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Mesonic and Dibaryonic Excitations in the πNN System

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T.-S. H. Lee

Argonne National Laboratory, Argonne, Illinois 60439

Abstract:

A πNN theory, incorporating mesonic and dibaryonic excitation mechanisms, is introduced to give a unified description of NN and πd reactions. The mesonic mechanism is built into the theory along the line of the Paris potential. The dibaryonic excitation at short distance is introduced according to current understanding of six quark dynamics. The effect of the 2^+,T=1 six-quark state on NN and πd scattering is presented. The implication of the theory in the study of electromagnetic interaction with deuteron is discussed.

An important achievement of theoretical nuclear physics in the past two decades is the development of a microscopic description of low energy nuclear phenomena from the elementary nucleon-nucleon (NN) interaction. Through the construction of meson-exchange NN potential, such as the Paris,[1] Bonn,[2] and Argonne-Urbana potentials,[3] the theory is further related to basic mesonic excitation mechanisms. In this talk, I would like to describe the extension of such an attempt to study intermediate energy nuclear physics.

The main feature of intermediate energy nuclear reaction, induced by pion, nucleon, electron or heavy ion, is the production or absorption of on-mass-shell pion. Therefore, a microscopic approach to the problem should start from a theory of the coupled NN+πNN system (called πNN system from now on). An acceptable πNN theory should describe simultaneously all of the following processes

$$\pi N \to \pi N \; (300 \text{ MeV} < E_L) \qquad (1)$$

$$NN \to NN \; (1000 \text{ MeV} < E_L) \qquad (2)$$
$$\to \pi NN$$

$$\pi d \to \pi d \; (300 \text{ MeV} < E_L) \qquad (3)$$
$$\to \pi NN$$
$$\to NN$$

In addition, we must face the fact that at this higher energy, two colliding baryons are more likely to overlap and the effect of their internal quark structure may not be possible to be parameterized in the same manner as the conventional meson-baryon-baryon form factors or a phenomenological repulsive core. In this talk, I will first outline a general πNN theory which can account for these two important dynamics. Then, I will discuss the status of the theory, and the use of the theory in the study of γd or ed reactions; in particular the question concerning the excitation of a dibaryon resonance.

Let us first discuss qualitatively the mechanisms which should be considered in defining the πNN interactions. The interaction at long distance is due to one-pion-exchange, which is conventionally taken to describe the high partial-wave NN phase shifts. This pionic force is also responsible for exciting the nucleon to the Δ isobar state, which then decay into the πN state asymptotically if the collision energy is above the pion production threshold. In the current πNN model, this pionic excitation is described by constructing an isobar model with a πB'-B vertex (B and B' could be N or Δ) to fit the πN scattering phase-shift. Its relation to the quark dynamics can be established through the chiral (cloudy) bag model,[4] although only limited success has been achieved so far.

The NN low partial wave phase-shifts clearly indicate that other mechanisms are at work at shorter distances. Here, we face an interesting and still unclear situation. First, it is undeniable that the heavy mesons, such as ω and ρ, are observed experimentally and they must play some role in determining the NN force. However, the exchange of heavy mesons is unrealistic if the size of a baryon is comparable to or larger than their Compton wavelength. Therefore, the most probable mesonic process other than the one-pion-exchange is sequential exchange of two pions. The most detailed analysis of the two-pion-exchange mechanism is the nonperturbative approach of the Paris group. We therefore take the Paris potential as the starting point to define the NN interaction. Here, we need to introduce a procedure to remove from the Paris potential the two-pion-exchange with intermediate Δ excitation, because in a πNN model the Δ excitation has to be treated explicitly in order to describe pion production. However, no similar model can be used to define the two-pion-exchange interactions between channels involving at least one Δ. In some of the πNN models, the exchange of a ρ is introduced to correct this part of physics.

The short range part is usually treated phenomenologically. However, much experimental evidence, in particular the NN and πd spin observables, have pointed to the need for a more microscopic approach in defining baryon-baryon (BB) interactions at very short distances. Especially, the question about the existence of dibaryon resonances can be better resolved if we relate the short range BB force to the "confined" 6-quark dynamics. We discuss this connection to quark dynamics in the framework of the bag model[5] and the resonating group method[6] calculation for the quark-exchange mechanism between baryons.

