while constant-E diffusion remains unchanged. Particles of low enough energy so that they can be derived directly from the source through constant-μ diffusion will be injected in increased numbers, so that their flux will increase. On the other hand, particles that have been accelerated through bimodal diffusion are exposed to a higher leakage rate through constant-μ diffusion, whereas their production does not increase accordingly, since constant-E diffusion is maintained unchanged; therefore their intensity will decrease. After the balance between the two modes is restored to its prestorm level, particles are accelerated by bimodal diffusion and high-energy fluxes rise again. Similar results would be obtained if constant-E diffusion is increased while maintaining the constant-μ process unchanged. Even an unequal increase of both diffusion rates would produce similar results, enhancing low-energy fluxes and depletion high-energy ones.

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[1]T. G. Northrop, The Adiabatic Motion of Charged Particles (John Wiley & Sons, Inc., New York, 1963).
[2]E. N. Parker, J. Geophys. Res. 65, 3117 (1960).
[3]C. G. Fälthammar, J. Geophys. Res. 70, 2503 (1965); and 71, 1487 (1966).
[4]J. G. Roederer, J. Geophys. Res. 72, 981 (1967).
[5]A. Eviatar, J. Geophys. Res. 72, 5997 (1967).
[6]L. A. Frank, J. Geophys. Res. 70, 3533 (1965).
[7]F. R. Paolini, G. C. Theodoridis, and S. Frankenthal, J. Geophys. Res. 72, 4590 (1967); and F. R. Paolini, G. C. Theodoridis, S. Frankenthal, and L. Katz, Ann. Geophys. 24, 129 (1968).
[8]S. M. Krimigis, in Earth's Particles and Fields, edited by B. M. McCormac (Reinhold Publishing Corporation, New York, 1968), p. 89.

PHOTOPRODUCTION OF η^0 MESONS AT 4 GeV*

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We have measured η^0 photoproduction at 4 GeV. We find our results to be consistent with a theoretical prediction relating this cross section to ω^0 production by π mesons using a vector-dominance model; there is no evidence for a dip or change of slope at $-t = 0.6$ as seen in π^0 photoproduction.

The study of η^0 photoproduction from protons is of considerable importance since any model or theory which describes π photoproduction should encompass a prediction for this process as well. It has been measured at low energies[1] (below 1.5 GeV) and more recently at high energies (6 GeV).[2] Total-cross-section measurements have been made up to about 4 GeV in a hydrogen bubble chamber.[3] We present here measurements down to small t at 4-GeV incident photon energy.

We used two hodoscopes, each a 4×6 array of lead-glass total-absorption counters,[4] to measure the energy and emission angle of the η^0 through its decay into two gamma rays. Each of the 48 individual counters had its own photomultiplier. The currents from the 24 counters in each hodoscope were summed to give the energy of each photon. The currents were also summed in proportion to distance along the x (or y) axis of the hodoscope; this sum when normalized to the total current is a measure of the striking point of the photon on the hodoscope. The angle between the two hodoscopes was set in each run to optimize detection of 4-GeV η^0's decaying into two gamma rays.

Because the lead-glass counters were sensitive to electrons as well as photons, a pair of plastic scintillators (28 cm$\times$46 cm) encased in several inches of polyethylene was placed in front of each of the hodoscopes to veto charged particles.

The experiment was run with a liquid-hydrogen target in a bremsstrahlung beam at the Cambridge Electron Accelerator. The electron energy was set at 4.2 and 3.8 GeV with the gamma detector placed at seven different angles with respect to the photon beam. The photon beam was monitored with a quantameter.[5]

An on-line computer calculated the effective mass of the parent particle for each event from the measured positions and energies recorded in each hodoscope, assuming that the particle decayed into two gamma rays. It also recorded all measurements on magnetic tape for later analysis. A check run was taken setting the detectors for π^0 detection; a "mass" plot for this run is shown in Fig. 1. The 4-Gev yield was obtained by subtracting the yields at 3.8 GeV from those at 4.2 GeV. A sample mass plot is shown in Fig. 1. This rate was corrected for chance coincidences, empty-target events, events where one or more of the gamma rays converted in the front polyethylene, and background events (see below). A Monte Carlo program was used to calculate our counter efficiency.

