CONF-830588--4

Meson-exchange Hamiltonian for NN scattering and isobar-nucleus dynamics

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I. INTRODUCTION

One of the recent developments in nuclear physics is to investigate the effects of non-nucleonic degrees of freedom. One approach is to follow the conventional meson theory to consider mesonic effects. The other is to consider more fundamental degrees of freedom: quark-gluon QCD dynamics. Qualitatively speaking, the first approach is appropriate for describing the physics mainly determined by nuclear forces at intermediate and long ranges, and the second is needed to describe the physics at very short distances. In this talk, I will report recent progress made in the somewhat traditional approach concerning the mesonic effects exhibited in terms of π, Δ and N^* excitations.

I will focus my discussions on a class of theoretical models[1-13] for describing interactions between π, N and two isobars: the Δ and the Roper $N^*(1470)$. The basic assumptions of the theory can be stated as follows:

(a) Nuclear phenomena can be described by a finite number of degrees of freedom. The necessary degrees of freedom in different energy regions are suggested by the elementary NN scattering processes. At low energy, we only consider N to account for the pure elastic NN scattering. As the energy increases, we need to also consider π, Δ and N^* to describe pion production from NN collisions.

(b) The interactions at intermediate and long ranges can be described by meson theory. The short range parts are phenomenologically parameterized as meson-baryon-baryon form factors which in principle are related to the complicated quark-gluon dynamics.

(c) The phenomenological parameters of form factors can be determined by fitting the data of elementary NN and πN data.

A class of models based on these three assumptions is shown in table 1. I also indicate the data which must be fitted by the models, and the corresponding numerical problems we must face. The complexities of the models increase rapidly when pion production is considered. These models can be considered as direct extensions of our conventional nuclear many-body theory to higher energies where on-mass-shell pions can be produced during nuclear reactions. These extended models are probably also needed to resolve several fundamental problems encountered[14] in the study of low energy nuclear phenomena.

The baryon-baryon interactions are usually taken to be the low order Feynman diagrams evaluated at appropriate static limits. The πN interactions are frequently taken to be the simple isobar models for Δ and N^* excitations, and separable two body potentials in less important πN channels. A more ambitious approach[3-6] is to describe all pionic processes by a $N \rightarrow \pi N$ vertex. In my opinion, this approach is very difficult to manage in practice and, at the end, needs to introduce additional phenomenological form factors to bypass the difficult renormalization problem. Once the phenomenological procedures are introduced, it is not worthwhile to take such a complicated approach at the present stage of development.

Today's talk is about our recent work[2] involving N, Δ, π and N^*. To see the progress we have made, it is necessary to first briefly summarize the current πNN models as shown in the third row of table 1. To describe pion production, all models are constructed so that 2- and 3-body unitarity are satisfied formally. The predictions of the model can only be obtained by carrying out lengthy 3-body calculations. To overcome numerical difficulties, all existing approaches parameterize baryon-baryon and πN interactions as low rank separable potentials in addition to appropriate $\pi N \leftrightarrow \Delta$ or $\pi N \leftrightarrow N'$ vertex interactions. Attempts to use meson-exchange baryon-baryon interactions are not very successful so far. Qualitatively, the main difference between these πNN models is in the treatment of pion absorption. In the models with a $\pi N \leftrightarrow N'$ vertex, the absorption is achieved by one-pion-exchange which is the extension of the old Koltun-Reitan model.[15] In the model with only a $\pi N \leftrightarrow \Delta$ vertex, the absorption is accomplished by a $NN \leftrightarrow N\Delta$ transition potential which is phenomenologically determined from the πN and NN scattering data. The results of the former ones are: (a) spin <u>averaged</u> cross sections of $\pi d \rightarrow \pi d$ and $\pi d \rightarrow pp$ are successfully described. (b) NN scattering is not satisfactorily described. One can say that the common problem of these models is the lack of a correct treatment of interactions in low partial waves; i.e. poor descriptions of the nuclear force at intermediate and short ranges.

The model with only a $\pi N \leftrightarrow \Delta$ vertex was quantitatively constructed by Betz and me[1] about 2 years ago. The interactions between NN and $N\Delta$ in each partial wave are suitably constructed so that the model can describe the NN scattering phase-shifts up to about 1 GeV. Our goal was not to give a microscopic model of NN scattering, but to use NN data as input to construct a many-body Hamiltonian for the study of Δ-nucleus interactions. We achieved a complete three-body calculation by using separable interactions as usual. Compared with other approaches, it is fair to say that our approach is less microscopic, but has stronger predictive power in many-body calculations. The model has been used to obtain a microscopic understanding[16] of the empirical Δ-nucleus spreading potential and the strong isospin dependence of pion absorption by ^{3}He. The details of each of these results require long discussion. I would simply emphasize here that our approach is an internally consistent one, and is capable of giving us a unified description of Δ-nucleus dynamics.

To make the theory as sophisticated as our conventional nuclear theory, we need to solve two problems: (a) the separable baryon-baryon interactions have to be replaced by the meson-exchange model, (b) the absorption through nonresonant πN waves, in particular the nucleon pole in P_{11}, has to be included. In the rest of the talk, I will report the recent progress we have made in item (a). Furthermore, we also include the Roper $N^*(1470)$ resonance. This extension is necessary for two reasons. First, since the threshold energies for exciting ΔΔ and NN^* are about the same, N^* and Δ must be treated on the same footing in order to realistically describe the inelasticities in the NN T=0 channels (note that the NΔ state does not contribute to T=0 channels). Second, to examine the problem of dibaryon resonances as suggested by pp polarization measurements,[17] it is necessary to have a careful description of channel coupling effects, for which the N^* could be as important as the Δ in the considered energy region. In addition, the extended model will allow us to describe NN scattering at higher energies $\lesssim 2$ GeV where 2π production through N^* can also be investigated.