The bag model calculation has predicted the masses of confined q^6 states in each B=2 color singlet eigenchannel. There are two possible interpretations of this theoretical result. The first one is the P-matrix approach, as introduced by Jaffe and Low[7] and explored by Mulders[8] in the study of NN scattering. This approach tries to use six quark dynamics to define the BB wavefunction at the point where two baryons start to overlap. The second interpretation is that the confined q^6 states are the dibaryon (one-body) states which could be excited at a very short distance during the NN or πd scattering. Through their coupling to NN, NΔ or πNN channels, they may be responsible to the strong energy dependence seen in NN and πd spin observables. This interpretation implies that the baryon-baryon interaction has two entirely different mechanisms, just like the situation in the study of low energy nuclear reactions. The first one is the fast direct process which can be described by an effective two-baryon potential, despite the involvement of internal structure of two interacting objects during the collision. The second process is the compound state formation in which each baryon has lost its own identity to excite a completely different q^6 configuration.

The second interpretation of 6q dynamics is adopted in our formulation of the πNN model. This is supported by resonating group method calculations of NN interaction within the nonrelativistic quark model, especially the calculation by the Tokyo group.[6] These calculations indicate that the quark exchange mechanism between two nucleons can be effectively represented by a repulsive two-body force as we have determined from S-wave NN phase-shifts. We therefore argue that the conventional phenomenology for treating short range BB interaction can effectively include this fast process of quark dynamics. On the other hand, the compound state formation of quark dynamics is beyond the description of the resonating group method and must be added into the theory separately. It is our assumption that this unknown compound state formation mechanism, could be mainly due to the confining force, can convert the incoming two baryons into a dibaryon state D with masses predicted by the q^6 Bag model calculation. In the same way we use a $\pi N \leftrightarrow \Delta$ vertex to describe the Δ resonance, we also introduce a $B_1 B_2 \leftrightarrow D$ vertex to describe the excitation of the dibaryon state D.

With the above arguments, we can now extend the approach of ref. (9) to write down the most general model Hamiltonian for the coupled NN + πNN system

$$H = H_0 + H' \tag{4}$$

$$H' = h_{\pi B \leftrightarrow B'} + V_{B_1 B_2, B_1' B_2'} + F_{B_1 B_2 \leftrightarrow D} \, , \tag{5}$$

where H_0 is the sum of kinetic energy operators, D denotes the dibaryon state, B can be N or Δ (the theory can be extended[9] to include higher mass isobars). Because of the vertex interaction $h_{\pi B \leftrightarrow B'}$, one can see that none of the one "bare" baryon states is stable asymptotically, and the model can generate multi-pion states. This nature of the model causes difficult theoretical problems in deriving a mathematically rigorous but also manageable πNN scattering theory. At the present time, this problem is overcome in practice by defining a scattering theory in a model space $\mathcal{H}_M$, and rewrite H' as an effective Hamiltonian in $\mathcal{H}_M$. This of course can be done in many different ways. In the following, I will describe a very specific model, which is the extension of the model in ref. (9).

The first simplification is to keep only the $\pi N \leftrightarrow \Delta$ vertex in H'. This approximation drastically simplifies the πNN scattering theory, because no mass renormalization problem of the nucleon will ever occur (the complications due to the mass renormalization is well known in many classical field theoretical models, even in considering the simplest $\pi N \to N$ vertex). However, some important physics is omitted by this simplification. First, πN scattering cannot occur except the process $\pi N \to \Delta \to \pi N$ in the P_{33} channel. Second, pion absorption or production by two nucleons cannot happen except through the formation of Δ resonance, i.e. $NN\pi \to N\Delta \to NN$. To correct this error, we add two-body potential $v_{\pi N}$ to describe πN scattering in channels other than P_{33}, and introduce a transition operator $G_{\pi NN \to NN}$ to describe nonresonant pion absorption mechanism. Then the interaction H' takes the form

$$H' \to H'_M = h_{\pi N \to \Delta} + V_{B_1 B_2, B_1' B_2'} + v_{\pi N} + G_{\pi NN \to NN} + F_{B_1 B_2 \to D} . \qquad (6)$$

By using well known theoretical methods, one can derive $v_{\pi N}$ and $G_{\pi NN \to NN}$ from the original Hamiltonian defined in eqs. (4)-(5). In practice these two operators are constructed phenomenologically.

