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ABSTRACT

We have measured the missing mass spectrum of nucleon isobars produced in the reaction $p + p \rightarrow N^* + p$ by 7.1 GeV/c protons incident on a liquid-hydrogen target. Scintillation counters detected the recoil protons after momentum analysis. Cross sections were obtained for production of isobars of mass 1238, 1512, and 1688 MeV at momentum transfers of 0.09, 0.15, 0.24, 0.33, and about 5 $(\text{GeV})^2$. At low momentum transfers, the spectrum has additional structure at a mass of about 1430 MeV. The $T = \frac{1}{2}$ isobar production cross sections at $|t| = 5$ $(\text{GeV})^2$ are comparable with the elastic scattering cross section.

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PRODUCTION OF NUCLEON ISOBARS BY 7.1 GEV/C PROTONS†

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We have measured distributions in momentum and angle of protons resulting from inelastic proton—proton collisions at 7.1 GeV/c. A liquid hydrogen target was located in the external proton beam of the Bevatron; an accurately calibrated ionization chamber monitored the incident flux. Two momentum spectrometers, one designed for momenta below 700 MeV/c, the other for momenta above 500 MeV/c, analyzed the scattered protons. Scintillation counter coincidence systems detected the protons after momentum analysis. The same experimental layout was used to measure differential elastic scattering cross sections; the report of these results(1) will include a complete description of the setup. The results obtained with the two momentum spectrometers will be discussed separately.

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Measurements at Low Momentum Transfer

In the low momentum channel, the distribution in angle of the recoil proton was measured for laboratory angles in the range $50^{\circ} \leq \theta \leq 80^{\circ}$ at fixed recoil momenta of 300, 400, 500, and 600 MeV/c, corresponding to fixed invariant momentum transfers, $|t|$, of 0.088, 0.153, 0.234, and 0.329 $(\text{GeV})^2$ respectively. The spectrometer accepted a momentum interval of 4.1%; the momenta were checked by range measurements.

Fig. 1 shows the missing mass spectra obtained. In each case there is a large elastic scattering peak (not shown), the size of which is consistent with published cross sections. (See, for example, the references on pp elastic cross sections cited by Cocconi, et al.[2]) At smaller angles, there is an inelastic continuum with peaks superimposed.

As is customary,[2,3] we tentatively interpret the inelastic spectra in terms of the reaction

$$p + p \rightarrow p + N^{*}, \quad N^{*} \rightarrow N + \text{pions} \qquad (1)$$

In this interpretation, the peaks are due to the "direct" proton produced with the nucleon isobar N^{*}; the smooth continuum corresponds to decay protons from the isobar and to protons from other inelastic processes. The momentum and angle at the peaks then determine kinematically the missing mass of the corresponding isobars. The spectra in Fig. 1 are plotted against the square of this missing mass, which has been corrected for momentum loss of the scattered protons in the target. The results of a one-pion exchange approximation for the direct proton spectra, calculated from the equations of Ferrari and Selleri,[4] are also shown in Fig. 1.

In all cases, the observed spectra show peaks around 1238 and 1688 MeV, the masses of known pion-nucleon resonances. In addition there is a peak of variable shape, position, and width in the region 1400 to 1550 MeV. Cocconi et al.[2] have observed a similar effect in this mass range at corresponding momentum transfers and lower incident energies. Possible explanations of this effect will be considered below.

Even apart from the unusual behavior in the neighborhood of the known 1512 MeV isobar, the determination of isobar production cross sections from the data is subject to considerable uncertainty due to the somewhat arbitrary nature of the large background subtraction. In the present work, production cross sections for the 1238 and 1688 MeV isobars were defined by the area under the peaks and above the smooth curves shown in Fig. 1. In the case of the 1512 MeV isobar, the cross sections were obtained from the portion of the peak centered at 1512 MeV as indicated by the dotted lines. The production cross sections so obtained are shown in Fig. 2.

