Title

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EVIDENCE FOR THE POSSIBLE EXISTENCE OF NEW NARROW INELASTIC PION-NUCLEON RESONANCES IN THE MASS RANGE 1400-1700 MEV*

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ABSTRACT

Starting from an energy-independent phase-shift analysis carried out at 26 momenta between 385 and 1700 MeV/c, we attempt to find the proper energy continuation through these momenta. Our "best" path agrees in general with paths found by other groups. However, there appears to be additional resonance structure in the P31, D35, and P13 partial waves between 1400-1700 MeV.

In a typical energy-independent phase-shift analysis there exist many possible solutions at a given energy. We hope that the tremendous ambiguities which result when each energy is considered separately will be reduced or removed by imposing certain theoretical assumptions on the behavior of each partial-wave amplitude as a function of energy. We assume that each partial-wave amplitude is continuous and maintains a certain amount of "smoothness" when plotted on an Argand diagram. In a previous paper [1] we investigated several path-finding schemes and developed a method that takes into consideration both continuity and the smoothness of each partial wave. In this letter we examine further the "best" path found in ref. 1.

We discuss briefly the methods used in obtaining the energy-independent phase-shift solutions; we review the method used to find the energy continuation; and we examine the properties of our "best" solution.

An energy-independent phase-shift analysis of pion-nucleon scattering was carried out at Berkeley several years ago [2]. Solutions were found at some 26 momenta from 385 to 1700 MeV/c. For completeness we briefly mention the method used to obtain the solutions.

At each of the 26 momenta initial guesses for the parameters $\eta_{I,j,\ell}$ and $\delta_{I,j,\ell}$ are made. Then by use of a variable-metric minimization scheme called ORPHEUS these parameters are varied in an attempt to get a good fit to the data by minimizing χ^2. The data include the π^+,π^- and charge-exchange differential cross sections as well as the π^+ and π^- polarizations. The analysis includes waves through G waves ($\ell = 4$).

The starting values of the η's and δ's for ORPHEUS are obtained by one of three methods. One uses a rather coarse survey conducted with a ravine-following minimization method using starting points chosen randomly in the general vicinity of the solutions published by other groups. A second method is to use the ORPHEUS solutions from the first method at momentum k_{n-1} or k_{n+1} as initial guesses in ORPHEUS at momentum k_n. This method is particularly useful when one is trying to continue to k_n a path that previously stopped at k_{n-1}. The third method consists of simply using solutions obtained by groups at other installations as starting points in ORPHEUS.

At each momentum, solutions with intolerable χ^2 are removed. In the earlier work done at Berkeley multiple solutions at each momentum (i.e., several with all parameters approximately equal) were reduced to one. In this work, however, we have included all solutions that are not exactly equal. We feel it is important when carrying out energy-continuation procedures to have many solutions at each energy. We must require, however, that the χ^2 of each solution remain reasonably good. The χ^2 value alone is not a very good way of deciding which solution at each energy is the right one. For example, an energy continuation made up of the best χ^2 at each energy has very discontinuous and rough behavior and hence is unsatisfactory. On the other hand, a method that imposes smoothness while ignoring χ^2 may give a poor fit to the data. The best method is one that keeps only solutions with reasonable χ^2, but has enough at each energy to allow the smoothing program freedom to find a smooth and continuous path.

The problem is to define a procedure by which a computer can pick out one solution at each energy such that the resultant path is both continuous and smooth when viewed on each Argand diagram. We define a "distance" D_i for the path i as

$$D_i = \sum_{\ell,j,I} \sum_{k=k_{min}}^{k_{max}} d(\ell,j,I,k,i), \tag{1}$$

where a path consists of one solution at each momentum k, and where ℓ is the orbital angular momentum, j the total angular momentum, and I the isospin. The simplest choice for the function $d(\ell,j,I,k,i)$ is the geometric distance between two points on the Argand diagram,

$$d_0(\ell,j,I,k,i) = |\underset{\sim}{T}(\ell,j,I,k,i) - \underset{\sim}{T}(\ell,j,I,k-1,i)|, \tag{2}$$

where $\underset{\sim}{T}$ is the appropriate partial-wave amplitude. The proper energy-continued path is assumed to be that path i_{min} for which the "distance" D_i is a minimum.

