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Quark Dynamics in the πNN System

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Abstract

The recently developed πNN theory based on quark dynamics is reviewed.

The intermediate energy nuclear reactions, induced by pions, nucleons, electrons or heavy-ions, are characterized by the production or absorption of on-mass-shell pions. Therefore, a theoretical approach to the problem should start from a theory (called the πNN theory in the literature) which can describe simultaneously all of the following processes

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

$$NN \to NN \ (1000 \text{ MeV} < E_L) \quad (2)$$

$$\to \pi NN$$

$$\pi d \to \pi d \ (300 \text{ MeV} < E_L) \quad (3)$$

$$\to \pi NN$$

$$\to NN$$

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 be important. In this talk I discuss a general πNN theory[1] which has been constructed according to our present understanding of the quark dynamics.

Let us first discuss qualitatively the mechanisms which should be considered in defining the πNN interactions. The NN interaction at long distances is due to one-pion-exchange, which is evident from examining the high partial-wave NN phase shifts. This pionic force is also responsible for exciting the nucleon to the Δ isobar state, which then decays into the πN state asymptotically if the collision energy is above the pion production threshold. The pionic excitation can be coneniently described by the Chiral (Cloudy) bag model which has been used in practice to define a $\pi B' \to B$ vertex (B and B' could be N or Δ) to fit the πN scattering phase shifts. In Fig. 1, I show a recent πN work along this line by Johnstone and myself.[2]

In considering NN, NΔ and $\Delta\Delta$ interactions at shorter distances, we face an interesting and still unclear situation. It is undeniable that the observed heavy mesons, such as ω and ρ, must play some role in determining the baryon-baryon 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[3] 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. No similar model has been developed to define the two-pion-exchange interactions between channels involving at least one Δ. So far the exchange of a ρ has been used to describe this part of the physics.

The least understood part of the baryon-baryon interaction is at the very distance $\lesssim 0.5$ fm, which is usually treated phenomenologically. Extensive experimental data on the NN and πd spin observables have pointed to the need for a more microscopic approach in defining 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 multi-quark dynamics in the framework of the bag model[4] and the resonating group method[5] calculation for the quark-exchange mechanism between baryons.

An interesting prediction by the bag model calculation is the energy spectrum of the 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[6] and explored by Mulders[7] in the study of NN scattering. This approach tries to use six quark dynamics to define the BB wave function 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 for the strong energy dependence seen in NN and πd spin observables.

We adopt the second interpretation and assume 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 the 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.

Our approach to the problem is further supported by resonating group method calculations of the NN interaction within the nonrelativistic quark model, such as the calculation presented at this conference by Professor Schmid. 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 the 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 the mass 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 $B_1B_2 \leftrightarrow D$ vertex to describe the excitation of the dibaryon state D.

With the above arguments, we can write down the most general model Hamiltonian for the coupled NN + πNN system

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

$$H' = h_{\pi B \leftrightarrow B'} + V_{B_1B_2, B_1'B_2'} + H_{B_1B_2 \leftrightarrow D} , \tag{5}$$

where H_0 is the sum of kinetic energy operators, D denotes the dibaryon state, B can be either N or Δ. Because of the vertex interaction $h_{\pi B \leftrightarrow B'}$, one can see that none of the one "bare" baryon states are 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 <u>manageable</u> 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 has been developed by Matsuyama and myself.[1]

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 $\pi N \leftrightarrow N$ vertex). However, some important physics is omitted by this simplification. First, πN scattering cannot occur except the process $\pi N \rightarrow \Delta \rightarrow \pi N$ in the P_{33} channel. Second, pion absorption or production by two nucleons can take place only through the formation of the Δ resonance, i.e. $NN\pi \leftrightarrow N\Delta \leftrightarrow NN$. To correct this error, we add a two-body potential $v_{\pi N}$ to describe πN scattering in channels other than P_{33}, and introduce a transition operator $F_{\pi NN \leftrightarrow NN}$ to describe nonresonant pion absorption. Then the interaction H' takes the form

$$H' \rightarrow H'_M = h_{\pi N \leftrightarrow \Delta} + V_{B_1 B_2, B'_1 B'_2} + v_{\pi N} + F_{\pi NN \leftrightarrow NN} + H_{B_1 B_2 \leftrightarrow D} \ . \qquad (6)$$