A model of the form of eq. (6) can be constructed in practice as follows. It is convenient to define a simple separable $v_{\pi N}$ to fit the πN scattering. The transition operator $G_{\pi NN \to NN}$ is determined by examining various $NN \to \pi NN$ processes near the threshold where the Δ contribution is suppressed. For example, the classical rescattering model of Koltun and Retain is used as a starting point in our study (with Matsuyama at SIN). All BB interactions involving at least one isobar are defined by one-pion and one-rho exchange in static limit. Because the vertex interaction $h_{\pi N \to \Delta}$ can generate the one-pion exchange between $N\Delta$ state, this part of the $N\Delta \to \Delta N$ interaction has to be omitted in defining BB interaction $V_{B_1 B_2, B_1' B_2'}$. The

NN→NN potential is derived from the Paris potential by the procedure of ref. (9).

The "bare" mass of the dibaryon state is taken from the q^6 Bag model calculation by Mulders et al.[5] So far, we have considered the D state of $J^\pi=2^+$, and T=1. Its mass is 2360 MeV. The $B_1B_2 \to D$ transition is parameterized as

$$F_{B_1B_2 \to D_\alpha} = f_\alpha \frac{1}{\sqrt{m_1+m_2}} \left(\frac{q}{m_1+m_2}\right)^{\ell_\alpha} \left(\frac{\Lambda_\alpha^2}{\Lambda_\alpha^2+q^2}\right) .$$

The range Λ_α must be ~ 1 fm^{-1}. The only unknown quantity is the coupling constant f_α. We therefore take special care in deriving the πNN scattering equation to isolate this dibaryon coupling from the rest of the interactions. One of the main objectives of our current study is to determine this coupling from the NN and πd data.

The πNN scattering theory is then constructed from the interaction defined in eq. (6) within the model space πNN+BB. The derivation is straightforward, although tedious. The resulting NN scattering equation can be cast into

$$T_{NN,NN}(E) = \langle NN|\mathcal{J}(E)|NN\rangle \qquad (7)$$

where $\mathcal{J}(E)$ is a scattering operator defined in the BB subspace $NN\oplus N\Delta\oplus\Delta\Delta$ by

$$\mathcal{J}(E) = \Omega_E^{(-)+} T_0(E)\Omega_E^{(+)} + T_c(E) + T_D(E) \qquad (8)$$

The BB interaction $V(V \equiv V_{B_1B_2,B_1'B_2'})$ is mainly contained in $T_0(E)$

$$T_0(E) = V + V \frac{1}{E-H_0-\Sigma_\Delta(E)} T_0(E)$$

$$+ V \frac{1}{E-H_0-\Sigma_\Delta(E)} T_c(E) \frac{1}{E-H_0-\Sigma_\Delta(E)} T_0(E) \quad , \tag{9}$$

where Σ_Δ is the Δ self energy due to $\pi N \leftrightarrow \Delta$ (Fig. 1a). The other pionic effects are contained in

$$T_c(E) = V_c(E) + V_c(E) \frac{1}{E-H_0-\Sigma_\Delta(E)} T_c(E) \tag{10}$$

$$\Omega_E^{(\pm)} = 1 + \frac{1}{E-H_0-\Sigma_\Delta(E)-V_c(E)} (\Sigma_\Delta(E) + V_c(E)) \tag{11}$$

with

$$V_c(E) = V_E(E) + V_3(E) + V_a(E) \tag{12}$$

Each mesonic interaction in eq. (12) is graphically shown in Fig. 1. Note that $V_a(E)$ is due to the pion production operator $G_{\pi NN \leftrightarrow NN}$. $V_3(E)$ and $V_a(E)$ are determined by a πNN scattering amplitude $\mathcal{J}_3$ which is only determined by the two-body πN and NN interactions $v_{\pi N}$ and V_{NN}

$$\mathcal{J}_3(E) = (v_{\pi N}+V_{NN}) + (v_{\pi N}+V_{NN}) \frac{1}{E-k_\pi-k_{N_1}-k_{N_2}-v_{\pi N}-V_{NN}} (v_{\pi N}+V_{NN}) \tag{13}$$

Eq. (13) can be solved by the usual Faddeev method.