II. ISOBAR MODEL FOR Δ AND N^*

To proceed, we need to construct an isobar model for the Δ and N^* excitations. It is assumed that the πN scattering in P_{11} and P_{33} channels can be described by a model Hamiltonian (in the c. m. frame)

$$h = h_0 + h' \qquad (1)$$

where h_0 is the sum of relativistic free energy operators $E_\pi(\vec{k})$, $E_N(\vec{p})$, $E_\Delta(\vec{p})$, and $E_{N^*}(\vec{p})$ for π, N, Δ and N^* respectively. The interaction h' is the sum of vertex interactions.

$$h' = h_{01} + h_{02} + h_{31} + h_{32} + h_{10} + h_{20} + h_{13} + h_{23} \tag{2}$$

where the lower indices 0, 1, 2, 3 denote the πN, Δ, N^* and $\pi\Delta$ states respectively. Note that $h^+_{ij} = h_{ji}$ in eq. (2) and hence h' is a hermitian operator. The main feature of this model is to have pion production in πN scattering; e.g. $\pi N \to N^* \to \pi\Delta \to \pi\pi N$. Our approach is to determine the vertex interaction h' by fitting the P_{11} and P_{33} πN phase-shifts up to ~ 1 GeV laboratory energy. The major complication involved in solving the πN scattering equation in this model is due to the coupling to the three-body $\pi\pi N$ channel. The pion can dress Δ and N^*. In the intermediate $\pi\Delta$ state, the interaction $\pi N \leftrightarrow \Delta$ can induce 2π contributions. If we neglect the pion crossing mechanism[2] between any two intermediate $\pi\Delta$ states, the πN scattering amplitudes take simple algebraic forms in the πN c. m. frame

$$t_\alpha(q,q_0,w) = \frac{h_{0\alpha}(q)h^*_{0\alpha}(q_0)}{w-m_\alpha-\Sigma_\alpha(w)}, \quad \alpha = 1,\ 2 \tag{3}$$

where $q = |\vec{q}|$ is the πN relative momentum, w is the collision energy, $m_1 = m_\Delta$, and $m_2 = m_{N^*}$ are respectively the <u>bare</u> masses of Δ and N^*; i.e. $\alpha = 1, 2$ represents respectively the πN P_{33} and P_{11} channels. The isobar self-energy Σ_α has two components

$$\Sigma_\alpha(w) = \Sigma_{\alpha,\pi}(w) + \Sigma_{\alpha,2\pi}(w) \qquad , \alpha = 1,2 \tag{4}$$

which can be explicitly calculated from the vertex interactions

$$\Sigma_{\alpha,\pi}(w) = \int_0^\infty \frac{|h_{0\alpha}(q')|^2 q'^2 dq'}{w-E_\pi(q')-E_N(q')+i\varepsilon} \tag{5}$$

$$\Sigma_{\alpha,2\pi}(w) = \int_0^\infty \frac{|h_{\alpha 3}(q')|^2 q'^2 dq'}{w-E_\pi(q')-E_\Delta(q')-\Pi_\Delta(w,q')} \tag{6}$$

with

$$\Pi_\Delta(w,q') = \int_0^\infty \frac{|h_{01}(q'')|^2 q''^2 dq''}{w-E_\pi(q')-[(E_\pi(q'')+E_N(q''))^2+q'^2]^{1/2}+i\varepsilon} \tag{7}$$

The isobar self-energies $\Sigma_{\alpha,\pi}$ and $\Sigma_{\alpha,2\pi}$ contain the contributions from one-pion and two-pion intermediate states. When the πN phase shifts are fitted properly, the effects of the pion crossing mechanism and other neglected mechanisms are then phenomenologically included in h'. The above simplified solution of Σ_α will allow us to avoid unmanageable complications when the same solution of the model is needed in the calculations of NN scattering.

All vertex functions are parameterized as

$$h_{\alpha\beta}(q) = g_{\alpha\beta} \frac{q}{\mu} \frac{1}{\sqrt{2(M+\mu)}} \left(\frac{\Lambda^2_{\alpha\beta}}{\Lambda^2_{\alpha\beta}+q^2}\right)^2 \tag{8}$$

where m and μ are respectively the masses of nucleon and pion. We adjust parameters $g_{\alpha\beta}$, $\Lambda_{\alpha\beta}$ and bare masses m_Δ and m_{N^*} to fit the P_{33} and P_{11} πN phase-shifts up to 1 GeV kinetic energy. The results are shown in Fig. 1 and Table 2. The present model should be sufficient to describe the main physics of pion production from NN collisions.

III. NN SCATTERING EQUATION

The model Hamiltonian for NN scattering is assumed to be

$$H = H_0 + h' + \sum_{i=1}^{5} v^i \tag{9}$$

where H_0 is just the h_0 of eq. (1), the sum of free kinetic energy operators for π, N, Δ and N^*, and v^i for i = 1, 2, 3, 4, 5 are respectively the transition interactions from NN to NN, NΔ, $\Delta\Delta$, NN^*, N^*N^* (Fig. 2a). We consider NN scattering in the subspace $C = BB \oplus BN\pi \oplus NN\pi\pi$, where B is N, Δ or N^*. The main feature of the model Hamiltonian eq. (9) is to have pion production from NN collisions (Fig. 2b). The interactions between isobar channels (i = 2, 3, 4, 5) within this model are automatically generated by the vertex interaction h'. The low order mechanisms are the pion contributions to the isobar self-energies in the presence of a spectator baryon and the pion-exchange between isobar channels. Furthermore, two baryons can interact in the π + two-baryon channels. A complete calculation including all of these mechanisms between isobar channels is simply beyond our present numerical capabilities in dealing with large complex matrix equations. Instead, we keep only pion contributions to the isobar self-energies. Then the NN→NN scattering equation in each partial-wave eigenchannel α=JST can be cast in the c. m. frame into

$$T^{\alpha}_{\ell'\ell}(p',p,E) = V^{\alpha}_{\ell'\ell}(p',p,E) + \sum_{\ell''} \int \frac{p''^2 dp'' \; V^{\alpha}_{\ell'\ell''}(p',p'',E) \; T^{\alpha}_{\ell''\ell}(p'',p,E)}{E - 2E_N(p'') + i\varepsilon} \tag{10}$$

where ℓ is the relative orbital angular momentum. The energy-dependent effective NN interaction $V^{\alpha}_{\ell'\ell}$ contains all contributions from the coupling of NN to inelastic channels involving pions. In deriving $V^{\alpha}_{\ell'\ell}$, we limit the number of pions in any intermediate state to be less than 2 and keep only self-energy contributions from the pion to one of the baryons. Then, it is straightforward to extend the procedures given in section IV of Ref. (1) to obtain

$$V^{\alpha}_{\ell'\ell}(p',p,E) = v^{1,\alpha}_{\ell'\ell}(p',p,E) + \sum_{i=2}^{5} \sum_{\ell''s''} \int p''^2 dp'' \; \frac{v^{i,\alpha}_{\ell',\ell''s''}(p',p'') \; v^{i\alpha}_{\ell''s'',\ell}(p'',p)}{E - (H_0(p''))_i - \Sigma_i(w_i(E,p''))} \tag{11}$$