A model of the form of Eq. (6) has been constructed in practice as follows. It is convenient to define a simple separable $v_{\pi N}$ to fit the πN scattering in nonresonant channels. Special care must be taken to describe the P_{11} channel. With the development of Ref. 2, we are able to use quark dynamics to separate the nucleon pole term from the full P_{11} amplitude. The transition operator $F_{\pi NN \leftrightarrow NN}$ is determined by examining various $NN \leftrightarrow \pi NN$ processes near the threshold where the Δ contribution is suppressed. For example, the classical rescattering model of Koltun and Retain[8] has been used in our study.[9] All BB interactions involving at least one isobar are defined by one-pion and one-rho exchange in the static limit. Because the vertex interaction $h_{\pi N \leftrightarrow \Delta}$ can generate the one-pion exchange interaction between two

$N\Delta$ states, this part of the $N\Delta \to \Delta N$ interaction has to be omitted in defining the 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. 3. The "bare" mass of the dibaryon state is taken from the q^6 Bag model calculation by Mulders et al.[4]

Within the NN and πNN unitarity conditions, the πNN scattering theory is constructed from the interaction defined in Eq. (6) within the model space πNN+BB. The derivation[1] is straightforward, although tedious. The resulting NN scattering equation can be cast into the form

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

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

$$\mathcal{T}(E) = \Omega_c^{(-)+} \, T_0(E) \, \Omega_c^{(+)} + T_c(E) + T_D(E) \ . \tag{8}$$

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

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

where Σ_Δ is the Δ self-energy due to $\pi N \leftrightarrow \Delta$ (Fig. 2a). The other pionic effects are contained in

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

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

with

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

Each mesonic interaction in Eq. (12) is graphically shown in Fig. 2. Note that $V_a(E)$ is due to the pion production operator $F_{\pi NN \leftrightarrow NN}$. $V_3(E)$ and $V_a(E)$ are determined by a πNN scattering amplitude $_3$ which is determined only 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

$$T_D(E) = \Omega_c^{(-)^+} H_{BB\to D} \frac{1}{E-M_D-W_D(E)-\delta W_D(E)} H^+_{BB\to D} \Omega_c^{(+)} . \tag{14}$$

Eq. (14) is graphically represented in Fig. 3 for the $J^\pi=2^+$, T=1 case where the coupling is mainly through the NΔ state according to Ref. 4. It is important to note that the width of D is now modified through $\mathcal{J}$ by all of the mesonic BB interactions. We therefore have developed a unitary description of "resonance" phenomena due to the coupling to NΔ↔πNN inelastic channel and to the genuine q^6 compound state excitation. Similar equations have also been derived[1] for all the πNN processes listed in Eqs. (1)-(3).

We have first extended the works of Refs. 3 and 10 to study NN and πd scattering, neglecting the coupling to the dibaryon state. The calculated NN phase shifts are in good agreement with Arndt's analysis. Figure 4 shows the results of a recent calculation[11] of the exclusive $pp \to pn\pi^+$ reaction. The agreement with the data is also satisfactory. However, the deficiency of the model is clearly seen in various spin-dependent total cross sections $\sigma_{tot}(E)$, $\Delta\sigma_T(E)$, and $\Delta\sigma_L(E)$ (Fig. 5). The formulation illustrated in Eq. (8), suggests that the neglect of the coupling to the dibaryon state could be responsible for the incorrect energy dependences. Now I turn to discussing our study of the dibaryonic excitation described by T_D.

So far, we have considered the D state of $J^\pi = 2^+$, and T=1. Its mass[4] is 2360 MeV. The $B_1B_2 \to D$ transition is parameterized as

$$H_{B_1B_2 \to D_\alpha} = f_\alpha \frac{1}{\sqrt{m_1+m_2}} \left(\frac{q}{m_1+m_2}\right)^{\ell_\alpha} \left(\frac{\Lambda_\alpha^2}{\Lambda_\alpha^2+q^2}\right) . \qquad (15)$$

The range Λ_α must be $\sim 1\ \mathrm{fm}^{-1}$. The only unknown quantity is the coupling constant f_α.