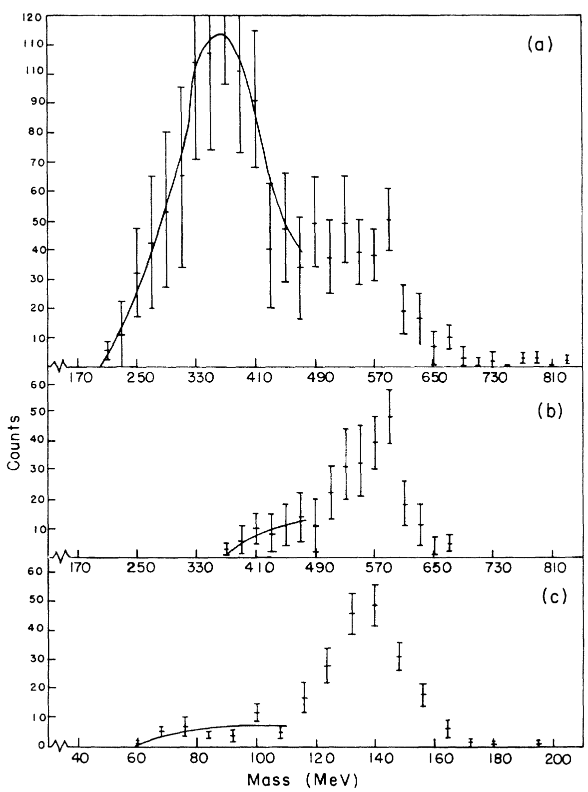

FIG. 1. Experimental mass plots. Solid lines are guides to background in mass region below meson. (a) $(12°)_{lab}$ η^0 mass spectrum, 4.2-GeV data minus 3.8-GeV data, removing events where both sets of veto counters fired. (b) Data from (a) with the additional requirement that the calculated photon energy be between 3.4 and 4.6 GeV. (c) $(15°)_{lab}$ π^0 mass spectrum, 1.5-GeV data with no subtraction done using events in which neither set of veto counters fired and a recoil proton was detected.

The data at $(9°)_{lab}$ was taken with a thick scintillator in coincidence to detect the recoil proton. (This was not possible at small angles.) This reduced the background substantially; the mass spectra and cross sections so obtained agreed with those calculated without the proton-coincidence information.

Restricting ourselves to events whose calculated photon energy was between 3.4 and 4.6 GeV (see Fig. 1), we plotted the data in the η^0 mass region as a function of geometric opening angle (see Fig. 2). By accepting only events with opening angles between appropriate limits, we could eliminate events due to the process

$$\gamma + p \rightarrow \eta^0 + N^*(1236). \tag{1}$$

This process, which produces an η^0 with about 300 MeV less energy, and therefore with a somewhat wider decay opening angle, was assumed to be the dominant competing η^0-production process. We then found the shape of the non-η^0 background in our mass plots in three ways, and estimated the contamination in the η^0 mass region by normalizing this curve to masses below 500 MeV. We generated a fictitious mass plot by taking the two gamma-ray energies and positions from different events; this gives a high background estimate since two such gamma rays are relatively unconstrained in energy. We computed fictitious mass plots for $2\pi^0$ and $3\pi^0$ events using a Monte Carlo program; this gave our "best guess." We assumed no background in the η^0 mass region;

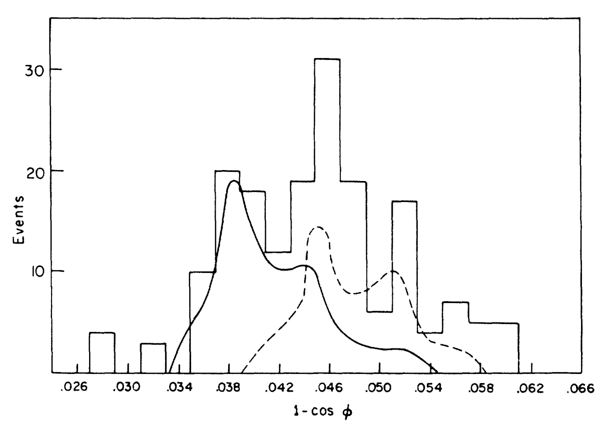

FIG. 2. Events in the η^0 mass region, with calculated photon energy between 3.4 and 4.6 GeV, plotted as a function of two-gamma opening angle. The data are those taken at $\theta_{lab} = 3°$. The solid line is the shape of the angular distribution expected for the $\eta^0 p$ final state, and the broken line is that expected for the $\eta^0 N^*$ final state. (The several peaks evident in these distributions are due to properties of the counter system.)

this is clearly a minimum. Our measured cross sections are shown in Fig. 3. The errors are a rms sum of the statistical error and an error from background uncertainty given by the high and low limits described above. (The point at $-t = 0.4$ represents the runs made detecting the recoil proton; no background correction was necessary for these data.)