The dibaryonic excitation mechanism is isolated in the last term of eq. (8). It is determined not only by the BB↔D coupling but also by mesonic excitation

$$T_D(E) = \Omega_E^{(-)^+} F_{BB \to D} \frac{1}{E-M_D-W_D(E)-\delta W_D(E)} F^+_{BB \to D} \Omega_E^{(+)} \, . \tag{14}$$

Eq. (14) is graphically represented in Fig. 2 for the $J^{\pi}=2^{+}$, T=1 case that the coupling is mainly through the NΔ state according to ref. (5). It is important to note that the width of D is now modified through $\mathcal{J}$ by all of the mesonic and BB interactions. We therefore have developed a unified description of "resonance" phenomena due to the coupling to NΔ↔πNN inelastic channel and the genuine q^6 compound state excitation. In this approach, the property of q^6 state can be dynamically related to NN data since all mesonic excitations can be calculated from eqs. (7)-(13) with established numerical methods. Similar equations have also been derived for the study of all πNN processes listed in eqs. (2)-(3).

We (Argonne-SIN collaboration) are extending the works of refs. (9) and (10) to solve the entire eqs. (7)-(14). We start with the coupled channel calculation of ref. (9), which neglected the terms T_C and T_D in solving eqs. (8)-(13). The calculated NN phase-shifts are in very good agreement with Arndt's analysis. However, the deficiency of the calculation is clearly seen in various spin-dependent total cross sections $\sigma_{tot}(E)$, $\Delta\sigma_T(E)$, and $\Delta\sigma_L(E)$ (Fig. 3). Similar results have also been obtained recently by the Hannover group. In the present formulation, it is clear that the neglect of T_C and the coupling to the dibaryon state is responsible to the incorrect energy dependences. The mesonic part of T_C can be calculated rigorously as discussed above, but it needs a sufficiently accurate model of $G_{\pi NN \leftrightarrow NN}$. This part of the work is being done along with the development of an efficient method of solving eqs. (10)-(13). Here, I only discuss our recent study of the dibaryonic excitation described by T_D.

We have carried out the following calculations. The transition matrices in the NN⊕NΔ space are generated from the coupled channel model of ref. (9) in order to calculate $\Omega_E^{(\pm)}$ and $\delta W_D(E)$. In the same approximation, the effect of dibaryon state on πd elastic scattering is also calculated consistently (we have also formulated the πd problem in a form similar to eq. (8)). The question we have attempted to answer is the following: Can the 2^+,T=1 dibaryon state predicted by the bag model give any striking "resonant" effect reported in a πd T_{20} measurement at SIN which disagrees with the measurement by the Argonne group. According to the bag model calculation, the bare mass of this dibaryon state is 2360 MeV. It mainly couples to NN and πd channels through the s-wave NΔ state. The only undetermined parameter in our calculation is f_α, the coupling constant of $F_{N\Delta \to D_\alpha}$. Our task is therefore to see the change in NN and πd scattering if f_α is varied.

We have found that a very small range of f_α is allowed if we require that <u>all</u> NN and πd data must be described reasonably well. In Fig. 4, the $^1D_2$ NN phase-shifts calculated with (dashed) and without (solid) $F_{BB \to D}$ coupling are compared. Both curves (with $f_\alpha = \sqrt{3}$, $\Lambda_\alpha = 200$ MeV/c) are in reasonable agreement with the data. Its corresponding effect on πd scattering is also shown in Fig. 6. Clearly, the striking structure in T_{20} reported by SIN measurement cannot be accounted for by the 2^+,T=1 six-quark excitation at short distance. Similar effects are also obtained in other energy regions, and also for other πd spin observables. Of course, our result does not rule out the possibility of genuine dibaryonic excitation in other eigenchannels. Unfortunately, the Bag model calculations for the $L \neq 0$ channel are much more uncertain and cannot be easily interpreted. In practice, we can go beyond Bag model calculations, and introduce the dibaryon coupling in other channels. For example, we can try the favored $^3P_1$ channel as suggested by the πd phase-shift analysis to reproduce the T_{20} data. However, the introduced dibaryonic excitation can be established, only when all other πd and NN data can also be described very well. In our theory, this search can be done realistically only when all mesonic excitations described by T_c in eqs. (9)-(13) can be calculated accurately. This is the main objective of our current study.

