*, Nucl. Phys. **B65**, 158 (1973).
[22] T. Fujii *et al.*, Nucl. Phys. **B120**, 395 (1977).