To obtain the full widths, Γ, of the isobars, the instrumental resolution was estimated by fitting a semiempirical formula to the observed width of the elastic peak. This formula included the effects of multiple Coulomb scattering in the target, angle spread in the incident beam, and uncertainties in the scattered angle and momentum. After unfolding the instrumental resolution, the average full widths of the peaks (at half-maximum above the smooth curves) were found to be 100 ± 20 MeV for the 1238 MeV isobar and 100 ± 15 MeV for the 1688 MeV isobar. The width of the whole peak around 1400–1550 MeV decreased smoothly from about 150 MeV at $|t| = 0.088\ (\text{GeV})^2$ to about 100 MeV at $|t| = 0.329\ (\text{GeV})^2$.

Several interpretations of the unexpected behavior in the neighborhood of the 1512 MeV isobar were considered.

The possibility that the effect might be due to one of the reactions

$$p + p \to d + \text{boson resonance}$$
$$\to K^{+} + \text{dibaryon resonance}$$
$$\to \pi^{+} + \text{dibaryon resonance}$$

can be excluded in this experiment because of the selection criteria imposed on the recoil particle.

Cocconi et al.[2] have suggested that it might be due to superposition of a peak at 1512 MeV and either 1) structure due to the decay proton from the 1512 MeV isobar, or 2) a peak representing another isobar of mass 1400 MeV. It seems unlikely that the decay proton from the 1512 MeV isobar could produce a bump or ledge around 1400 MeV for the incident momentum used in this experiment. This mechanism should give rise to structure in the neighborhood of the kinematic limit of the decay proton. For an incident momentum of 7.1 GeV/c, the missing mass corresponding to the kinematic limit is about 1100 MeV.

The second explanation is consistent with our data; in particular, the spectrum at 300 MeV/c suggests two barely resolved peaks. If this interpretation is correct, our data indicate a mass of about 1430 MeV for the new isobar. Though no peak occurs at this energy in pion-nucleon scattering, some analyses[5] have indicated a resonance near this energy.

However, since there is no peak in pion-nucleon scattering at this energy, the one-pion exchange model predicts that there would also be no peak in the inelastic proton spectra. Moreover, it is possible to understand the inelastic proton spectra without invoking a new isobar. The peak or ledge may be caused by decay protons from the reaction

$$p + p \rightarrow N^*_{33} + N^*_{33} \qquad (2)$$
$$N^*_{33} \rightarrow N + \pi, \quad N^*_{33} \rightarrow N + \pi$$

To examine this possibility, a Monte Carlo calculation of the decay proton spectra from reaction (2) was undertaken. The following assumptions were made:

1. The mass $M_{N^*_{33}}$ follows a Breit-Wigner distribution of the form

$$\frac{\text{Const.}}{(M-M_o)^2 + (\Gamma/2)^2}$$

with M_o = 1225 MeV, Γ = 80 to 95 MeV. The assumed central value M_o agrees with the position of the peak in πN scattering, whereas $\delta_{33} = 90^o$ around 1238 MeV.[6]

2. The angular distribution of the N^*_{33} production is sharply peaked forward and backward in the center-of-mass system. This assumption is justified by the one-pion exchange model[4] and also by experiment.[7,8] The shapes of the calculated spectra are insensitive to the exact form of this distribution.

3. The decay protons have an angular distribution of the form $(1 + 3 \cos^2\theta_p)$ in the N^*_{33} rest system. This form is also suggested by the one-pion exchange model.[4]

Figs. 1 and 3 exemplify the good agreement of the Monte Carlo calculations with our data and with that of Cocconi et al,[2] respectively. Both the shift in mass from 1400 MeV at p_{inc} = 3.6 GeV/c to 1430 MeV at p_{inc} = 7.1 GeV/c and the rapid disappearance of the effect with increasing momentum transfer are explained. Experience with the Monte Carlo calculation indicates that the effect is mainly of a kinematical origin. Within the general framework of the assumptions stated above, there is considerable latitude in the choice of the numerical parameters needed to give a satisfactory fit to the data.

