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NN single pion production cross sections below 1500 MeV

B. J. VerWest
Physics Department, Texas A&M University, College Station, Texas 77843

R. A. Arndt
Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
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The isospin reaction cross sections for NN single pion production are extracted from data for the processes $NN\rightarrow\pi d$ and $NN\rightarrow NN\pi$. New data in conjunction with older existing data have precisely determined the components of the cross sections for the isospin one (pp) initial state. Other new data for the np initial state and correct treatment of some older data indicate that the isospin zero reaction cross section is essentially zero below 1000 MeV, which indicates against the presence of inelastic isospin zero NN resonances.

[NUCLEAR REACTIONS Nucleon-nucleon scattering, π production reaction cross sections, isospin decomposition, isospin cross sections deduced from data.]

I. INTRODUCTION

Precise knowledge of the reaction cross sections for NN single pion production is necessary as input to the NN amplitude analyses above the pion production threshold and as tests for models of NN pion production. Unfortunately, until now the data for these cross sections have been sparse and in one notable case inconsistent. Attempts to analyze these data in terms of isospin components go back nearly thirty years[1]; but it is only now with the appearance of important new data that one gets a precise determination of the $I=1$ components up to 1500 MeV and a fairly clear picture of the $I=0$ component. The results will be significant in constraining the NN inelasticities in amplitude analyses for $I=1$ and $I=0$, and make strong indications against the presence of $I=0$ inelastic NN resonances.

In Sec. II of this paper the isospin decomposition of the reaction cross sections will be presented, along with the forms which will be used to represent the cross sections as a function of the total energy of the system. These forms are motivated by the dynamics underlying the reaction in order to obtain forms which represent the data over a wide energy range with very few parameters. In Sec. III the data used in the analysis will be discussed along with the results and in Sec. IV the implications on the dynamics and other problems are discussed.

II. ISOSPIN REACTION CROSS SECTIONS

The reaction cross sections for pion production can be reduced to four independent cross sections. These represent the transition from a state of initial isospin I of the two nucleons to a final state isospin I' of two nucleons coupled to isospin one for the pion to give a total final isospin I.[1] Each of these isospin cross sections varies independently with energy and the various charge channels are related to these cross sections as shown in Table I. The Coulomb interaction will break this isospin symmetry to some extent, but the limit to which this occurs can now be checked by direct comparison to the data and is less than the accuracy of the data except for the obvious differences in the thresholds. At energies above the threshold by about 75 MeV, the data are not sufficiently precise to distinguish the Coulomb isospin symmetry violation. In order to fit the cross sections over a wide range of energies with a small number of parameters it is necessary to choose physically reasonable functional forms to represent them. The single most important feature in the data at these energies is the domination of the P_{33} πN resonance (Δ) as a substate of the πNN final state.

In the πd final state the kinematics of the quasi-

TABLE I. Isospin decomposition of reaction cross sections.

Reaction	Reaction cross section in terms of $\sigma_{II'}$
$pp \to d\pi^+$	σ_{10}^d
$pp \to pp\pi^0$	σ_{11}
$pp \to pn\pi^+$	$\sigma_{10}+\sigma_{11}$
$np \to d\pi^0$	$(\frac{1}{2})\sigma_{10}^d$
$np \to np\pi^0$	$(\frac{1}{2})[\sigma_{10}+\sigma_{01}]$
$np \to nn\pi^+$	$(\frac{1}{2})[\sigma_{11}+\sigma_{01}]$
$np \to pp\pi^-$	$(\frac{1}{2})[\sigma_{11}+\sigma_{01}]$
$pp \to$ inelastic	$\sigma_{10}^d+\sigma_{10}+2\sigma_{11}=\sigma_{I=1}=\sigma_{\text{inel}}^{pp}$
$np \to$ inelastic	$(\frac{1}{2})[\sigma_{10}^d+\sigma_{10}+2\sigma_{11}+3\sigma_{01}]$ $=(\frac{1}{2})[\sigma_{I=1}+\sigma_{I=0}]=\sigma_{\text{inel}}^{np}$ where $\sigma_{I=0}=3\sigma_{01}$.