We note that our points are in fair agreement with a theoretical calculation by Dar and Weisskopf,[6] shown in Fig. 3, which predicts this cross section from the reaction

$$\pi^- + p \to \omega^0 + n \qquad (2)$$

at 3.25 GeV, assuming ρ^0-exchange dominance. There are no data for process (2) at our energy; the data at 10 GeV have a steeper angular distribution than those at 3.25 GeV. At small t we have extended the theoretical curve by adding the calculable Primakoff-effect amplitude,[7] using the measured partial lifetime[8] for η^0 decay into two gamma rays. We assumed the relative phase of the two production amplitudes to be 0°, 90°, and 180°, and the nuclear cross section to be all spin-nonflip. The data suggest 180°, if the nuclear cross section is indeed all spin-nonflip. The model of Ref. 6 would favor 0° for the relative phase. Note that a comparison of the data of Ref. 2 with ours indicates some narrowing of the t distribution ("shrinkage") with energy as is also true of the related process[6] [Eq. (1)]. We see no evidence for a "dip" or change of slope at $t = -0.6$ as would be expected from a simple Regge-exchange model.[9]

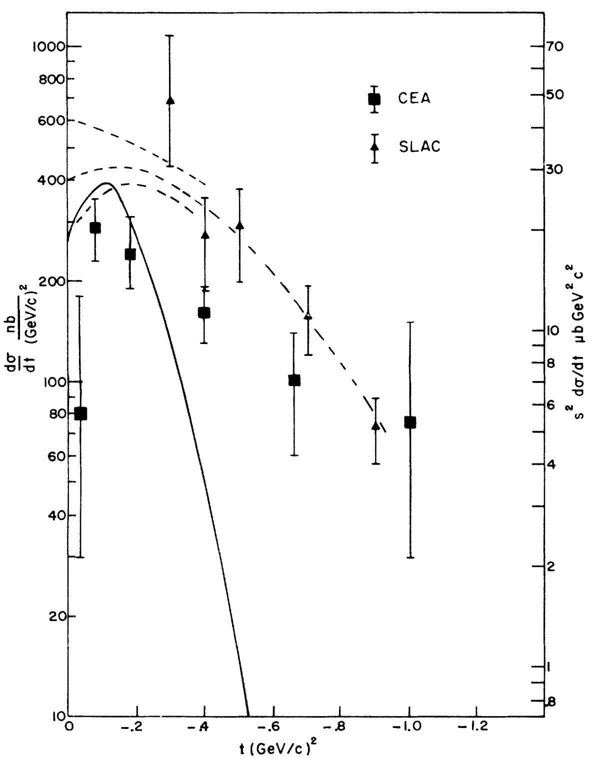

FIG. 3. Cross section for $\gamma + p \to \eta^0 + p$ at 4 GeV. The Stanford Linear Accelerator Center data of Ref. 2 taken at 6 GeV is shown for comparison, plotted against $s^2(d\sigma/dt)$. The dashed line is the prediction of Dar and Weisskopf, based on 3.25-GeV data (Ref. 6), also plotted against $s^2(d\sigma/dt)$. The envelope around it at small $-t$ shows the result of considering the Primakoff effect (see text). The solid line is the prediction of Di Vecchia and Drago (Ref. 9). Note that our errors are not statistical alone, but include our estimates of systematic errors in the background estimate as well.

The total cross section is 0.18 ± 0.05 μb at 4 GeV. This compares with the results of the DESY bubble chamber group[3] and with our extrapolation (flat to small t) of the Stanford Linear Accelerator Center data[2] which gives 0.16 ± 0.05 μb. The total cross section is decreasing like E^{-2} over the range from 1 to 6 GeV.

Using the excess of events at wide opening angles (see Fig. 2) we also calculated a cross section for

$$\gamma + p \to \eta^0 + \mathrm{MM}^+, \qquad (3)$$

where MM^+ could be a missing mass between approximately 1100 and 1500 MeV. We assume that this reaction is dominated by $N^+(1236)$ production (process 1). The results are consistent with a differential cross section of the same shape as that for simple photoproduction, with an absolute value approximately 2.5 times as great.

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[1]C. Bacci, G. Penso, G. Salvini, A. Wattenberg, G. Mencuccini, R. Querzoli, and V. Silvestrini, Phys. Rev. Letters 11, 37 (1963); B. Delcourt, J. Lefrancois, J. P. Perez y Jorba, and J. K. Walker, Phys. Letters 7, 215 (1963); C. Bacci, G. Penso, G. Salvini, C. Mencuccini, and V. Silvestrini, Phys. Rev. Letters 16, 157 (1966); C. Heusch, C. Prescott, E. Bloom, and L. Rochester, Phys. Rev. Letters 17, 573 (1966);

R. Prepost, D. Lundquist, and D. Quinn, Phys. Rev. Letters 18, 82 (1967); C. Bacci, R. Baldini-Celio, C. Mencuccini, A. Reale, M. Spinetti, and A. Zallo, Phys. Rev. Letters 20, 571 (1968).