The Monte Carlo spectra of Figs. 1 and 3 were fit to the data by assuming that the total cross sections for reaction (2) are 1.6 mb at 3.6 GeV/c and 1.4 mb at 7.1 GeV/c. These values depend rather critically on the assumed form of the angular distributions for production and decay of the N_{33}^*. For comparison, previous estimates based on various models include 4.22 or 5.40 mb at 2.8 GeV/c[7] and 2.9 mb at 9.9 GeV/c.[9]

Measurements at High Momentum Transfer

The high momentum channel was used to measure the inelastic proton momentum spectrum at a fixed laboratory angle of 27.05°, corresponding to center-of-mass angles near 90°. Measurements were made at momenta corresponding to missing masses M_{N*} up to 2000 MeV and invariant momentum transfers around 5 $(\mathrm{GeV})^2$. As opposed to previous observations of N* production at low momentum transfer which have been interpreted in terms of various peripheral models, the present results may shed some light on processes normally associated with high momentum transfer events, such as the core interaction and the statistical model.

The isobar production cross sections at high momentum transfer are but a small fraction of the inelastic cross section. The nonresonant background counting rate was thus large; moreover, it rose steeply with increasing isobar mass. In a direct measurement of the inelastic spectrum, the isobar peaks are obscured by the steeply rising background and by difficulties associated with fluctuations in operating conditions. It was found, however, that these problems could be circumvented by use of two counters of different widths, i.e., different momentum resolutions. For two counters aligned on the same beam axis having widths W_1 and W_2, the difference of the normalized counting rates, $(C_1/W_1 - C_2/W_2)$, depends only on the second and higher derivatives of the counting rate with respect to momentum. This difference function also averages out the effects of fluctuations in operating conditions. The properties of this function thus greatly facilitate the separation of small peaks from a smoothly varying background.

Fig. 4 shows the difference of normalized counting rates as a function of missing mass squared. A smooth nonresonant background has been subtracted. The peaks occur approximately at the proton mass and at 1238, 1512, and 1688 MeV, the masses of the first three known isobars. Each peak has been fitted with a form which represents the effect of a Breit-Wigner peak on the difference function defined above.

The ratios of the isobar production cross sections to the elastic cross section at $|t| = 5.44\ (\text{GeV})^2$ can be calculated from the parameters of the fitted curves. The results are

Mass (MeV)	$(d\sigma/dt)/(d\sigma/dt)_{\text{elastic}}$	$\lvert t\rvert\ (\text{GeV})^2$
1238	0.2 ± .2	5.06
1512	2.5 ± 1.25	4.59
1688	1.3 ± .65	4.24

The estimated errors arise from counting statistics, from fluctuations in operating conditions, and from the critical dependence of the cross section on the fitted width of the peak. The large uncertainty of the 1238 MeV production cross section reflects the marginal possibility of fitting the data without the 1238 peak. For reference, a determination of the elastic cross section with the same apparatus(1) yields a preliminary value of 1 $\mu b/(GeV)^2$ at $|t| = 5.44\ (GeV)^2$.

Several conclusions may be drawn from the high momentum transfer measurements:

1. The 1512 and 1688 MeV isobar production cross sections at high momentum transfer are comparable with the elastic cross section.
2. The 1512 MeV peak is well defined; there is no indication of unusual structure or peculiar shape at high momentum transfer.
3. Within the resolution, the resonances appear at masses that are consistent with the pion-nucleon results.