two-body $N\Delta$ state are severly restricted. The cross section for σ_{10}^d will be parametrized by

$$\sigma_{10}^d(s)=\frac{\pi(\hbar c)^2}{2p^2}\alpha\left[\frac{p_r}{p_0}\right]^\beta \times\frac{m_0{}^2\Gamma^2}{(s_{\pi N}-m_0{}^2)^2+m_0{}^2\Gamma^2}\,, \quad (1)$$

where

$$p^2=s/4-m_N{}^2,\ \ s=4m_N{}^2+2m_NT_L\ ,$$
$$s_{\pi N}=(\sqrt{s}-m_N)^2\ ,$$
$$p_r{}^2(s)=\frac{[s-(m_d-m_\pi)^2][s-(m_d+m_\pi)^2]}{4s}\ ,$$
$$p_0{}^2=s_0/4-m_N{}^2,\ \ s_0=(m_N+m_0)^2\ ,$$

and T_L is the laboratory kinetic energy of the incident nucleon. We will use the values $m_\pi=138.0$ MeV, $m_N=938.9$ MeV, and $m_d=2m_N$ in these calculations. This form crudely incorporates the effective πN resonant subsystem with parameters m_0 and Γ, and leaves as additional parameters the normalization α and the πd threshold power β. To avoid problems with the interpretation and representation of data in the region very close to threshold (where Coulomb differences will be significant) we will only consider data above about 350 MeV.

The three-body final states for $I=1$ present more of a problem since above the required energy to form the $N\Delta$ system, the extra variables intrinsic to the three-body problem will always permit the formation of a Δ in some region of phase space no matter how high the energy is. Thus the forms for the $NN\to NN\pi$ cross sections must reflect this basic difference compared to those for two-body final states. To approximate this difference we will use an effective Δ mass which is a function of the total energy and reflects this extra degree of freedom. The form used is

$$\langle M(s)\rangle=\frac{1}{N}\int_{m_N+m_\pi}^{\sqrt{s}-m_N} dM\,\sigma(M)M\ , \quad (2)$$

where

$$N=\int_{m_N+m_\pi}^{\sqrt{s}-m_N} dM\,\sigma(M) \quad (3)$$

and

$$\sigma(M)=\frac{1}{\pi}\frac{\Gamma_0/2}{(\Gamma_0/2)^2+(M-M_0)^2}\ . \quad (4)$$

$\langle M(s)\rangle$ is a weighted mean over the energies available to the πN subsystem. This integral can be solved analytically to give

$$\langle M(s)\rangle=M_0+(\arctan Z_+-\arctan Z_-)^{-1} \times(\Gamma_0/4)\ln\left[\frac{1+Z_+{}^2}{1+Z_-{}^2}\right]\,, \quad (5)$$

where

$$Z_+=(\sqrt{s}-m_N-M_0)(2/\Gamma_0)\ ,$$
$$Z_-=(m_N+m_\pi-M_0)(2/\Gamma_0)\ . \quad (6)$$

This function has the value m_N+m_π at $\sqrt{s}=2m_N+m_\pi$ and increases rapidly to approximately M_0 for $\sqrt{s}\gtrsim m_N+M_0$ after which it increases very slowly. For the isospin one initial state cross sections we will use the values $M_0=1220$ MeV and $\Gamma_0=120$ MeV (see Fig. 1). The exact values are not critical since other parameters which are varied would compensate for any variations in M_0 and Γ_0. When this mass, $\langle M\rangle$, is used as the effective πN energy in a Breit-Wigner cross section form, the cross section will rise as $\sqrt{s}$ approaches M_0+m_N and then remain roughly constant. Thus we will parametrize the σ_{10} and σ_{11} cross sections by

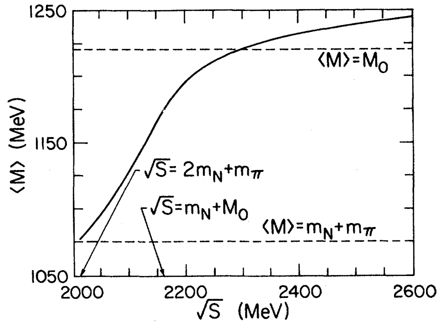

FIG. 1. The effective isobar mass $\langle M \rangle$ as a function of the total *NN* energy $\sqrt{s}$ for $M_0=1220$ MeV and $\Gamma_0=120$ MeV.