where s'' is the total spin of channels containing Δ or N^*, $(H_0(p''))_i$ is the free energy of the i-th two-baryon state; e.g. $(H_0(p''))_2 = E_N(P'') + E_{\Delta}(p'')$ etc. $v^{i,\alpha}_{\ell,\ell''s''}$ is the partial-wave matrix element of v^i of eq. (10) in momentum space. All the pion contributions are contained in the isobar self energy $\Sigma_i(w_i(E,p''))$ which depends on the collision energy E and the intermediate relative momentum $\vec{p}''$. In practice, the baryons are treated nonrelativistically in calculating $\Sigma_i(w_i(E,p))$. Then, for each E and p'', the isobar self energies of each intermediate state i in eq. (11) can be calculated from eqs. (4)-(7) by substituting

$$w \to w_i(E,p'') = E - \tilde{m}_i - \frac{p''^2}{2\tilde{m}_i} - \frac{p''^2}{2(\bar{m}_i + E_{\pi}(q'))} \quad , \quad i = 2,3,4,5 \tag{12}$$

where $\tilde{m}_2 = \tilde{m}_4 = m$, $\tilde{m}_3 = m_{\Delta}$, $\tilde{m}_5 = m_{N*}$, $\bar{m} = m$ and m_{Δ} respectively for calculating $\Sigma_{\alpha,\pi}$ and $\Sigma_{\alpha,2\pi}$, and $E_{\pi}(q')$ is the pion energy evaluated in the πN or $\pi\Delta$ c. m. frame in which the integrands of eqs. (5)-(7) are defined. In doing this calculation, the nucleon is also treated nonrelativistically in eqs. (5)-(7). Clearly, our procedure for calculating Σ_i is very different from Refs. (9)-(13).

As emphasized in Ref. (2), the energy and momentum dependences of $\Sigma_i(w_i(E,p''))$ are the consequences of treating pion-production inelastic cuts. They have important dynamical effects on NN scattering. At energies below the pion production threshold $E \leq 280$ MeV in the laboratory frame, Σ_i is real and leads to pure elastic scattering from solving eq. (11). The model will produce NN inelasticity when Σ_i becomes complex at higher energies. This "off-shell width" effect of the isobar has been found in Ref. (2) to give a satisfactory description of T=1 NN scattering phase shifts up to 1 GeV. Including N^* here, we now can examine also the inelasticities in T=0 channels and NN scattering at higher energy up to ~ 2 GeV.

Our remaining tasks are to define the matrix elements of NN→NN interaction $v^{1,\alpha}_{\ell',\ell}(p',p)$ and transition interactions $v^{i,\alpha}_{\ell',\ell''s''}(p',p)$ for $i = 2, 3, 4, 5$. All transition interactions include one-pion-exhange evaluated by taking appropriate static limits of Feynman amplitudes. A form factor $(\Lambda^2-\mu^2)/(q^2+\Lambda^2)$ is introduced in each meson-baryon-baryon vertex to regularize the interaction at short distance. Following Ref. (18), we also include the one-rho exchange in the transitions to NΔ and ΔΔ states. The resulting potentials in r-space have been explicitly given by Niephaus, et al.[18] for transitions to NΔ and ΔΔ, and by Lomon[12] for NN^* and N^*N^*. To limit the number of parameters, we also take their coupling constants determined from the decay widths of Δ and N^*. In this way, the cut-off parameter Λ of the form factors is the only parameter of the transition interactions.

The last step of our calculation is to define the NN→NN interaction v^1. Following the procedure introduced in Ref. (2), v^1 is defined by subtracting an energy-independent contribution of the intermediate NΔ, ΔΔ, NN^* and N^*N^* from the Paris potential.[19] In our model, we assume that v^1 is defined by the following matrix elements

$$v^{1,\alpha}_{\ell',\ell}(p',p) = [V^{\alpha}_{\ell',\ell}(p',p)]_{\text{Paris}} - [\text{second term of eq. (12)}]_{E=E_s} \tag{13}$$

where E_s is chosen to be well below the pion production threshold so that the second term of eq. (14) is real as required by the hermiticity of v^1. This construction is consistent with the Paris potential which calculates the 2π-exchange mechanism in a nonperturbative approach based on dispersion relations.

IV. RESULTS AND DISCUSSION

The model Hamiltonian defined above only has two free parameters: E_s for the subtraction in eq. (13) and the cutoff Λ of transition potentials $v^{i>2}$. For simplicity, the same Λ is used for all meson-baryon-baryon vertices. By choosing E_s=10 MeV and Λ≈650 MeV/c, we find that the Arndt[20] phase-shifts up to 1 GeV can be satisfactorily described (Figs. 3 5). In particular, we have predicted the isoscalar T=0 NN inelasticities which are not well determined due to the lack of sufficient np scattering data at higher energies. It is important to note that both the model and data show very small inelascities ρ in all T=0 partial waves. But the model predicts non-zero ρ in $\ell>2$ partial waves, while some of them are set to zero in the analysis of Arndt et al. Our predictions can only be verified from more precise np scattering measurements which are currently being carried out in several meson facilities.

In view of the great interest in dibaryon resonances, we compare in Figs. 6 and 7 the data[21] with the calculated reaction cross section σ^R, and total cross sections σ^{tot}, $\Delta\sigma_L^{tot}$ and $\Delta\sigma_T^{tot}$ corresponding to various spin orientations in the incident beam and target nucleons (as defined in Ref. 17). First, we see that the model gives good descriptions of the pp reaction cross section σ^R. The three-body model of Kloet and Silbar[4] is also very successful in describing this data which contain the information of pion-production. In fact, any model with vertex interactions properly fitted to the πN scattering could achieve the same success, if the two- and three-body unitarities are retained. Compared with Ref. (4) the main achievement of the present theory is to give an overall correct description of both the magnitudes and signs of the considered total cross sections in the entire energy region from 0-2 GeV.

The model, however, does not give sufficient energy dependences of all pp total cross sections in the region from 0.6 to 1 GeV. The calculated total cross section σ^{tot} in this region is only about 80% of the data. It is clear that if the amplitudes in one or two partial waves had stronger energy dependences, the shapes of $\Delta\sigma_L^{tot}$ and $\Delta\sigma_T^{tot}$ could be well described. Within our model, we have investigated this possibility by examining the sensitivity of the calculation to the only free parameter of the model, the cutoff Λ of the from factor of transition interactions. The value of another parameter E_s=10 MeV is pretty much fixed by getting good fits to the phase-shifts at low energy. We found that by changing Λ from 650 MeV/c to 1000 MeV/c, we can get the correct energy dependence of σ^{tot} up to 1 GeV. But the resulting $\Delta\sigma_L^{tot}$ has wrong signs at ~ 0.7 GeV. The calculated phase-shifts are also in severe disagreement with the Arndt phase-shifts; indicating poor descriptions of all NN scattering observables. Furthermore, the calculations with Λ=1000 MeV/c do not come close to yielding the pronounced minima in $\Delta\sigma_L^{tot}$ and $\Delta\sigma_T^{tot}$ near 800 MeV.