The problem with using just the geometric distance [eq. (2)] for d is that although it does incorporate the idea of continuity (i.e., the solution does not change much when the energy is changed slightly), it does not produce paths that are smooth. They are not smooth because the angles may change erratically even though the distance on the Argand diagram from energy to energy changes smoothly. To correct this we define

$$d(\ell,j,I,k,i) = [1/(a + \cos\theta)]\, d_0(\ell,j,I,k,i), \tag{3}$$

where θ is the angle between the vectors

$$\underset{\sim}{A} = \underset{\sim}{T}(\ell,j,I,k-1,i) - \underset{\sim}{T}(\ell,j,I,k-2,i)$$

and

$$\underset{\sim}{B} = \underset{\sim}{T}(\ell,j,I,k,i) - \underset{\sim}{T}(\ell,j,I,k-1,i),$$

and where $d_0(\ell,j,I,k,i)$ is defined in eq. (2) (see Fig. 1a). In ref. 1 we find the best value for a is $a = 1.5$. An example of the effect of including the "smoothing factor" $(1.5 + \cos\theta)^{-1}$ in the definition of d can be seen in Fig. 1. Figure 1b shows the P33 wave for the path found by using $d = d_0$; Fig. 1c shows the same wave for the path found by using the "smoothing factor" [eq. (3)]. In Fig. 2 we exhibit the π^+p and π^-p elastic and inelastic total cross sections as a function of center-of-mass energy W for our "best" path. For a more complete study of the effects of using the "smoothing factor" and the results of using other definitions of the "distance" D see ref. 1.

Our best path agrees in general with the paths found by other groups. However, there appears to be additional resonance-like structure in the P31, D35, and P13 partial waves (see Figs. 3 and 4). Further investigation of this behavior indicates that, in addition to loops in the Argand diagrams, each of the above partial waves has a peak in the partial-wave total, elastic, and inelastic cross sections. Also, each of the loops has a corresponding maximum in the speed, where the speed is defined by

Speed(I,j,ℓ,k) =

$$= \frac{1}{2}\left\{\frac{|\underset{\sim}{T}_{I,j,\ell}(k+1) - \underset{\sim}{T}_{I,j,\ell}(k)|}{E_{k+1} - E_k} + \frac{|\underset{\sim}{T}_{I,j,\ell}(k) - \underset{\sim}{T}_{I,j,\ell}(k-1)|}{E_k - E_{k-1}}\right\} .$$

The loops on the Argand diagrams alone or the peaks in the partial-wave cross sections alone, or the maxima in the speed plots alone would not be compelling evidence for the existence of resonances in these waves. However, the fact that each of these partial waves exhibits all three properties leads us to believe that they may indeed be resonances. A crude estimate of the resonance parameters yields**

Partial wave	Mass (MeV)	Total width Γ (MeV)	$X_e = \Gamma_e/\Gamma$
P31	1630	50	0.17
D35	1660	40	0.07
P13	1480	40	0.12 .

For comparison in Fig. 4 we exhibit the Argand diagram, speed, and partial-wave total cross section, respectively, for the well-established D15 resonance. It is of interest that a narrow $I = \frac{1}{2}$ peak ($\Gamma \approx 50$ MeV) at 1462 MeV has been reported recently in πN invariant-mass plots from $pp \to pN\pi$ at 6.6 GeV/c [3]. The peak is considered to be different from the well-known broad $N(1470)\frac{1}{2}^+$. From our analysis it could well be our P13 resonance.

These tentative new resonances are narrow and mainly inelastic. As noted by other authors [4] all path-finding techniques tend to be biased against narrow resonances. This can on the one hand explain why these resonances have escaped notice until now, and on the other hand lend support for their existence because of their survival of our method's attempts to smooth them away. The χ^2 values of the solutions around these tentative resonances are all reasonably good (i.e., χ^2 per degree of freedom ≈ 1) and hence they cannot be ruled out on the basis of their χ^2 values. It can be argued, however, that more solutions with reasonable χ^2 can be found at each energy, thereby possibly changing our results. This is possible, but the original search for solutions was quite exhaustive and as many as 80 solutions at each energy were found.

In summary, we have applied a path-finding scheme to an energy-independent pion-nucleon phase-shift analysis and found, in addition to the generally accepted resonances, three partial waves apparently possessing previously unseen resonant behavior (i.e., an Argand loop, peaks in both the speed and partial-wave cross sections). Of the three the P31 structure at 1630 MeV is the most convincing.