To close this talk, I would like to make brief comments on γd reaction which is also an important source for investigating dibaryon resonance. In our πNN formulation, the electromagnetic field can couple to N, Δ, π and also to diabaryon state D. The coupling to the first three degrees of freedom can be handled by conventional method (apart from the problem concerning relativistic effects and currents at short distance). The contribution from these "conventional" currents can be calculated rigorously, if the coupled $NN+\pi NN$ problem has been solved. The only mechanism which can be responsible for any difference between the theory and data is the coupling to dibaryon state. Therefore, any dibaryon state, which could be missed in the πNN study, can be further explored by making use of some special properties of electromagnetic probes. The work on $\gamma d \to \vec{p}n$ reaction by the Tokyo group[11] have indicated this possibility. In order to make quantitative conclusions, their treatment of πNN dynamics has to be treated by the present approach.

Finally, I would like to point out that very extensive NN, πd, ed and γd data are now available. It is the time for us to construct a πNN theory so that the intermediate energy nuclear reaction can be studied microscopically.

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PIONIC INTERACTIONS

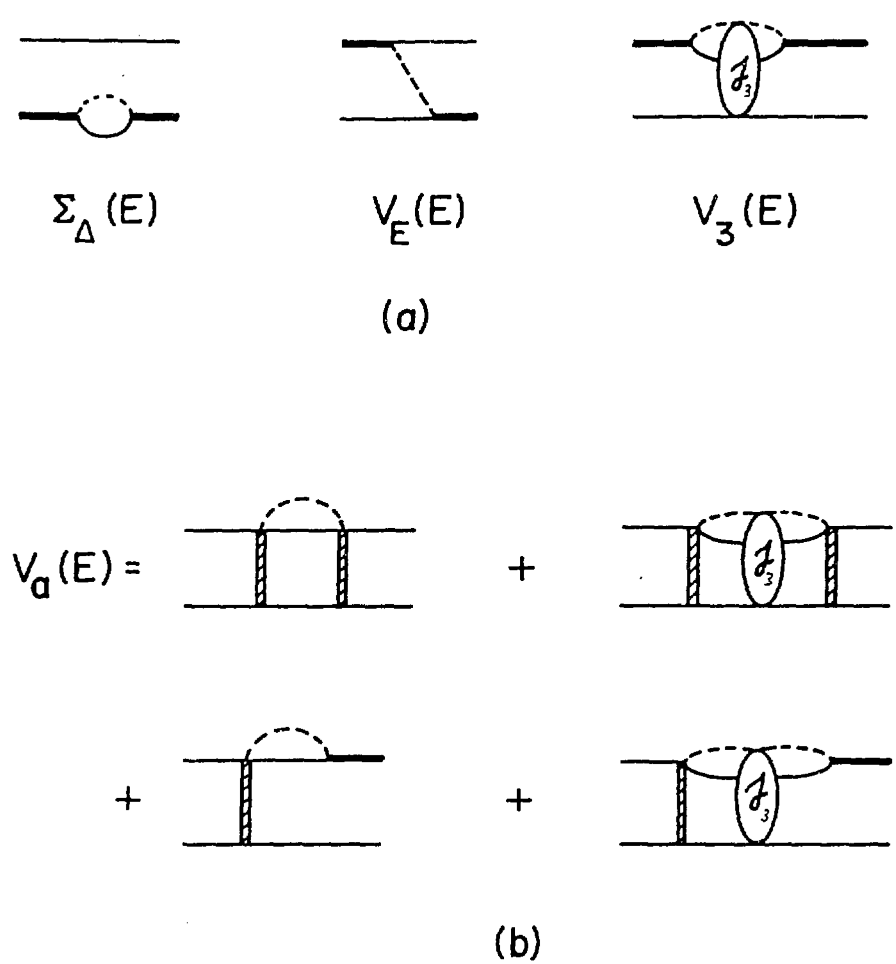

Fig. 1

DIBARYONIC EXCITATION THROUGH NΔ STATE

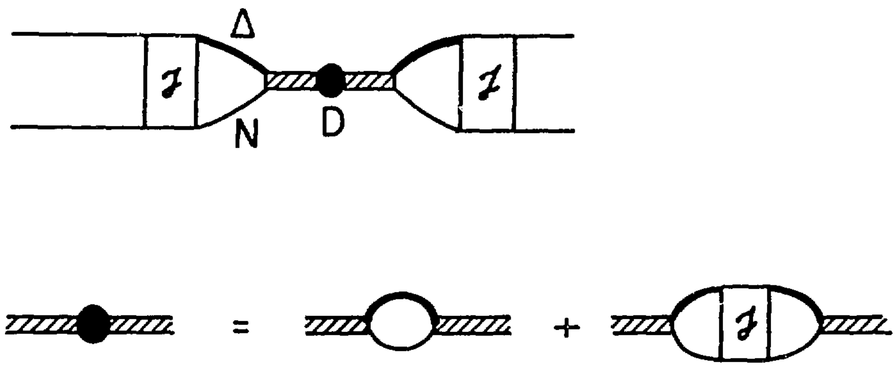

Fig. 2

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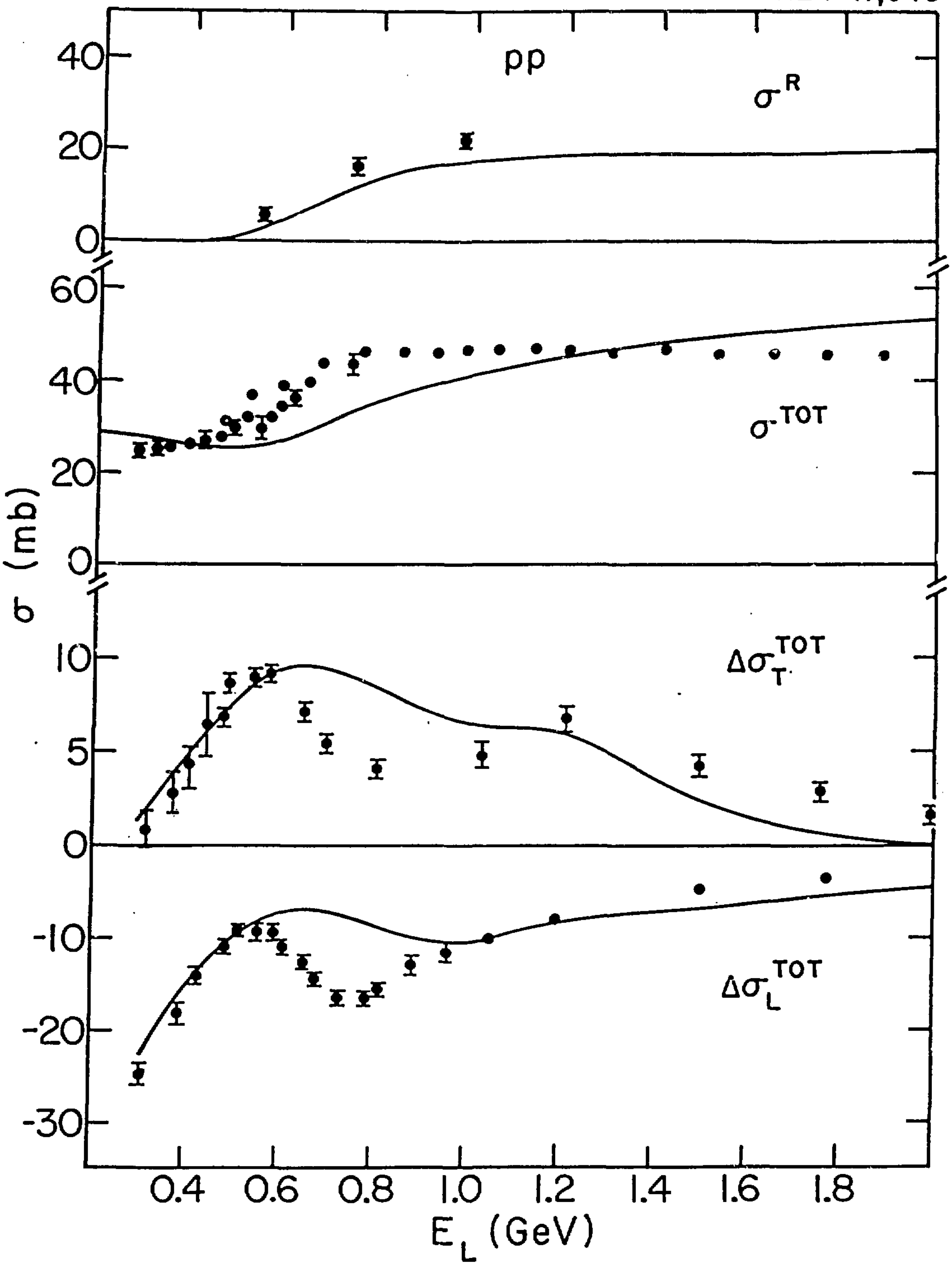