We have carried out the following calculation. The transition matrices in the $NN \oplus N\Delta$ space are generated from the solution of Eqs. (7)-(13) in order to calculate $\Omega_c^{(\pm)}$ and $\delta W_D(E)$. A similar procedure is also used to calculate the effect of the dibaryon state in πd elastic scattering (we have also formulated[1] the πd problem in a form similar to Eq. (8)). The question we have attempted to answer is the following: Can the lowest 2^+,T=1 dibaryon state, predicted by the MIT bag model, play a role in improving the energy dependences of NN total cross sections and πd data? This q^6 state mainly couples to NN and πd channels through the s-wave $N\Delta$ state. The only undetermined parameter in our calculation is the coupling constant f_α of Eq. (15). 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 all NN and πd data must be described reasonably well. In Fig. 6, the $^1D_2$ NN phase shifts calculated with (dashed) and without (solid) the $H_{BB \to D}$ coupling are compared. Both curves (with $f_\alpha = \sqrt{3}$, $\Lambda_\alpha = 200$ MeV/c) are in reasonable agreement with the data (comparison with the data can be found in Ref. (3)). The corresponding effects on NN total cross sections are less than 5%, and cannot improve their energy dependence shown in Fig. 5. The corresponding effect on πd scattering is shown in Fig. 7. Clearly, no striking change can be produced by the coupling to this lowest 2^+ T=1 q^6 state. Similar effects are also obtained in other energy regions. Of course, our result does not rule out the possibility of dibaryonic excitation in other eigenchannels, or some other unconventional mechanisms as suggested by recent developments of soliton models of hadrons.

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

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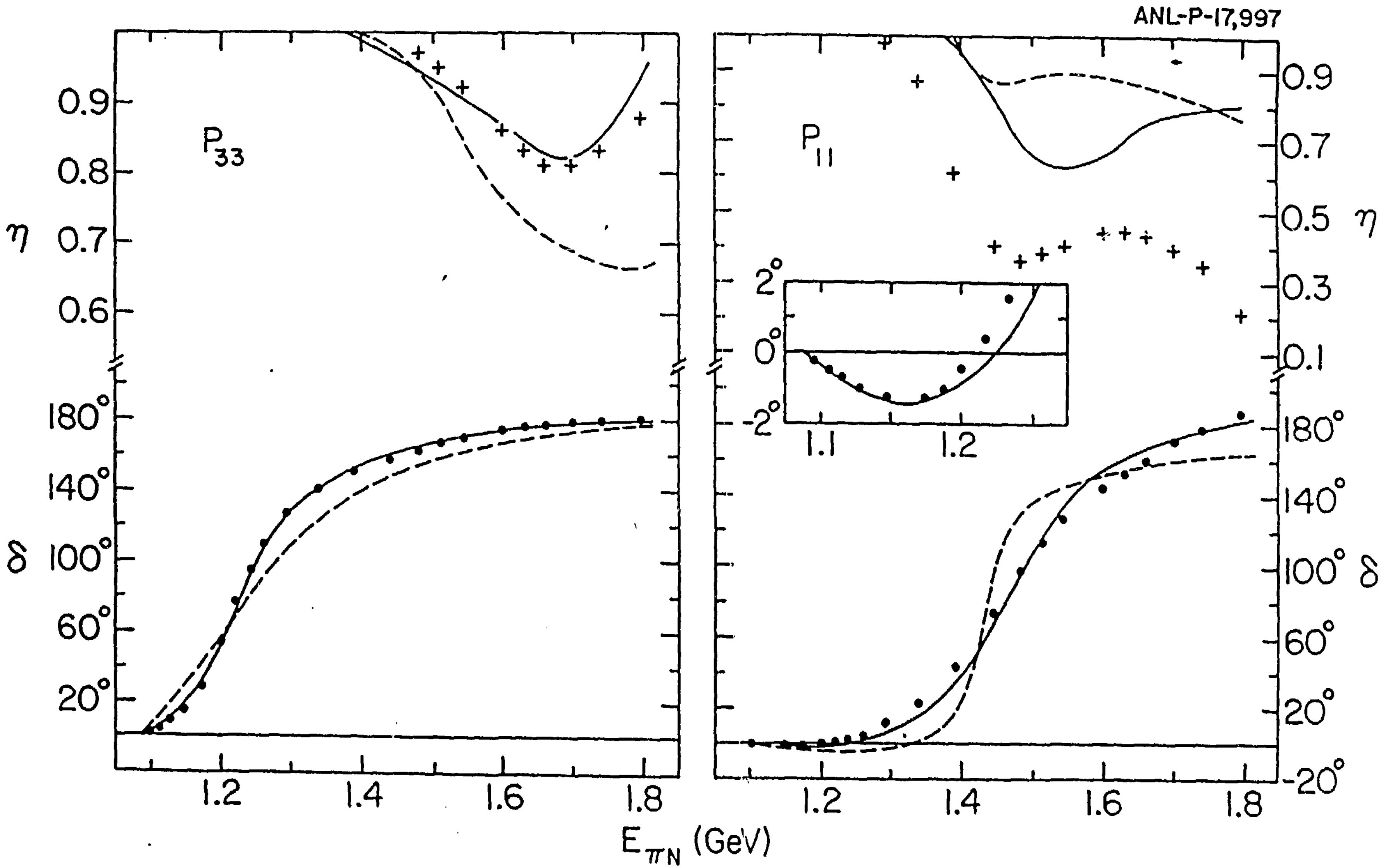
ANL-P-17,997
P33
P11
η
δ
0.9
0.8
0.7
0.6
180°
140°
100°
60°
20°
0.5
0.3
0.1
-20°
2°
0°
-2°
1.1
1.2
1.4
1.6
1.8
E πN (GeV)