One possible way to resolve the problem is to introduce dibaryon resonances in some of the partial waves. However, I think that it is premature to proceed immediately in this direction. The first important step is to carefully investigate the energy-dependence of other meson-exchange mechanisms which are omitted in this calculation. The most important one is the effect due to NN interactions in the πNN three-body intermediate state. The input P_{11} isobar model should also be improved to also describe the negative πN phase-shifts at low energies. Finally, we should explore a better description of the meson-baryon-baryon vertex interaction. Chiral (cloudy) quark-bag model calculations of the form factors for N, Δ and N^* could be useful in this regard.

V. CONCLUSION

In conclusion, we have constructed a meson-exchange Hamiltonian for π, N, Δ and N^* for NN scattering up to 2 GeV. The model gives good descriptions of the Arndt phase-shifts up to 1 GeV in both the T=0 and T=1 channels. The calculated total cross sections σ^{tot}, $\Delta\sigma_L^{tot}$ and $\Delta\sigma_T^{tot}$ agree to a large extent with the data in both the magnitudes and the signs. The present calculation gives a sound starting point for future refinements. Among them, a large-scale three-body calculation could be needed to investigate the energy dependence of the effect due to NN interactions in the πNN channel. Until this effect is carefully studied, it is premature to extract information on dibaryon resonances, if they exist, from the data. Our model also gives definite predictions of np scattering. Precise np polarization measurements at higher energy $\gtrsim$ 0.6 GeV are needed to have a complete test of our model. Finally, the present model Hamiltonian can be used to carry out many-body calculations as illustrated in the works by Ohta and me.[16]

This work was supported by the U. S. Department of Energy under Contract Number W-31-109-ENG-38.

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Table 1. Meson-exchange models for NN scattering and isobar-nucleus dynamics.

Solve: $(H = H_0 + H')\,\psi^{(+)} = E\psi^{(+)}$

Energy	Degrees of Freedom	Interactions (H') Baryon-baryon		Pionic	Basic Processes (fits)		Numerical Problems
≲400 MeV	N	NN→NN		-	NN→NN	-	2-body scattering
≲400 MeV	N Δ	NN→NN	NN↔ΔN NN↔ΔΔ NΔ↔NΔ NΔ↔ΔΔ ΔΔ↔ΔΔ	- -	NN→NN	-	C.C. (coupled-channel) 2-body scattering
≲1000 MeV	N Δ π	NN→NN	NN↔NΔ NN↔ΔΔ NΔ↔NΔ NΔ↔ΔΔ ΔΔ↔ΔΔ	πN↔Δ (NΔ→πNN→ΔN) πN↔πN (πN↔N')	NN→NN NN→NNπ	πN→πN (≲300 Mev)	3-body scattering or C.C. 2-body scattering + Δ↔πN
≲2000 Mev	N Δ π N*	NN→NN	NN↔NΔ NN↔ΔΔ NN↔NN* NN↔N*N* NΔ↔ΔN NΔ↔ΔΔ ΔΔ↔ΔΔ NN*↔NN* . . .	πN↔Δ πN↔N* πΔ↔N*	NN→NN NN→NNπ NN→NNππ	πN→πN πN→ππN (≲1000 Mev)	3-body, 4-body scattering or C.C. 2-body scattering + Δ, N*↔πN, ππN

Table 2. The parameters of the isobar model for $\Delta(P_{33})$ and $N^*(P_{11})$ excitations. The parameters are defined in eq. (9) and Fig. 1.

$h'_{\alpha\beta}$	$g_{\alpha\beta}$	$\Lambda_{\alpha\beta}$ (MeV/c)	
$\pi N \leftrightarrow \Delta$	0.98	358	M_Δ = 1300 MeV
$\pi N \leftrightarrow N^*$	0.463	599	M_{N^*} = 1575 MeV
$\pi\Delta \leftrightarrow N^*$	2.013	251	
$\pi\Delta \leftrightarrow \Delta$	0.689	356.4	

Figure Captions

Fig. 1 The calculated πN scattering phase-shifts are compared with the data of Ref. 22. ($E_{c.m.}$ is the total πN energy in c.m. frame)

Fig. 2 (a) The baryon-baryon interactions v^{i} of the model Hamiltonian eq. (9).

(b) The mechanisms of one-pion and two-pion productions generated by the model Hamiltonian eq. (9).

Figs. 3-5 The calculated NN scattering phase-shifts are compared with the energy independent analysis of Arndt et al.

Fig. 6 The calculated pp reaction cross section σ^{R}, total cross sections σ^{tot}, $\Delta\sigma_{T}^{tot} = (\sigma^{tot}(\uparrow\uparrow) - \sigma^{tot}(\uparrow\downarrow))$, $\Delta\sigma_{L}^{tot} = (\sigma^{tot}(\overset{\uparrow}{\rightarrow}) - \sigma^{tot}(\overset{\uparrow}{\leftarrow}))$ are compared with the data.

Fig. 7 Same As Fig. 6, except for the np scattering.