Fig. 3

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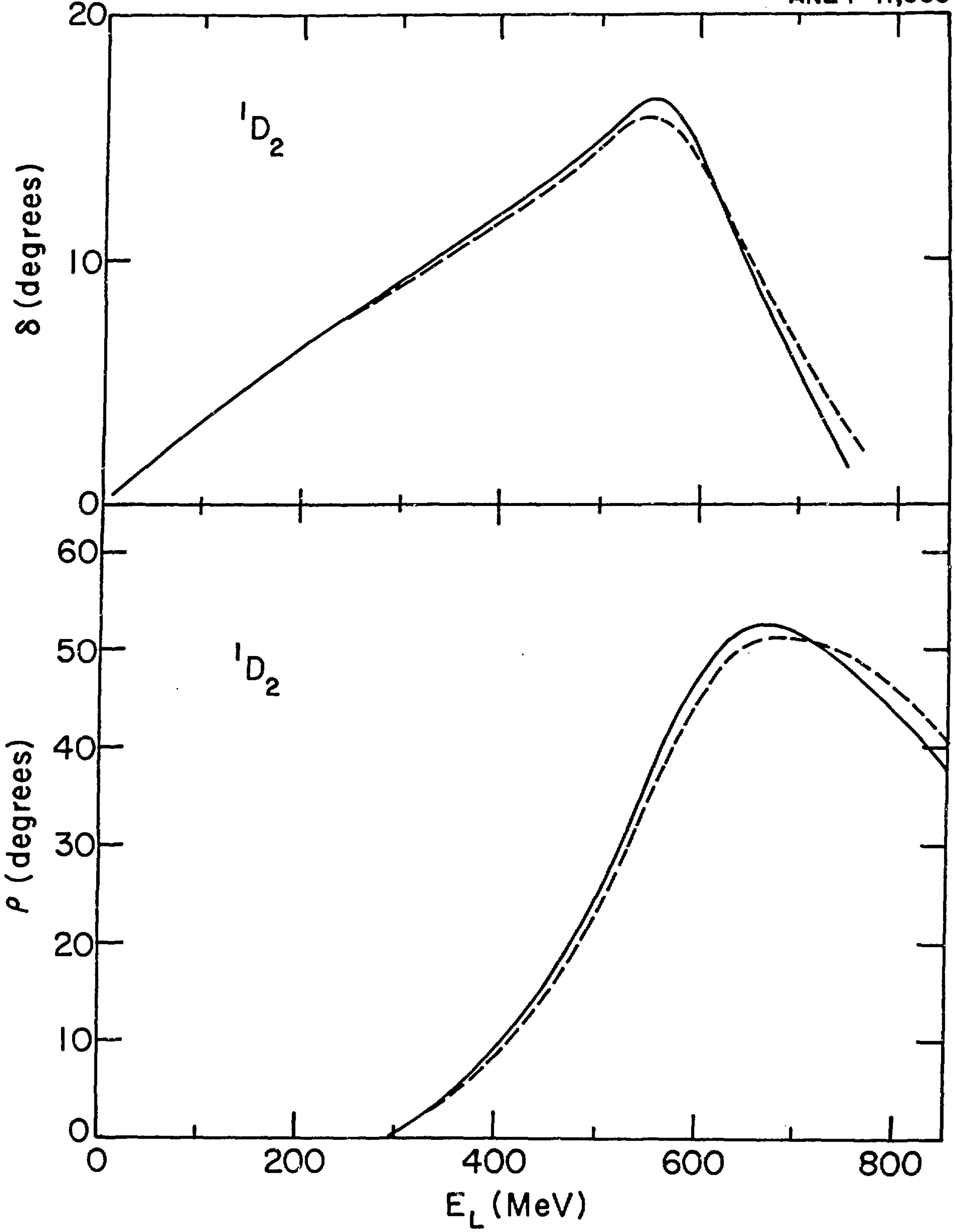