ACKNOWLEDGMENTS

I am grateful to Professor Herbert Steiner, without whose encouragement this work would never have been accomplished, and to C. H. Johnson for introducing me to this subject. Also, I thank Professor Owen Chamberlain for the generous use of computer time.

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3. Z. Ming Ma and Eugene Colton, Phys. Rev. Letters 26, 333 (1971).
4. See, for example, A. D. Brody, R. J. Cashmore, A. Kernan, D. W. G. S. Leith, B. S. Levi, B. C. Shen, J. P. Berge, D. J. Herndon, R. Longacre, L. R. Price, A. H. Rosenfeld, and P. Söding, A Comparison of the Results of Elastic Scattering Phase-Shift Analyses, UCRL-20223, 1971 (unpublished).

FOOTNOTES

* This work was done under the auspices of the U.S. Atomic Energy Commission.

** For a discussion on how to determine the resonance parameters see, for example, Particle Data Group, πN Partial-Wave Amplitudes, UCRL-20030, 1970 (unpublished).

FIGURE CAPTIONS

Fig. 1. (a) Argand diagram illustrating the vectors $\underset{\sim}{A}$ and $\underset{\sim}{B}$ and the angle Θ used in defining the function $d(\ell,j,I,k,i) = [1/(1.5 + \cos\Theta)]d_0$. (b), (c) Illustration of the effect of including the "smoothing factor" in the definition of d. Notice that the path found (b) by using simply $d = d_0$ has a jagged structure around 1716 MeV, whereas the path found (c) by using the "smoothing factor" no longer exhibits this unwanted behavior.

Fig. 2. Plot of the π^+p and π^-p elastic and inelastic total cross sections versus c.m. energy W for our "best" path.

Fig. 3. The Argand diagram and plots of the speed, partial-wave total, elastic, and inelastic cross sections versus c.m. energy W for the P31 and D35 partial waves obtained from our "best" path. The arrow indicates the position of a possible resonance.

Fig. 4. The Argand diagram and plots of the speed, partial-wave total, elastic, and inelastic cross sections versus c.m. energy W for the P13 and D15 partial waves obtained from our "best" path. The arrow indicates the position of a possible resonance.

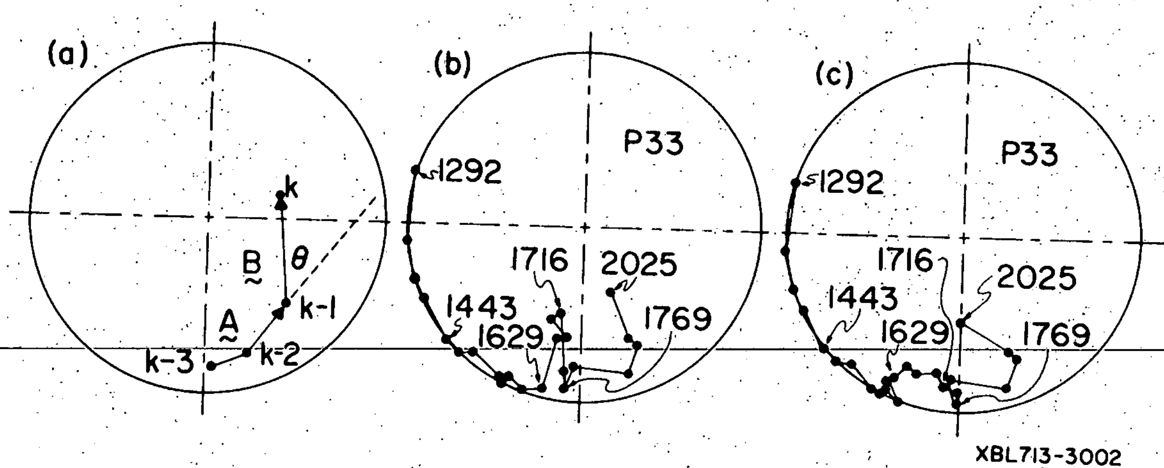

(a)
k
B
θ
A
k-1
k-2
k-3
(b)
P33
1292
1716
2025
1443
1629
1769
(c)
P33
1292
1716
2025
1443
1629
1769
XBL713-3002

Fig. 1.