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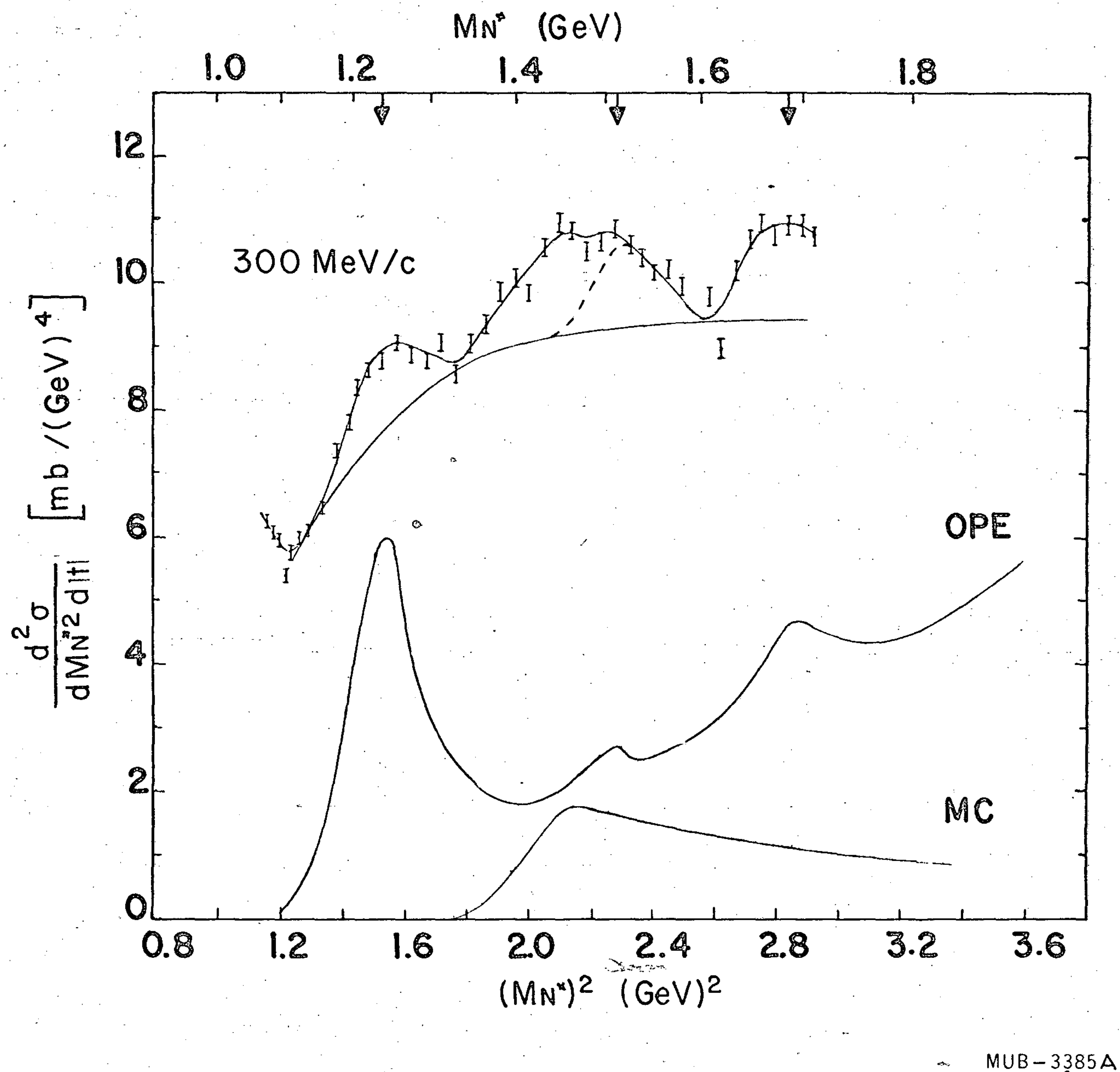
FIGURE LEGENDS

Fig. 1 Missing mass spectra of recoil protons produced in inelastic proton-proton collisions at 7.1 GeV/c. The spectra were measured at fixed recoil momenta of (a) 300 MeV/c, (b) 400 MeV/c, (c) 500 MeV/c, and (d) 600 MeV/c. The smooth curves associated with the data show how the background was subtracted. The smooth curves below the data show the results of a one-pion exchange calculation of the direct proton spectra (OPE) and the results of a Monte Carlo calculation of the proton spectra from the reaction $p + p \to N_{33}^* + N_{33}^*$ (MC).

Fig. 2 Differential cross sections for production of the first three nucleon isobars. The points have a large uncertainty (~ 50%) due to the arbitarry nature of the background subtraction.