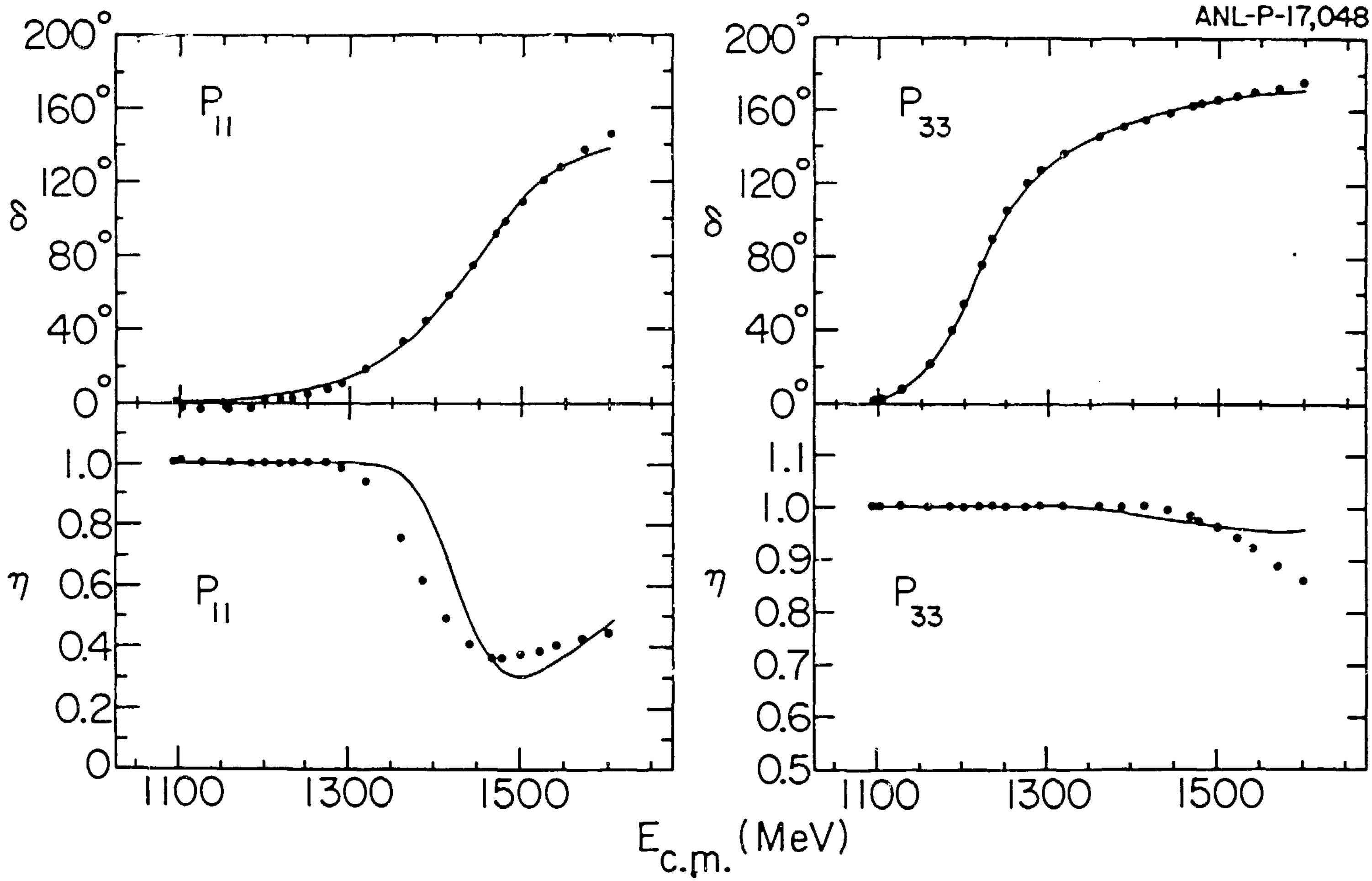

ANL-P-17,048
P11
P33
δ
η
200°
160°
120°
80°
40°
0°
1.0
0.8
0.6
0.4
0.2
0
1.1
0.9
0.7
0.5
1100
1300
1500
Ec.m. (MeV)