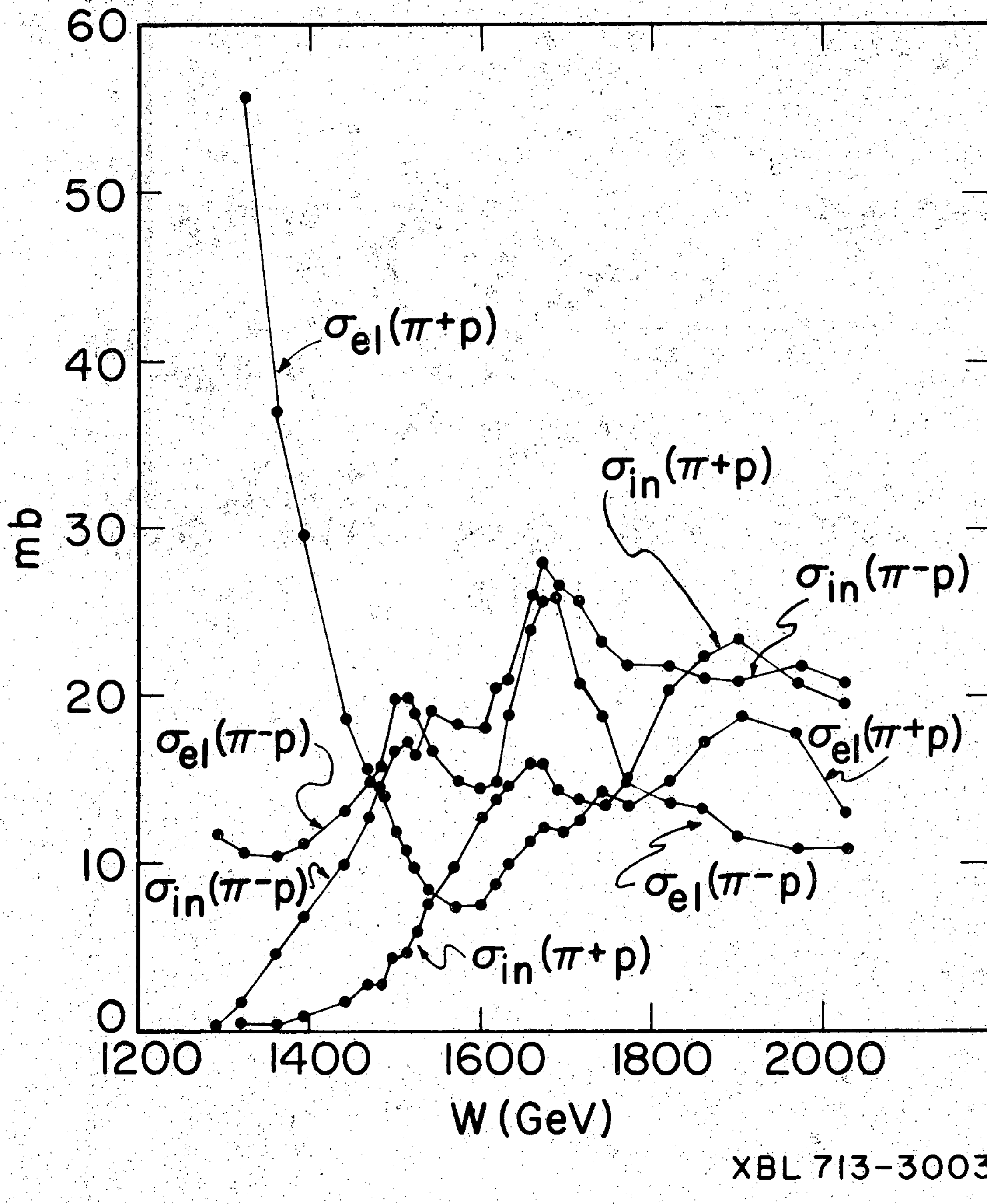