Fig. 1

PIONIC INTERACTIONS

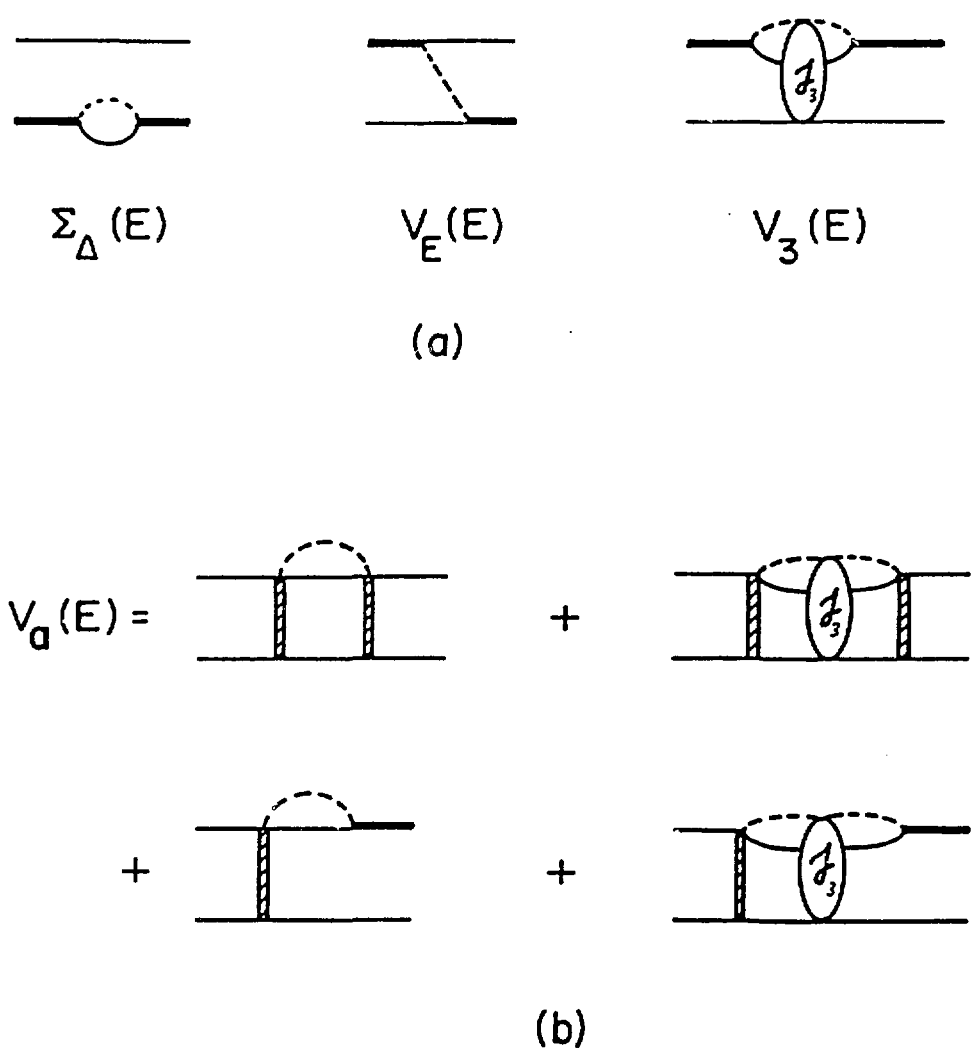

Fig. 2

DIBARYONIC EXCITATION THROUGH NΔ STATE