Figure 1

ANL-P-17,051

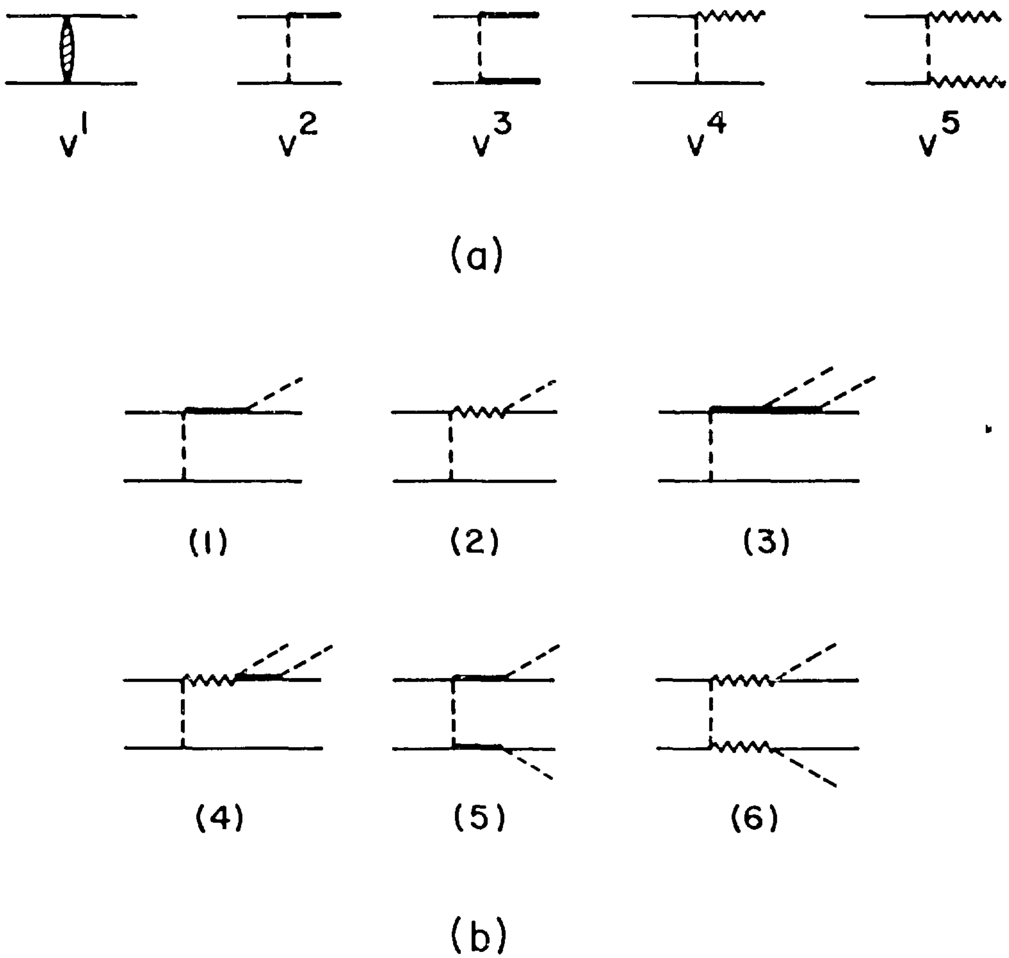


Figure 2

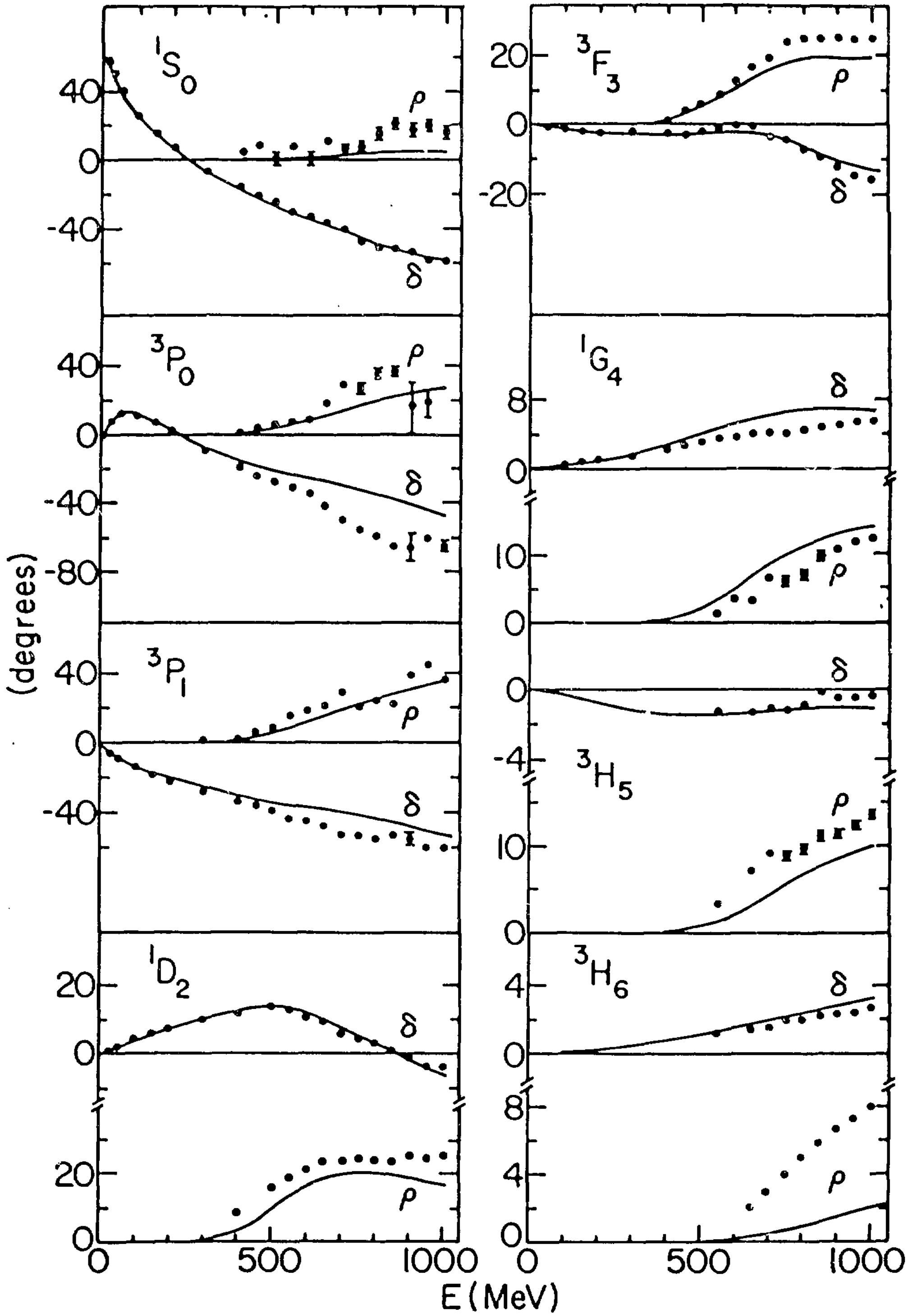
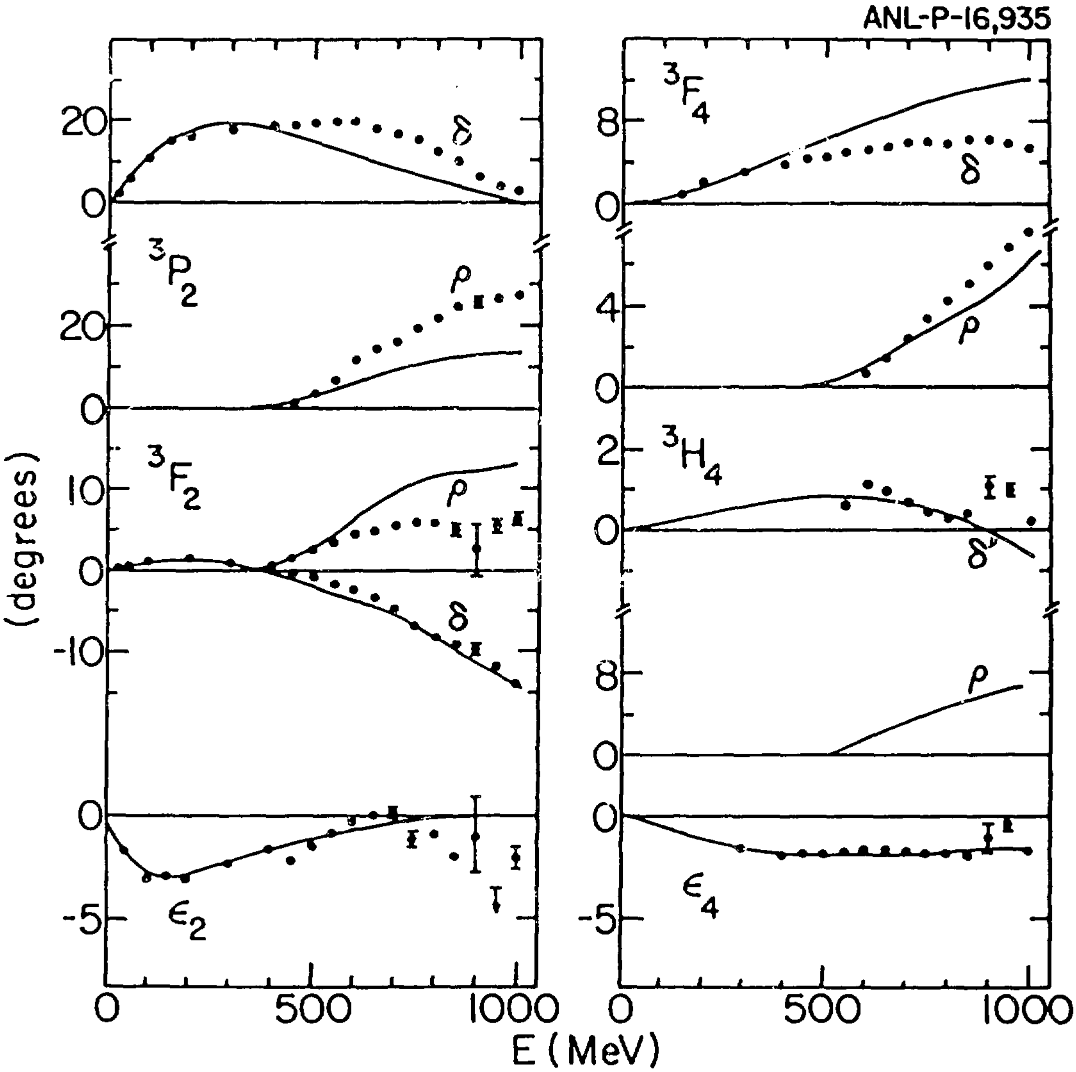