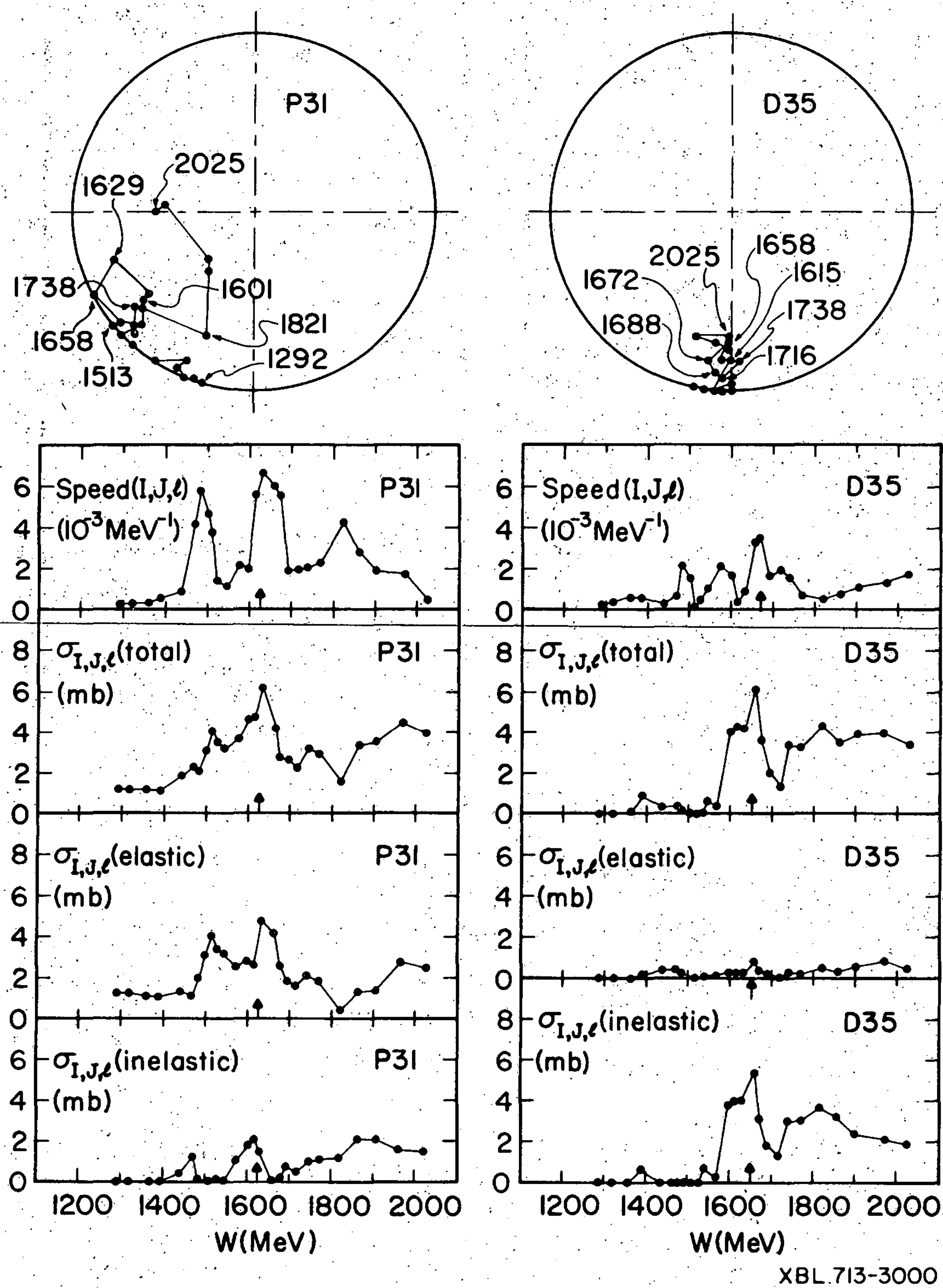