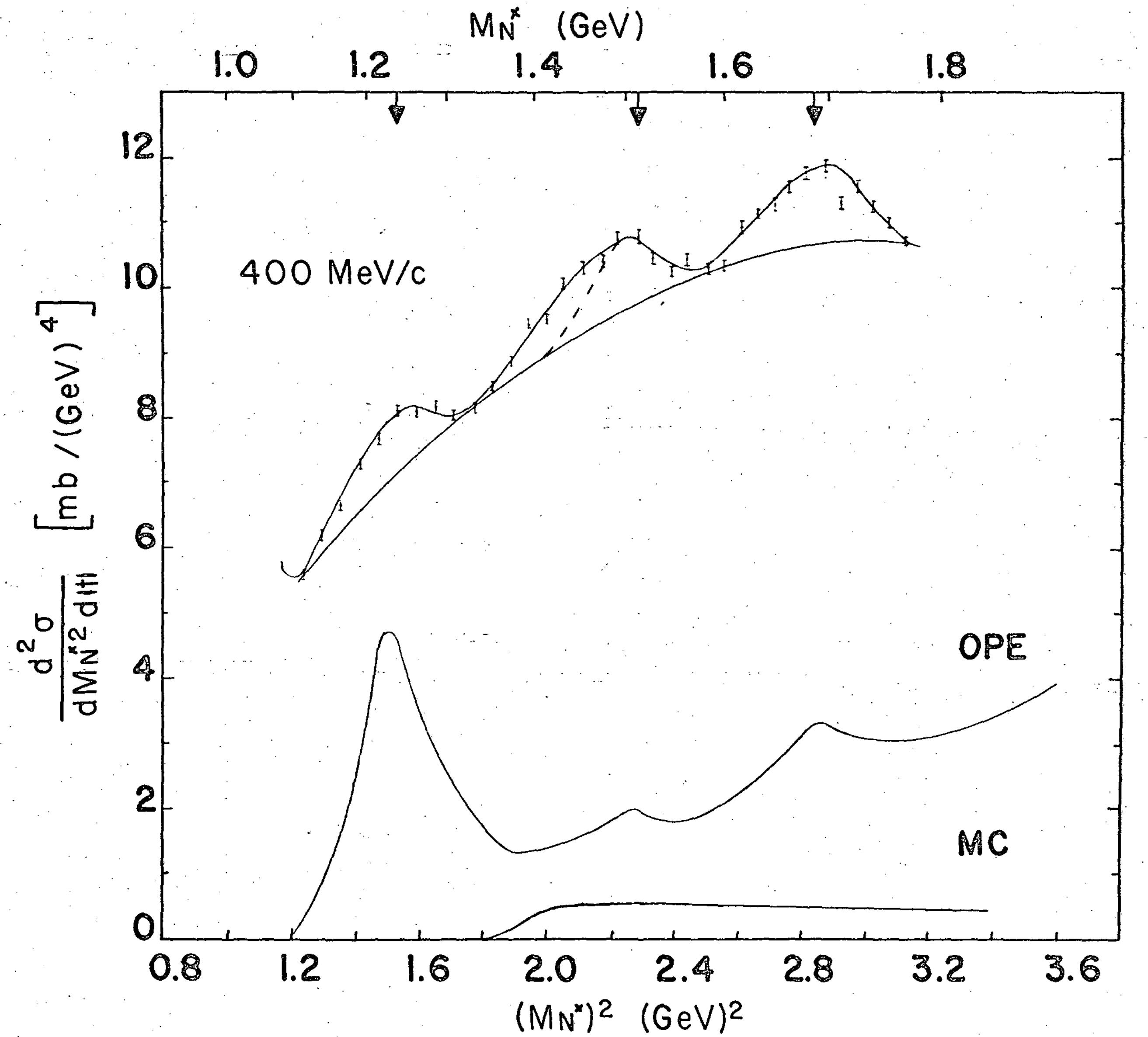
Fig. 3 The experimental data from Cocconi et al;[(2)] the spectrum from double isobar production ($p + p \to N_{33}^* + N_{33}^*$) around 1400 MeV is calculated by the Monte Carlo Method.

Fig. 4 The difference between the normalized counting rates of two counters having different momentum resolutions. Each peak has been fitted by a form which indicates how a Breit-Wigner peak would affect the difference function. For further explanation, see the text.