$$\sigma_{II'}(s)=\frac{\pi(\hbar c)^2}{2p^2}\alpha\left[\frac{p_r}{p_0}\right]^{\beta}\times\frac{m_0{}^2\Gamma^2(q/q_0)^3}{(s^*-m_0{}^2)^2+m_0{}^2\Gamma^2}\,, \qquad (7)$$

where $s^*=\langle M\rangle^2$,

$$p_r{}^2(s)=\frac{[s-(m_N-\langle M\rangle)^2][s-(m_N+\langle M\rangle)^2]}{4s}\,,$$

$$q^2(s^*)=\frac{[s^*-(m_N-m_\pi)^2][s^*-(m_N+m_\pi)^2]}{4s^*}\,,$$

$$q_0=q(m_0{}^2)\,.$$

For the isospin 0 cross section, the first resonance that can influence the cross section is the P_{11} (1430) with width of 200 MeV. Thus a similar form is used for σ_{01} except that the values $M_0=1430$ MeV and $\Gamma_0=200$ MeV are used to calculate $\langle M\rangle$. Thus one has four parameters α, β, m_0, and Γ for each of the four isospin cross sections.

III. DATA AND RESULTS

The majority of the data used for this analysis came from the compilation by Bystricky and Lehar.[2] However, there are several data sets which require special attention. First, all of the large sets of data from Dubna (*D*-18, *N*-7, and *D*-32) were taken as measurements relative to one absolute cross section with an associated absolute uncertainty. Hence these sets of data have been treated as relative data with overall normalization uncertainties of 5%, 10%, and ∞ (floated). The last set (*D*-32) was floated since there has been some question about this data set and because of possible problems in establishing its normalization uncertainty in light of the quasielastic extraction of the data. In the end though, these data will only be renormalized by 6% in the fitting procedure. Another problem is that all of the data that we have listed as $np\to np\pi^0+d\pi^0$ in Table II have been listed as just $np\to np\pi^0$ in Ref. 2 and used that way in several other calculations. This has lead to the claim of a large violation of isospin invariance in these cross sections.[3] The wording of the title of reference *D*-32 indicated that the data were $pn\to pn\pi^0$ measurements but it was common at that time to refer to "nucleons" in the final state whether they were unbound or bound into a deuteron (see Ref. 1). Careful reading of the paper, the way the data were used in their isospin analysis and the fact that the data were taken quasielastically indicate that the data were definitely $pn\to pn\pi^0+d\pi^0$ measurements. Checking the other references for the $np\to np\pi^0+d\pi^0$ data one finds that this is the correct assignment of all of these data points. By correctly treating these data, we remove the isospin contradiction and can qualitatively fit them with only a 6% renormalization. The data are still not of high quality and it would be nice to have more, but the only practical experiment would be $np\to\pi^0X$ with monoenergetic neutrons and a π^0 spectrometer at one of the meson laboratories. In this experiment the $d\pi^0$ final state can be distinguished from the $np\pi^0$ final state.

The situation in $I=1$ has been helped considerably by the appearance of new data over a wide energy range from the National Laboratory for High Energy Physics, Japan (KEK).[4] These data have established the normalization of the old Dubna data, and with the older data give very restrictive predictions for the three $I=1$ isospin cross sections. Thus the $I=1$ cross sections were fit first and the parameters for the $\sigma_{II'}$ are given in Table III. The normalization of the two relative sets of data are indicated in their entries in Table II and are of the same order as their normalization uncertainties. The data and the fits for the various *pp* charge channels are shown in Figs. 2, 3, and 6 and the isospin cross sections $\sigma_{1I'}$ are shown in Fig. 7. Also shown on Fig. 6 are the total *pp* reaction cross sections $\sigma_{\text{inel}}=\sigma_{\text{tot}}-\sigma_{\text{el}}$ from Ref. 4. The difference between these data and our curve for $\sigma_{\text{inel}}^{pp}$ shows clearly the onset of 2π production at about 1000 MeV. The consistancy of the entire collection of *pp* data and the forms used is indicated by the final χ^2/datum of 1.4.

Since the three $I=1$ $\sigma_{II'}$ are determined by *pp*

TABLE II. Data used in the analysis. The references indicated by a letter and number refer to the references in the Physics Data compilation (Ref. 2). Those given by number only are references in this paper.