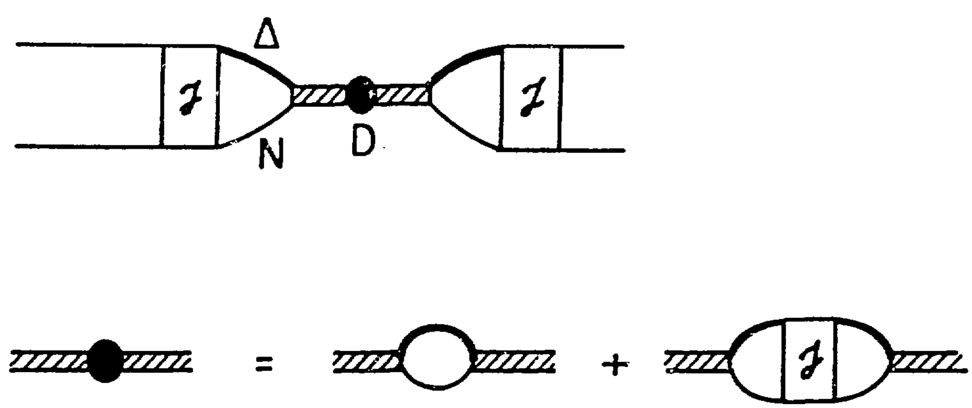

Fig. 3

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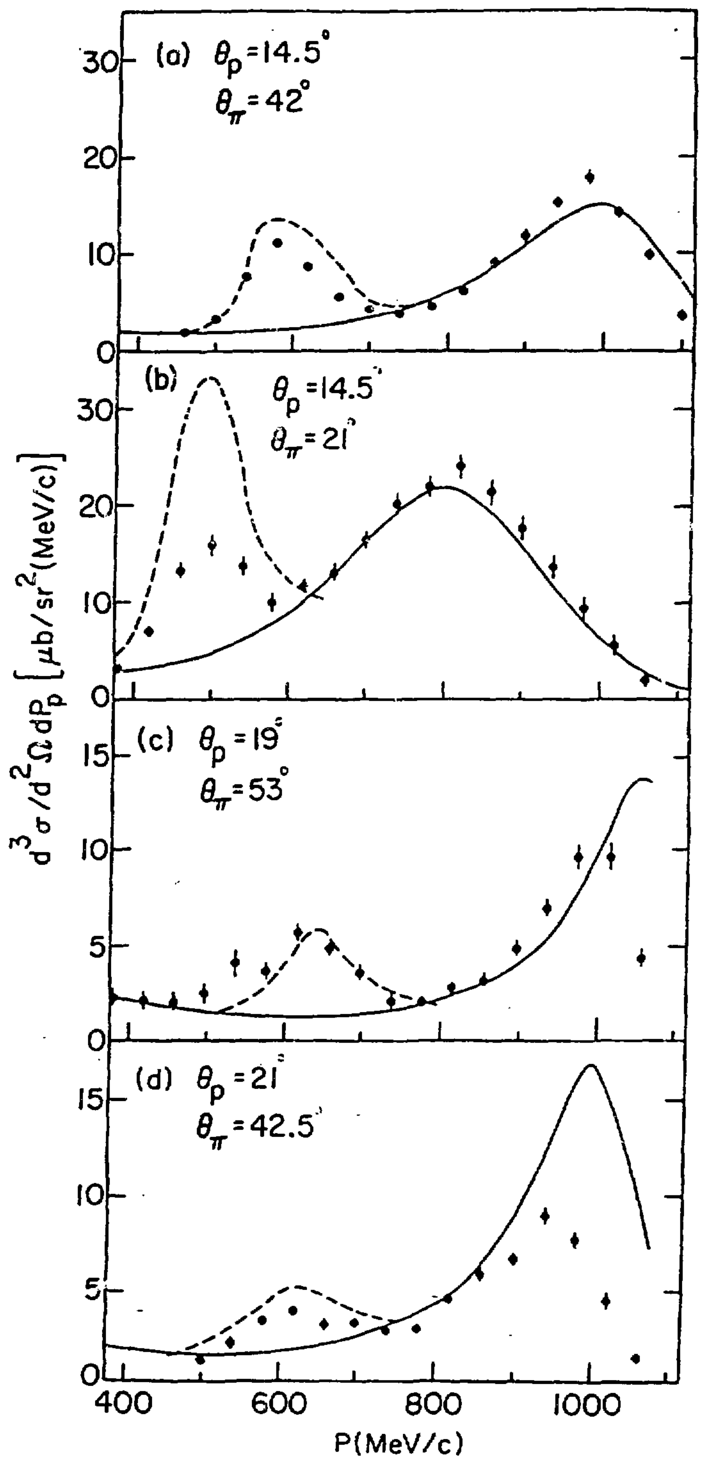

