the Landau and Lifshitz (Ref. 2) time which varies continuously as one traverses the spatial surface is resolved when one notes that theirs is the time of a nonrotating observer of the rotating spatial surface.

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Dynamics of *N-N* Total Cross Sections at Medium Energies

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We show that a relativistic, one-pion-exchange, three-body theory including the (3,3) isobar and full spin dependence adequately describes the inelastic nucleon-nucleon cross section at energies where only single-pion production is important. Unitarization of the amplitude plays a significant role in obtaining the correct energy dependence. To fit elastic cross sections, however, will require inclusion of short-range potentials.

There is a surprisingly rich dependence on energy and spin in nucleon-nucleon total cross sections around 1 GeV.[1] At least in part this reflects the copious single-pion production at these energies. Therefore, any dynamical description of the nucleon-nucleon interaction in this region must provide for unitary coupling of the elastic and inelastic channels. Fortunately, multiple-pion production is strongly suppressed up to 2 GeV. Thus, what is required is a relativistic three-body dynamical formalism capable of describing particle production.

Most theoretical attempts to incorporate inelastic processes in this energy range have invoked the isobar model for pion production, $NN \to N\Delta$, followed by $\Delta \to N\pi$, with the isobar production amplitude being calculated in what is basically the one-pion-exchange (OPE) Born approximation.[2] Although the Born approximation cannot be expected to reproduce the interesting experimental energy dependence and cannot be trusted without unitarization, nonetheless OPE is expected to be the principal dynamical mechanism for pion production.

We have calculated the coupled $NN \to N\Delta$ and $NN \to NN$ amplitudes in a relativistic OPE model which respects two- and three-body unitarity. The model includes some of the two-pion-exchange contributions, usually referred to as "box diagrams." Our main conclusions are these:

(1) The spin-averaged inelastic cross section, $\sigma_{\rm inel}$, is quite closely given by the OPE model, which basically has no free parameters. To our knowledge, this is the first time the energy dependence of $\sigma_{\rm inel}$ has been correctly predicted in any model.

(2) The spin-averaged total elastic cross section, $\sigma_{\rm el}$, is not well reproduced. This is as expected, since the OPE model contains no short-range NN forces (such as those due to ρ or ω exchange). If we make crude estimates we find that $\sigma_{\rm el}$ is quite sensitive to the inclusion of such forces, but $\sigma_{\rm inel}$ is not. This confirms that $\sigma_{\rm inel}$ is largely given by the peripheral OPE forces, as has long been expected.

(3) Some features of the spin-dependent cross

sections can be understood in terms of OPE, but most cannot. Again, inelastic processes are less sensitive to dynamical details than are elastic processes.

To calculate the $NN\rightarrow NN$ and $NN\rightarrow N\Delta$ amplitudes we employ the Aaron-Amado-Young three-body model.[3] Details will be presented elsewhere. Briefly, we solve the three-particle Blankenbecler-Sugar (BbS) integral equations[4] depicted in Fig. 1, assuming separable two-body interactions. Going to the LSJ partial-wave representation reduces these to tractable one-dimensional equations.

The initial state consists of a bare nucleon N and an interacting pion and nucleon which constitute a P_{11} (πN) bound state N'. At the end of the calculation we antisymmetrize our partial-wave amplitudes between N and N'. The only two-body interactions in our model are the P_{11} and P_{33} pion-nucleon interactions. In the P_{11} case, we require a bound-state pole at the mass of the nucleon. The P_{33} is fitted to the experimental (3, 3) phase shift. We do not fit the P_{11} phase shift. To keep the number of coupled channels tractable, we have not (at this stage of development) included a pion-deuteron channel. This may be justified in that the $NN\rightarrow d\pi$ cross section at these energies is small compared with the unbound $NN\rightarrow NN\pi$ cross section.

The Born terms and Green's functions needed are chosen in the BbS prescription so as to satisfy two- and three-body unitarity.[3] The Born term, $B_{\rm BbS}$, however, can also have any arbitrary left-hand-cut contribution added to it without destroying the unitarity cut structure. This freedom is essential to permit the introduction of "forces" not already contained in our treatment. For example, $B_{\rm BbS}$ does not even include

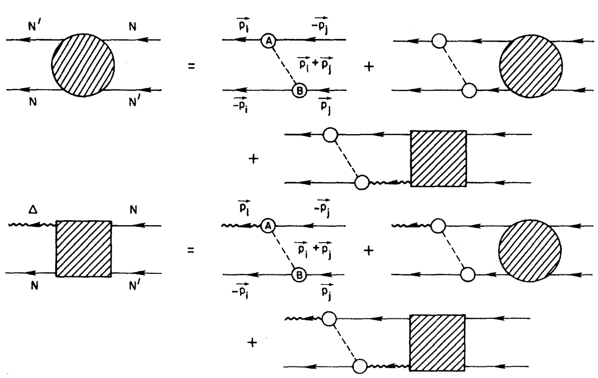

FIG. 1. Schematic representation of the coupled-channel Blankenbecler-Sugar integral equations.

all of the usual OPE force. If the static, on-shell limit of $B_{\rm BbS}$ is taken, one finds an OPE potential which has half the desired residue at the pion-exchange pole. Restriction to three particles allows only one of the two possible time orderings for the pion propagator. To have an OPE potential of full strength, then, we use a Born term which consists of $B_{\rm BbS}$ plus a *static* OPE term of half the usual strength.