Number of points	Energy	Reference	Comments	Number of points	Energy	Reference	Comments
$pp \to d\pi^+$							
3	346–413	*D*-57		5	570–810	*R*-28	
2	363–409	*S*-57		1	575	*C*-80	
1	380	*H*-10		5	634–900	*N*-21	
1	381	*B*-40		1	650	*G*-10	
2	398–455	*A*-132		1	657	*M*-24	
1	418	*F*-13		1	800	*M*-96	
1	425	*D*-56		1	970	*B*-25	
1	437	*F*-1		1	990	*C*-78	
1	448.4	*P*-14		3	1000–1500	*H*-54	
1	460	*M*-21		1	1481	*E*-6	
1	556	*M*-17		10	433–1261	4	a
1	560	*B*-12					
$pp \to pp\pi^0$							
23	313–665	*D*-18	b	1	657	*S*-7	
5	346–437	*S*-4		1	660	*D*-18	
1	419	*F*-13		1	735	*D*-34	
2	470–670	*K*-16		1	925	*H*-13	
1	560	*B*-12		1	970	*B*-28	
1	560	*M*-17		1	970	*B*-25	
1	650	*G*-10		1	1481	*E*-6	
1	650	*D*-18		10	433–1261	4	a
$pp \to pn\pi^+$							
1	405	*M*-78		1	650	*G*-10	
1	418	*F*-13		1	650	*B*-29	
1	437	*F*-2		1	970	*B*-28	
1	448.4	*P*-14		1	970	*B*-25	
2	460–556	*B*-13		1	1000	*V*-14	
10	485–657	*N*-7	c	1	1481	*E*-6	
1	560	*B*-12		10	433–1261	4	a

data, there remains only one cross section, σ_{01}, to be determined and two checks on isospin symmetry. The first isospin check involves the prediction that the cross section for $np \to d\pi^0$ is half of the cross section for $pp \to d\pi^+$. As can be seen in Fig. 3, there seems to be confirmation of this, at least to the accuracy of the reaction cross section data. This supports our initial assumption that we can make the isospin decomposition for the cross sections. Another check of isospin symmetry comes from the $np \to \pi \pm NN$ experiment at Clinton P. Anderson Meson Physics Facility (LAMPF) (*T*-41) where the differential cross sections for π^+ and π^- production were compared directly at 790 MeV. There it was seen that the isospin prediction that these cross sections are equal, is good to the level of the experiments, and we have used this fact in determining σ_{01}. Some of the experiments for $np \to \pi^{\pm} X$ have involved measuring the cross sections for both charge states and some of the cross section for one or the other. We have assumed they are equal and fit the cross section for $np \to \pi^+ nn + \pi^- pp$ which is $\sigma_{11} + \sigma_{01}$. As can be seen in Table II there has been a recent sudden interest in these reactions which has resulted in data of good accuracy[5–7] and significant increase in our knowledge of this reaction. The results of this fit are shown in Fig. 4 and the results for $np \to np\pi^0 + d\pi^0$ in Fig. 5. Also shown in Fig. 4 is σ_{11} since the difference between this curve and the data indicates the size of the $I = 0$ production cross section. Below 1000 MeV this cross section is consistent with zero except for the possible question of the scatter of points around 600 MeV. The older points, however, seem to be discounted by the energy dependence of the new preliminary results from

TABLE II. (*Continued.*)

Number of points	Energy	Reference	Comments	Number of points	Energy	Reference	Comments
$pp \to$ inelastic							
1	437	*F*-2		1	650	*B*-29	
2	528–940	*E*-7		1	810	*M*-30	
1	600	*K*-18					
$np \to d\pi^0$							
1	400	*S*-1		9	425–705	*B*-90	
$np \to np\pi^0 + d\pi^0$							
17	290–665	8,*D*-32	d,e	1	600	*K*-18	e
1	340	*H*-57	e	1	670	*K*-16	e
1	437	*S*-4	e				
$np \to nn\pi^+$ or $pp\pi^-$							
1	409	*Y*-2		2	1140–1371	*B*-32	
1	585	*D*-21		6	480–578	5	
1	586	*K*-20		3	624–1481	6	f
1	600	*K*-18		9	545–977	7	f
1	790	*T*-41					

Comments:
[a]Preliminary data (private communication).
[b]5% normalization uncertainty—renormalized by 0.9363.
[c]10% normalization uncertainty—renormalized by 1.060.
[d]Floated normalization—renormalized by 0.9425.
[e]These data are listed as np—$np\pi^0$ in Ref. 2 (see text).
[f]Preliminary data (report).