[2]R. Anderson, D. Gustavson, J. Johnson, D. Ritson, W. G. Jones, D. Kreinick, F. Murphy, and R. Weinstein, Phys. Rev. Letters 21, 384 (1968).

[3]E. Lohrmann, in Proceedings of the Third International Symposium on Electron and Photon Interactions at High Energies, Stanford Linear Accelerator Center, 1967 (Clearing House of Federal Scientific and Technical Information, Washington, D. C. 1968), p. 199.

[4]R. Lewis, D. Luckey, and J. Uglum, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965 (Springer-Verlag, Berlin, Germany, 1965), Vol. 2, p. 424.

[5]J. de Pagter and M. Fotino, Cambridge Electron Accelerator Report No. CEAL-1022, 1965 (unpublished).

[6]A. Dar and V. F. Weisskopf, Phys. Rev. Letters 20, 762 (1968). Their model requires the poorly determined ω-γ direct coupling constant $g_{\omega\gamma}$. The results of this experiment cannot be used to determine $g_{\omega\gamma}$, however, because the model also requires ρ_{00} for process (2) and this is not well known at our energy.

[7]G. Bellettini, C. Bemporad, P. Braccini, L. Foa, and M. Toller, Phys. Letters 3, 170 (1963).

[8]C. Bemporad, P. Braccini, L. Foa, K. Lebelsmeyer, and D. Schmitz, Phys. Letters 25B, 380 (1967). We use their result as a measurement of $\Gamma_{\gamma\gamma}(\Gamma_{\gamma\gamma}/\Gamma_{\rm tot}) = 0.38 \pm 0.08$ keV and use 0.38 for $\Gamma_{\gamma\gamma}/\Gamma_{\rm tot}$, as reported by C. Baltay, P. Franzini, J. Kim, L. Kirsch, R. Newman, N. Yeh, J. Cole, J. Lee-Franzini, and H. Yarger, Phys. Rev. Letters 19, 1498 (1967).

[9]P. Di Vecchia and F. Drago, Phys. Letters 24B, 405 (1967).

SOLAR NEUTRINOS AND THE SOLAR HELIUM ABUNDANCE*

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The upper limit on the solar neutrino flux set by Davis, Harmer, and Hoffman places an upper limit on the sun's initial helium abundance that is small compared with that estimated for other galactic objects. Adopting current estimates of low-energy nuclear cross-section factors, the upper limit is essentially equal to a lower bound set by demanding that the sum is at least $4\frac{1}{2}\times10^9$ yr old.

The preliminary upper limit on the solar neutrino flux set recently by Davis, Harmer, and Hoffman[1] is an order of magnitude smaller than the flux that had been expected on the basis of solar model calculations prepared prior to the establishment of this limit. The Davis, Harmer, and Hoffman result has therefore forced a rethinking of the standard assumptions concerning both the input parameters and the input physics that are necessary for the construction of solar models.[2-4]

In an effort to contribute to a better understanding of the implications of the Davis, Harmer, and Hoffman limit, I have prepared an extensive analysis of the relationship between the neutrino flux derived from solar models and several solar input parameters. Many of my results are consistent with those already in the literature.[2-7] However, several new results have emerged and several conclusions are at variance with inferences drawn in two recent papers.[2,8] In this communication, a statement of my basic conclusions will be offered first, followed by a summary of the supporting evidence. A more complete discussion will appear elsewhere.

(1) With the standard choice of solar input parameters, the Davis, Harmer, and Hoffman limit implies an upper limit on the sun's initial helium abundance that is small compared with the helium abundance estimated for other galactic objects. The upper limit on Y (initial He^4 abundance by mass) required for consistency with the Davis, Harmer, and Hoffman limit is $Y_0 \cong 0.16$-0.17. On the other hand, almost every attempt to estimate Y for galactic objects other than the sun has led to values in the range 0.2-0.4, the most probable values clustering about 0.25-0.30. The evidence for a possibly universal, high value for Y has been amply catalogued.[5,9]

Bahcall, Bahcall, and Shaviv[2] claim that a solar $Y = 0.22 \pm 0.03$ (~0.22 with standard assumptions) is consistent with the Davis, Harmer, and Hoffman limit. Despite this claim, the quantitative results in the Bahcall, Bahcall, and Shaviv paper clearly indicate that consistency with the Davis, Harmer, and Hoffman upper bound can be achieved only with $Y \leq Y_0 \sim 0.16$ (with standard assumptions), in agreement with the limit presented here.

(2) With the standard assumptions, the upper