Fig. 4

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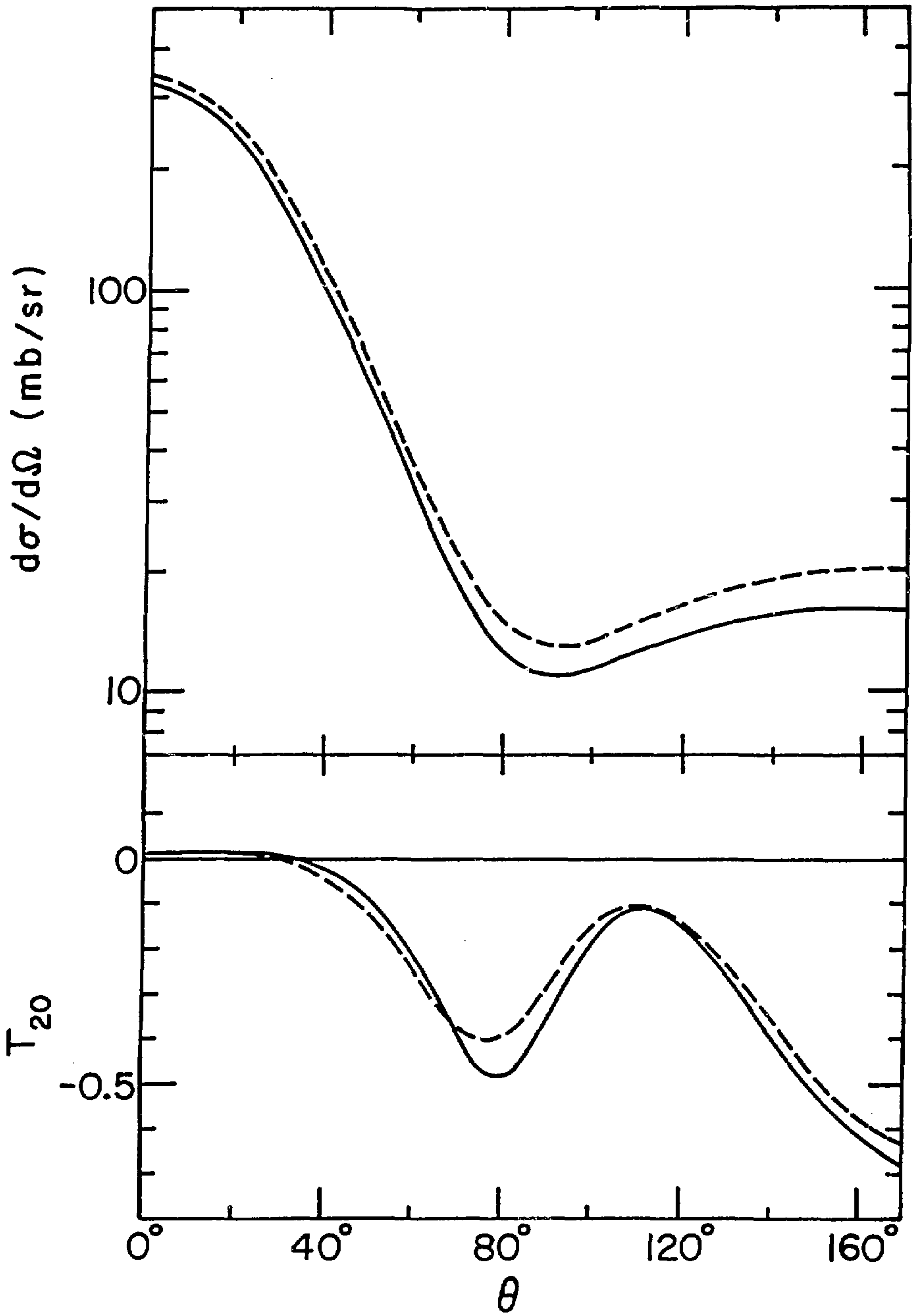

Fig. 5