Ref. 7. While these data are preliminary, they do agree very well with the low-energy data of Ref. 5 and the point at 790 MeV from LAMPF. Above 1000 MeV the $I=0$ cross section begins to grow as peripheral production through the P_{11} resonance begins to be important, but the cross section in this region is still poorly determined. The data for $np \to np\pi^0 + d\pi^0$ are shown on Fig. 5 along with the prediction for this reaction and $np \to np\pi^0$. While there is some energy-dependence problem with these data, the qualitative agreement of the data and the predictions indicate that there is probably no large violation of isospin symmetry here either. The past problems have arisen when the data have been associated with the curve for $np \to np\pi^0$ and this leads to an obvious discrepancy. The resulting parameters for σ_{01} are given in Table III and the normalization of the $np \to \pi^0 X$ data in Table II. The prediction for the np total reaction cross section is shown in Fig. 6 and that for σ_{01} is shown in Fig. 7. Some work still needs to be done on the np initial state because of the scatter in the data which leads to a χ^2/datum of about 5. Some of this high χ^2 is due to the disagreement in the $np \to np\pi^0 + d\pi^0$ en-

TABLE III. Isospin cross section parameters.

	σ_{10}^d	σ_{11}	σ_{10}	σ_{01}
α	6.030	3.772	15.28	146.3
β	1.700	1.262	0	0
m_0 (MeV)	1203	1188	1245	1472
Γ (MeV)	134.3	99.02	137.4	26.49

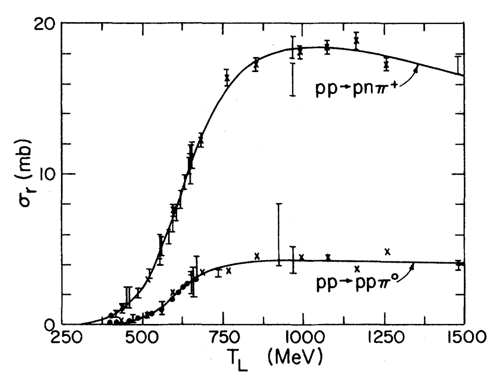

FIG. 2. Reaction cross sections for reactions $pp \to pp\pi^0$ and $pp \to pn\pi^+$. Data are as indicated in Table II with data from Ref. 4 indicated by $\times$.

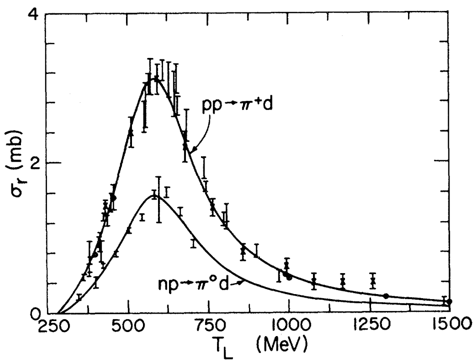

FIG. 3. Cross sections for reactions $pp \to d\pi^+$ and $np \to d\pi^0$. Data indicated as in Fig. 2.

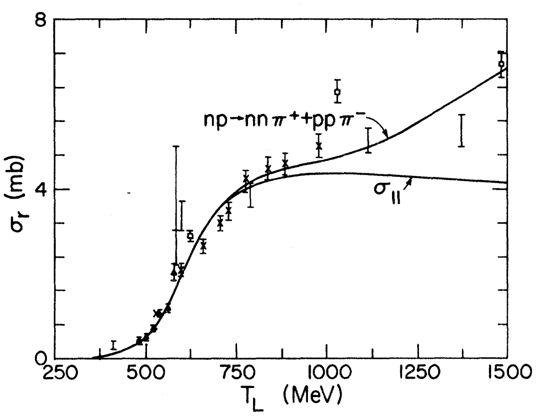

FIG. 4. Reaction cross section for $np \to nn\pi^+ + pp\pi^-$ and isospin cross section σ_{11}. Data are as indicated in Table II with data from Ref. 5 indicated by △ , from Ref. 6 by □, and Ref. 7 by ×.