Fig. 4

ANL-P-17,046

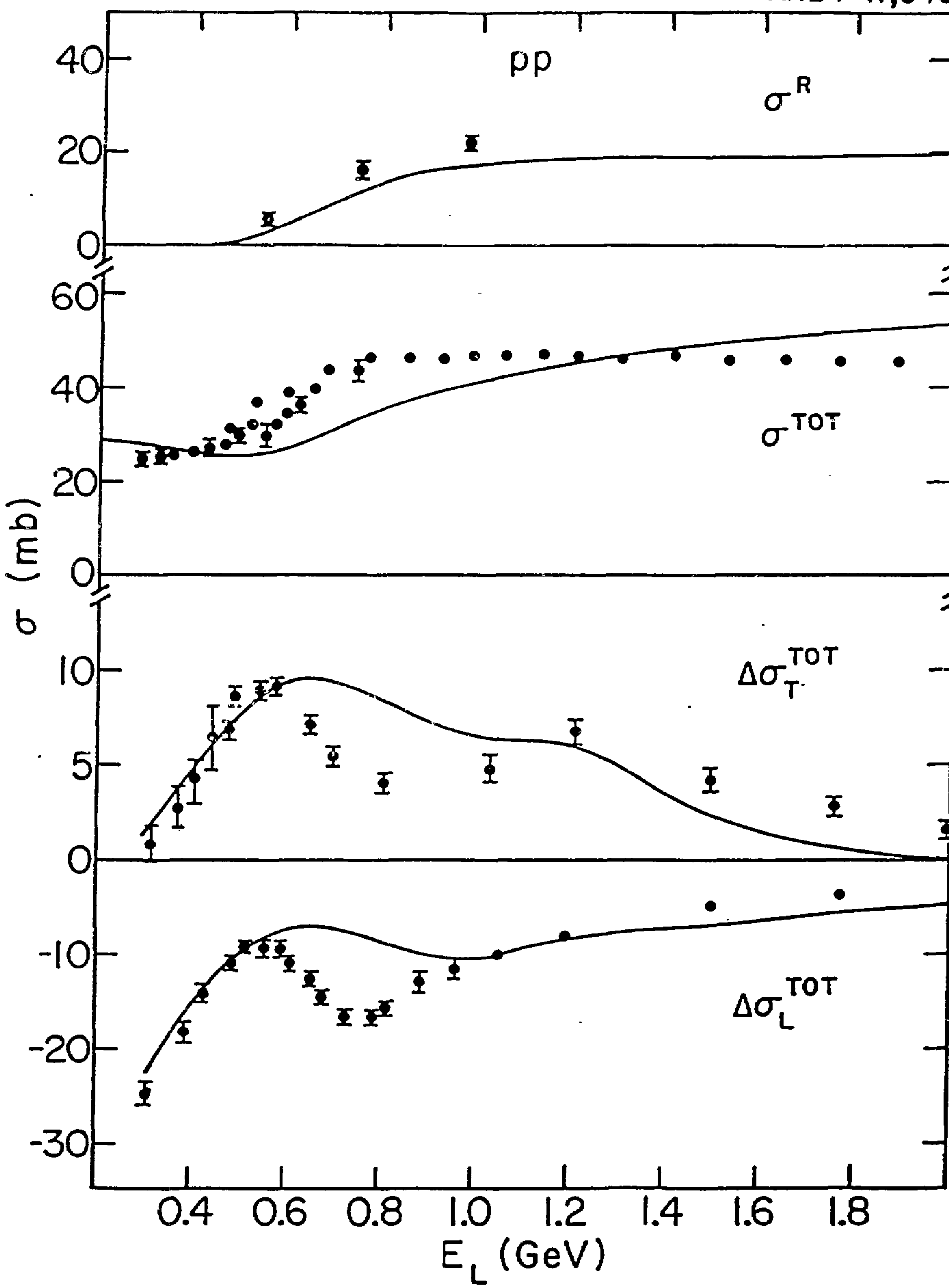

Fig. 5

ANL-P-17,583