60
50
40
30
20
10
0
mb
1200
1400
1600
1800
2000
W (GeV)
$\sigma_{el}(\pi^+p)$
$\sigma_{in}(\pi+p)$
$\sigma_{in}(\pi^-p)$
$\sigma_{el}(\pi^-p)$
$\sigma_{el}(\pi+p)$
$\sigma_{in}(\pi^-p)$
$\sigma_{el}(\pi^-p)$
$\sigma_{in}(\pi^+p)$
XBL 713-3003

Fig. 2.



P31
2025
1629
1738
1601
1821
1658
1292
1513
D35
2025
1658
1672
1615
1738
1688
1716
Speed(I,J,ℓ)
(10⁻³MeV⁻¹)
σI,J,ℓ(total)
(mb)
σI,J,ℓ(elastic)
(mb)
σI,J,ℓ(inelastic)
(mb)
1200 1400 1600 1800 2000
W(MeV)
XBL 713-3000

Fig. 3.

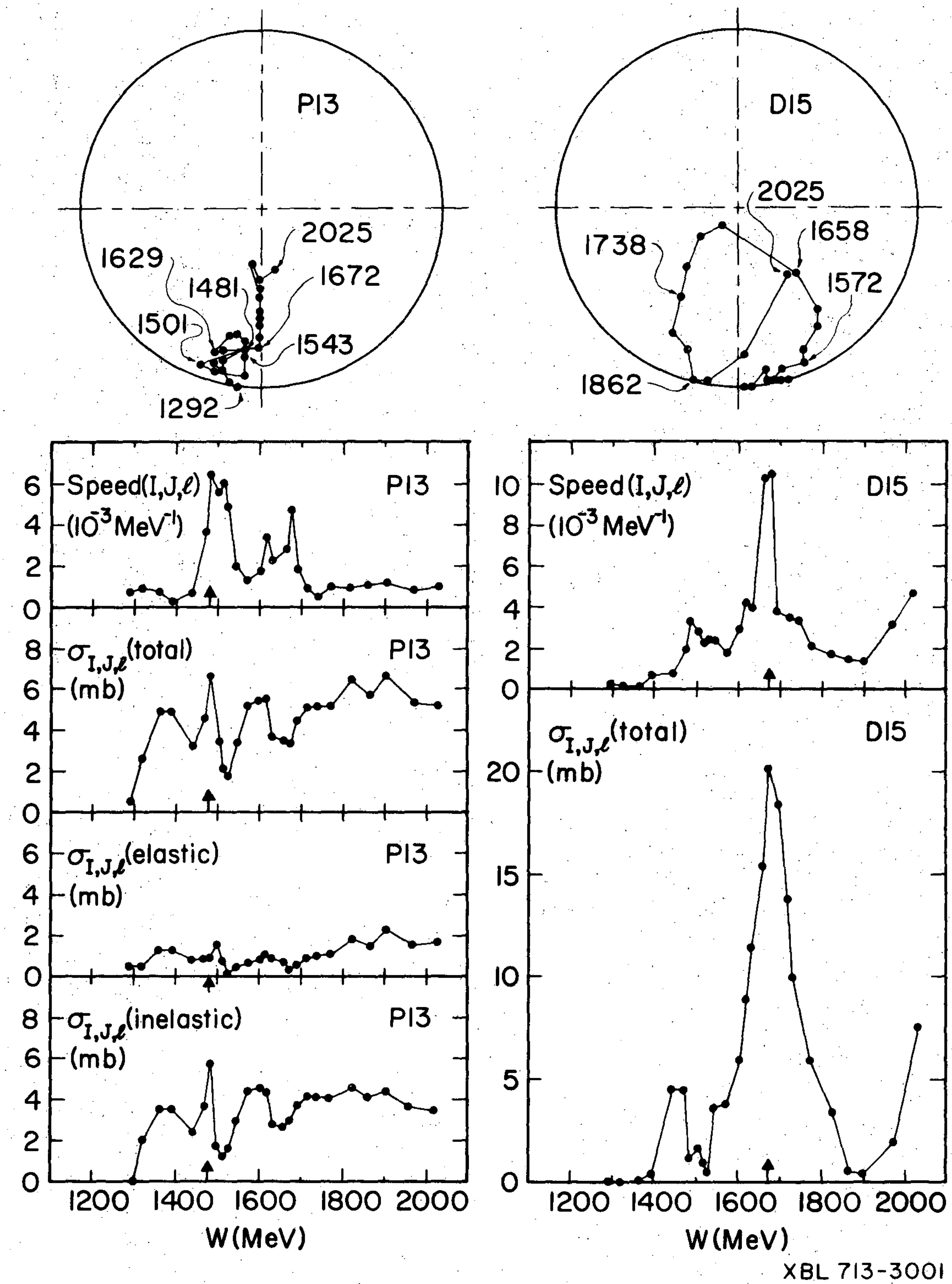

P13
2025
1629
1481
1672
1501
1543
1292
D15
2025
1738
1658
1572
1862
Speed(I,J,ℓ)
(10^-3 MeV^-1)
P13
σ_{I,J,ℓ}(total)
(mb)
σ_{I,J,ℓ}(elastic)
(mb)
σ_{I,J,ℓ}(inelastic)
(mb)
D15
W(MeV)
XBL 713-3001

Fig. 4.

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