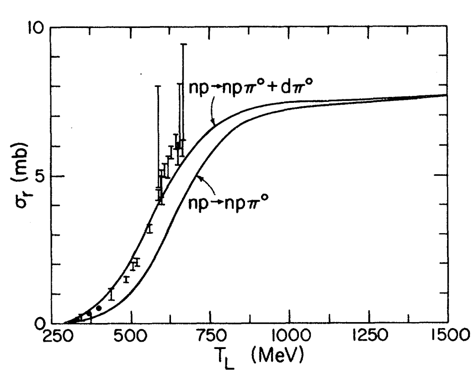

FIG. 5. Reaction cross sections for $np \to np\pi^0 + d\pi^0$ and $np \to np\pi^0$. The data are all for the first reaction as indicated in Table II.

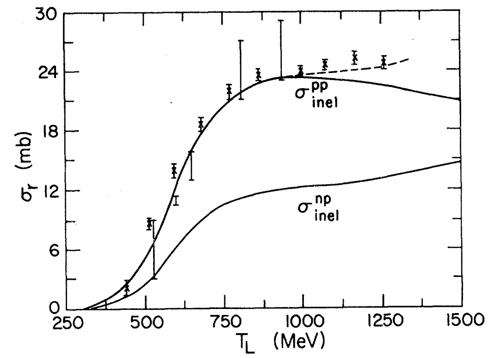

FIG. 6. Total reaction cross sections for single pion production for pp and np scattering. The data are as indicated in Table II except for those indicated by × which were obtained from $\sigma_{\rm tot} - \sigma_{\rm el}$ from Ref. 4. Also the dashed curve indicates the result of adding the cross section for 2π production from Ref. 4 to the single pion production curve.

ergy dependence and some is due to the disagreement of the various $np \to nn\pi^+ + pp\pi^-$ data sets at higher energies.

IV. CONCLUSIONS

The isospin decomposition of the reaction cross sections for single pion production are now well determined by the data for the $I=1$ initial state. This allows one to begin to extract reliably the $I=0$ component of NN single pion production. The best reaction for this is $np \to \pi^{\pm}NN$, and recent data of increasing accuracy indicate that the cross section is essentially zero below 1000 MeV and increases smoothly above that energy with the increasing influence of the P_{11} resonance. This late onset of

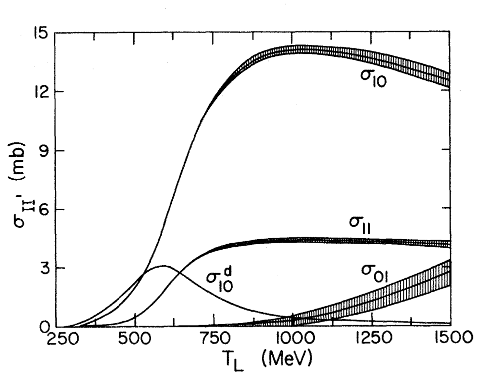

FIG. 7. Isospin reaction cross sections. The shaded areas indicate the relative uncertainties of their determination.

pion production in $I=0$ and its dependence on the presence of a πN resonance strengthens the evidence that pion production occurs mostly peripherally in conjunction with strong πN resonance quasiparticles. Evidently little real pion production occurs out of the NN impulse approximation terms (nonresonant intermediate states). The indications are also that there is probably no strongly inelastic resonance behavior in the NN system for $I=0$ below 1000 MeV ($I=0$ dibaryon resonances) since this must be accompanied by a large reaction cross section. There is still considerable scatter in the $np \rightarrow \pi^{\pm}NN$ data which must be cleaned up, but the results now give a clear indication of the energy dependence of the cross section. Also with the proper treatment of the old $np \rightarrow np\pi^0 + d\pi^0$ quasielastic data there is no large isospin violation. In the NN amplitude analysis efforts one can now reasonably safely set the $I=0$ inelasticities to zero below 1000 MeV. This will eliminate many degrees of freedom in these analyses and lead to better determination of the phases. In the $I=0$ analyses the precise knowledge of σ_{inel} provides a sum constraint on the inelasticities and will help to insure that some of the ambiguities which can occur in phase shift analyses do not occur.

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