Figure 3



ANL-P-16,935
³P₂
³F₂
³F₄
³H₄
δ
ρ
ε₂
ε₄
(degrees)
E (MeV)
0
500
1000
20
10
-10
-5
8
4
2

Figure 4

ANL-P-17,047

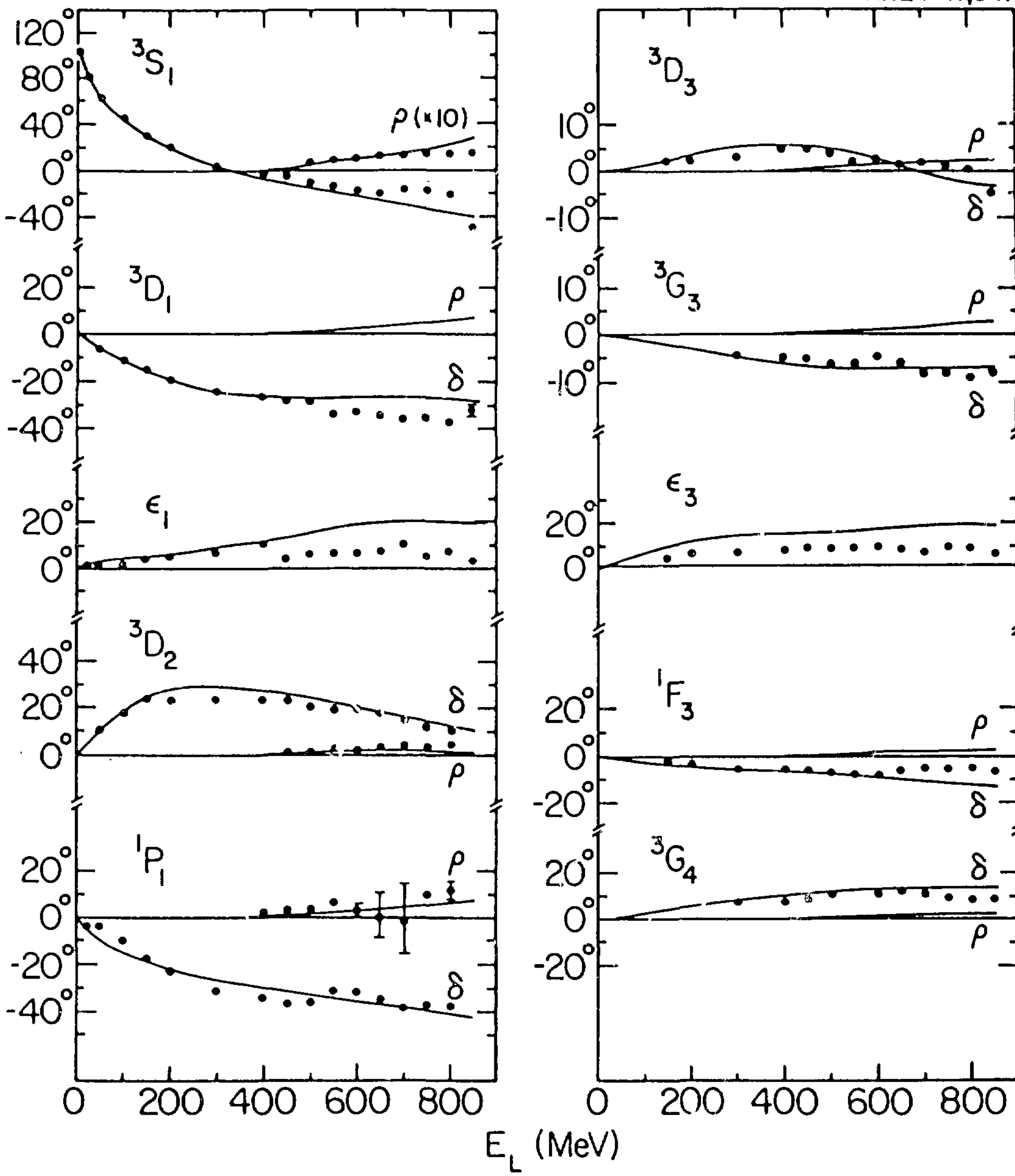


Figure 5

ANL-P-17,046

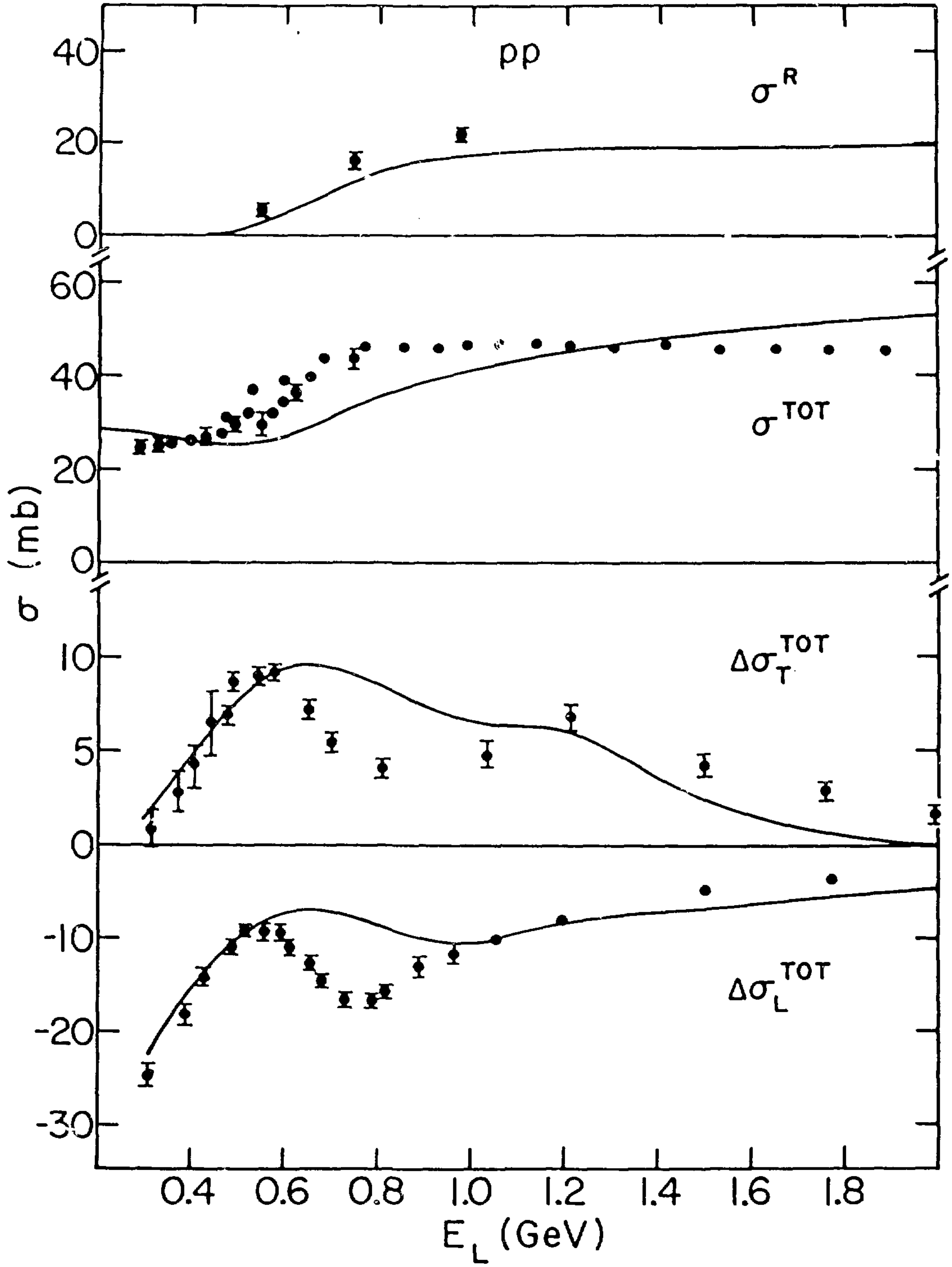