The integral equations form a 6×6-channel problem when all spin complications are taken into account. They have been solved in the partial-wave representation by iteration and use of a Padé-approximant technique.[5] The elastic and total cross sections are then obtained from the imaginary parts and squared magnitudes of the partial-wave amplitudes in the usual way.

Results for $\sigma_{\rm inel}$, $\sigma_{\rm el}$, and $\sigma_{\rm tot}=\sigma_{\rm el}+\sigma_{\rm inel}$ are shown in Fig. 2(a), along with representative experimental data.[6] As discussed above, $\sigma_{\rm inel}$ is in good agreement with the data, but $\sigma_{\rm tot}$, because of $\sigma_{\rm el}$, is not. We emphasize that the effect of unitarization on $\sigma_{\rm inel}$ is large. For example, the Born-approximation calculation (with form factors) of Epstein and Riska[7] gives a cross section for $NN\rightarrow N\Delta$ that is 35 mb at 1 GeV and which drops to less than 20 mb by 2 GeV. In contrast, our $\sigma_{\rm inel}$ is flat over this energy range.

Recent experiments have measured two differences of spin-dependent proton-proton total cross sections, namely, $\Delta\sigma_T=\sigma(\uparrow\downarrow)-\sigma(\uparrow\uparrow)$ for spin alignment transverse to the beam,[8] and $\Delta\sigma_L=\sigma(\rightleftarrows)-\sigma(\rightrightarrows)$ for longitudinal alignment.[9] Experimentally, $\Delta\sigma_T$ is positive, as one might expect from dominance of inelasticity in the $^1D_2$ wave corresponding to a relative s wave between the final N and Δ.[7,10] Our OPE model predictions for $\Delta\sigma_T$ and $\Delta\sigma_L$ are compared with experiment in Figs. 2(b) and 2(c). The inelastic contributions to both are positive because of dominant $^1D_2$ production, but $^3P_1$ and $^3F_3$ production ($N\Delta$ in p wave) reduces the inelastic contribution to $\Delta\sigma_L$ considerably. For $\Delta\sigma_T$ the elastic contribution involves a near cancellation between $^1D_2$ and $^3P_2$ scattering, giving the rapid rise near 500 MeV. For $\Delta\sigma_L$ the elastic contribution is much more negative (the $^3P_2$ scattering is surprisingly large). Thus there is a strong cancellation between elastic and inelastic contributions which drives $\Delta\sigma_L$ negative at energies above 900 MeV. The agreement with experiment for either $\Delta\sigma_T$ or $\Delta\sigma_L$ is not very good.

The most important thing left out of our three-body model at this stage of development are the

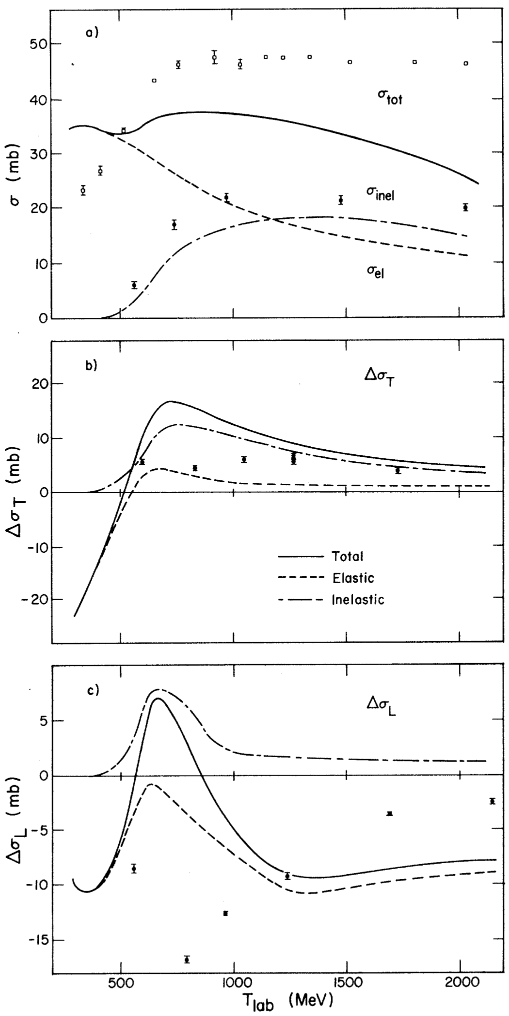

FIG. 2. Predictions of the three-body OPE model compared with experiment (Refs. 6, 8, and 9). (a) Spin-averaged proton-proton total cross sections. (b) Transverse spin-dependent total-cross-section difference, $\Delta\sigma_T$. (c) Longitudinal difference, $\Delta\sigma_L$.