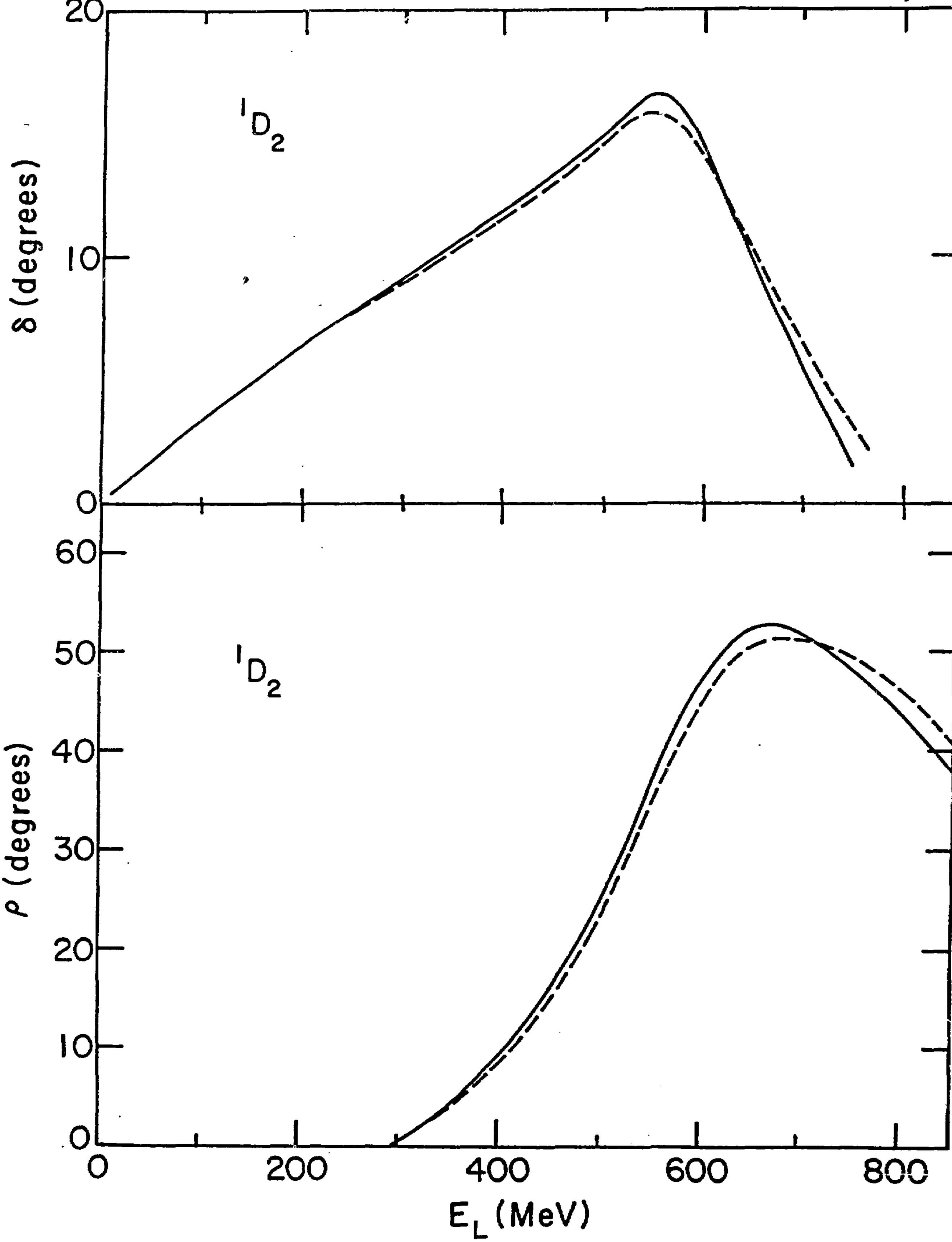

Fig. 6

ANL-P-17,584