Figure 6

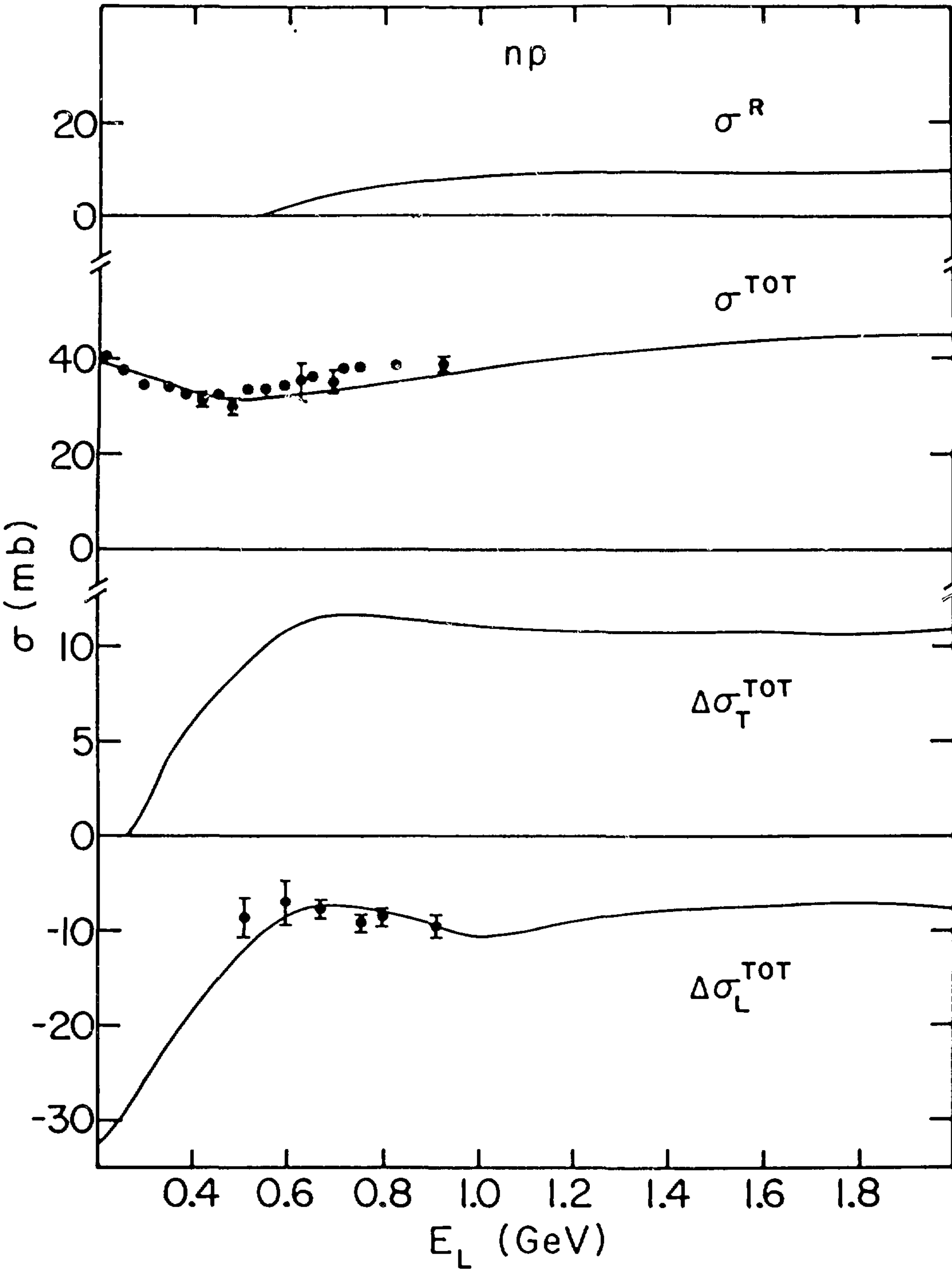

np
σ^R
20
0
σ^{TOT}
40
20
0
σ (mb)
10
$\Delta\sigma_T^{TOT}$
5
0
-10
$\Delta\sigma_L^{TOT}$
-20
-30
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
E_L (GeV)

Figure 7