short-range nuclear forces known to be necessary for understanding the nucleon-nucleon phase at lower energies.[11] We are in the process of including static ρ- and ω-exchange potentials in the model (in such a way as not to upset the three-body unitarity requirement). For present purposes, however, we can make a crude estimate of the sensitivity to such forces by including a static heavy-boson–exchange potential in the Born term with the same spin structure as OPE. The coupling constant and range for this new term can be fitted in each partial wave to reproduce (as well as possible) the low-energy pp phases up to 200 MeV. Table I compares, at 800 MeV, the various partial-wave contributions

TABLE I. Contributions (in millibarns) to the elastic and inelastic components of $\sigma_{\rm tot}$, $\Delta\sigma_T$, and $\Delta\sigma_L$ at 800 MeV from various partial waves. Columns labeled A are from our OPE model. Columns B have included short-range forces in the driving Born term with parameters fitted separately for each partial wave so as to reproduce the known low-energy N-N phases.

		Elastic		Inelastic	
	J^P	A	B	A	B
$\sigma_{\rm tot}$	0^+	1.7	2.6	0.0	0.0
	2^+	4.4	4.8	6.5	6.5
	1^-	0.3	6.5	1.3	1.4
	3^-	0.2	0.3	3.1	3.1
	0^-	0.8	2.6	0.0	0.0
	2^-	15.8	12.2	1.2	1.2
	Others	1.0	0.8	1.1	1.1
	Total	24.2	29.8	13.2	13.3
$\Delta\sigma_T$	0^+	3.4	5.2	0.1	0.1
	2^+	8.9	9.5	13.0	13.1
	0^-	−1.6	−5.2	−0.1	−0.0
	2^-	−7.9	−5.9	−1.8	−1.7
	Others	0.5	0.5	1.0	0.9
	Total	3.3	4.1	12.2	12.4
$\Delta\sigma_L$	0^+	3.4	5.2	0.1	0.1
	2^+	8.9	9.5	13.0	13.1
	1^-	−0.5	−12.9	−2.5	−2.7
	3^-	−0.5	−0.5	−6.2	−6.2
	0^-	1.6	5.2	0.1	0.2
	2^-	−15.9	−12.5	0.8	1.0
	Others	−0.8	−0.7	0.7	0.7
	Total	−3.8	−6.7	6.0	6.2

to $\sigma_{\rm el}$, $\sigma_{\rm inel}$, $\Delta\sigma_T$, and $\Delta\sigma_L$ for our standard model (A) and this modification (B). The elastic contributions in the low partial waves are quite sensitive to these short-range forces. It is encouraging that the changes generally go in the direction of reducing the disagreements with experiment. On the other hand, the inelastic contributions are remarkably unaffected. This shows the peripheral nature of pion production in this energy region.

To close, we comment on a suggestion of Hidaka *et al.* that the structure in $\Delta\sigma_L$ near 800 MeV might be due to a ${}^3F_3$ dibaryon resonance.[12] As can be seen from Table I, the $J^P = 3^-$ contribution to $\Delta\sigma_L$ is important but not big enough by itself to account for the dip. Moreover, its contribution is not much affected by short-range forces. Nonetheless, we have plotted our ${}^3F_3$ partial wave on an Argand diagram. It shows a distinct counterclockwise looping with greatest speed at 900 MeV. Similar loops exist for the

$^3P_1$ and $^1D_2$ amplitudes. This behavior, already present in the "box diagram," is clearly due to the opening of inelastic channels. We do not wish to enter the controversy about whether these should be called resonances.[13]

In conclusion, we have shown that, using OPE forces and the isobar model, a relativistic unitary theory of N-N scattering and single pion production at intermediate energies can adequately describe the inelastic cross section. To fit the elastic data, however, will require more detailed dynamics. Combining this three-body theory with what is known from one-boson–exchange potentials at lower energies should permit the extension of our understanding of nucleon-nucleon dynamics into this region. In particular, the spin-dependent cross sections around 1 GeV promise to be a very interesting testing ground for any model.

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Coherent Dissociation of Neutrons on Nuclei at 100 – 300 GeV/c

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We have studied the coherent dissociation of neutrons into $p\pi^-$ systems, for a variety of nuclear targets, at incident momenta up to 300 GeV/c. Using a model incorporating both electromagnetic and hadronic production, we have extracted total cross sections for scattering of unstable $p\pi^-$ systems on nucleons.

We have studied the dissociation of neutrons into $p\pi^-$ systems on the nuclear targets Be, C, Al, Ti, Cu, Ag, Ta, and Pb, for neutron momenta in the range 100–300 GeV/c. These measurements differ from those we made using a hydrogen target[1,2] in that no total-absorption calorimeter was present at the downstream end of the apparatus, and the use of a solid target precluded any measurement of the recoiling nucleus. Similar studies of neutron and proton dissociation at lower