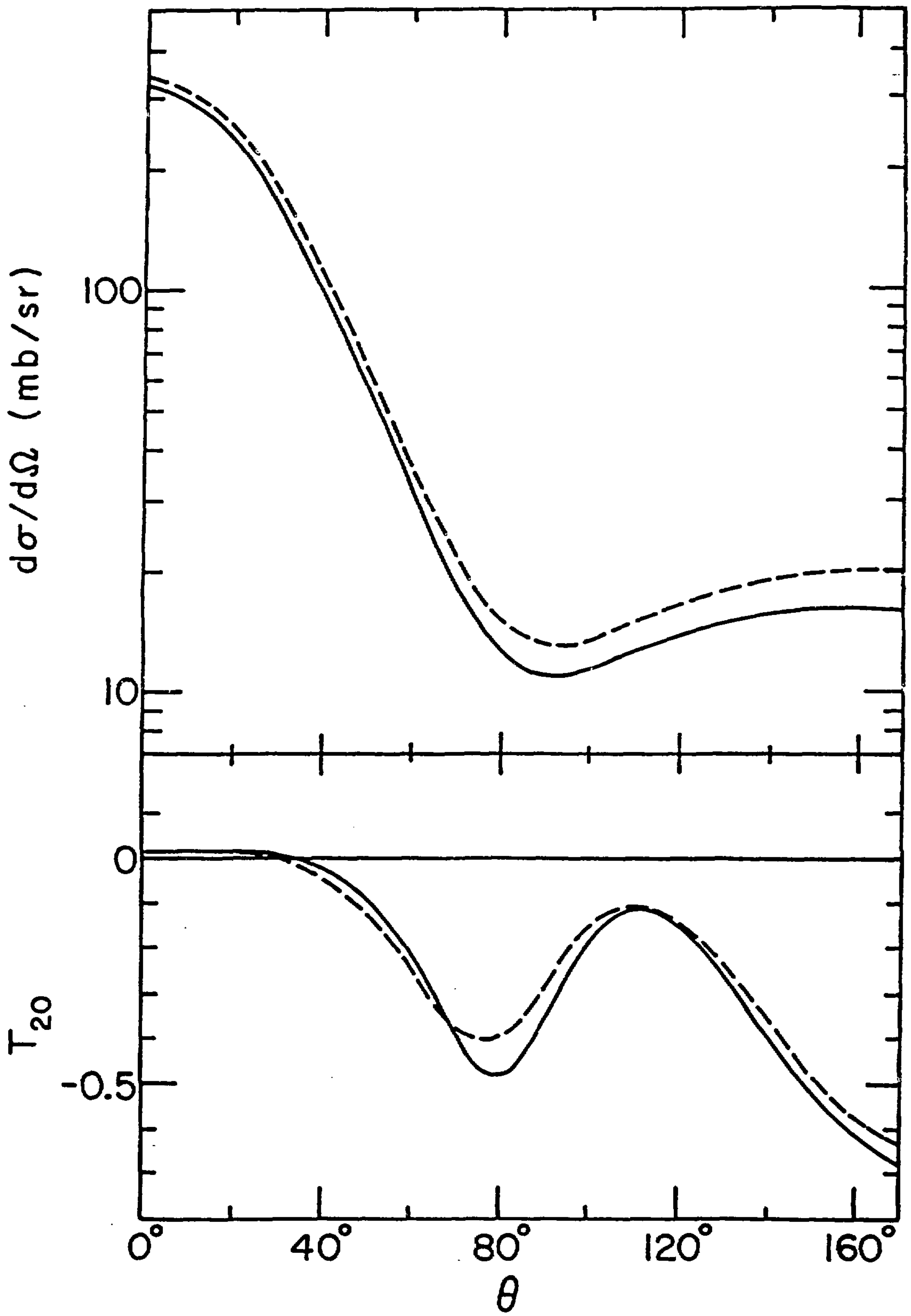

Fig. 7

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