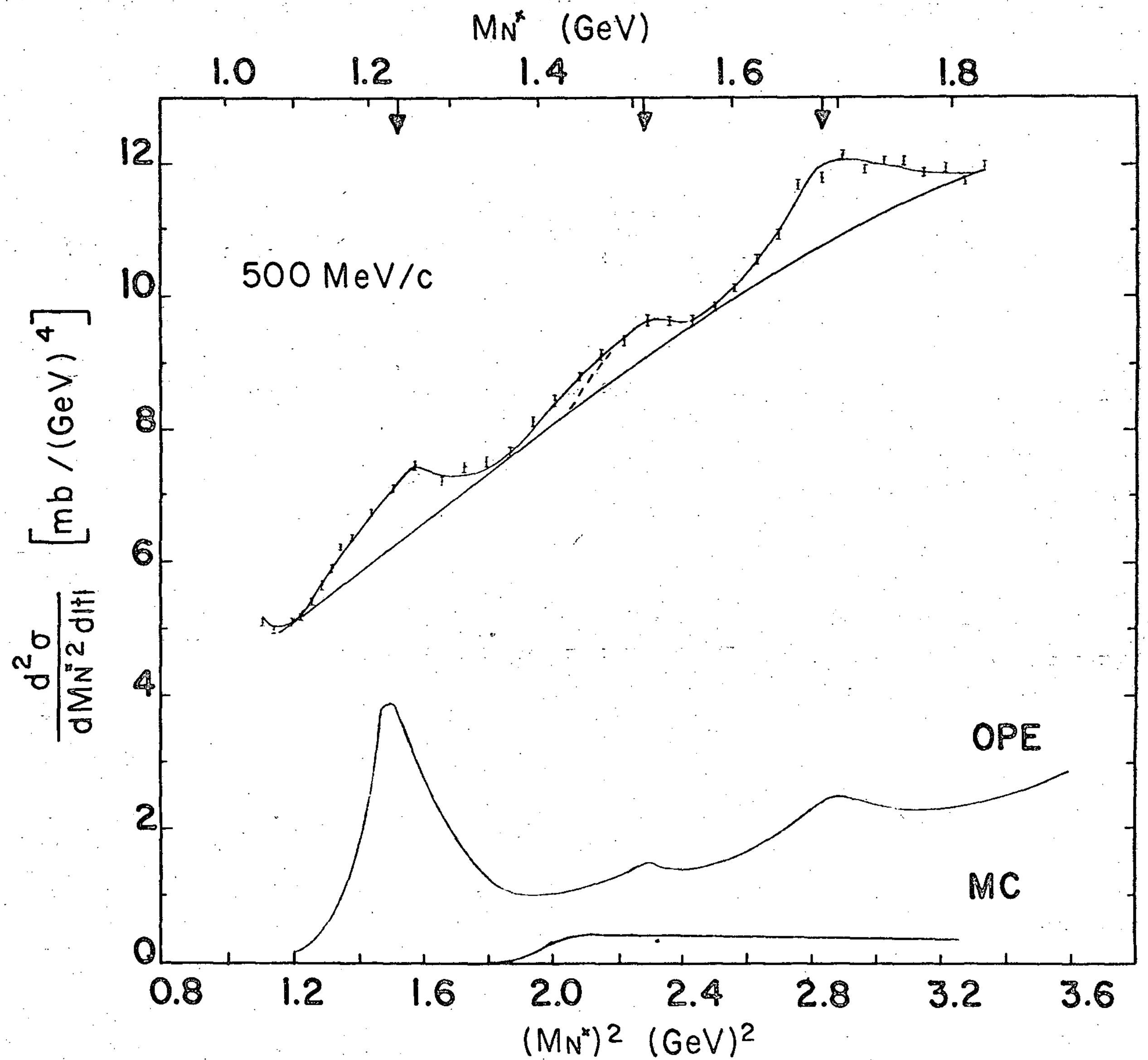
MN* (GeV)
1.0
1.2
1.4
1.6
1.8
12
10
8
6
4
2
0
300 MeV/c
OPE
MC
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
(MN*)2 (GeV)2
MUB-3385A

Fig. 1(a)



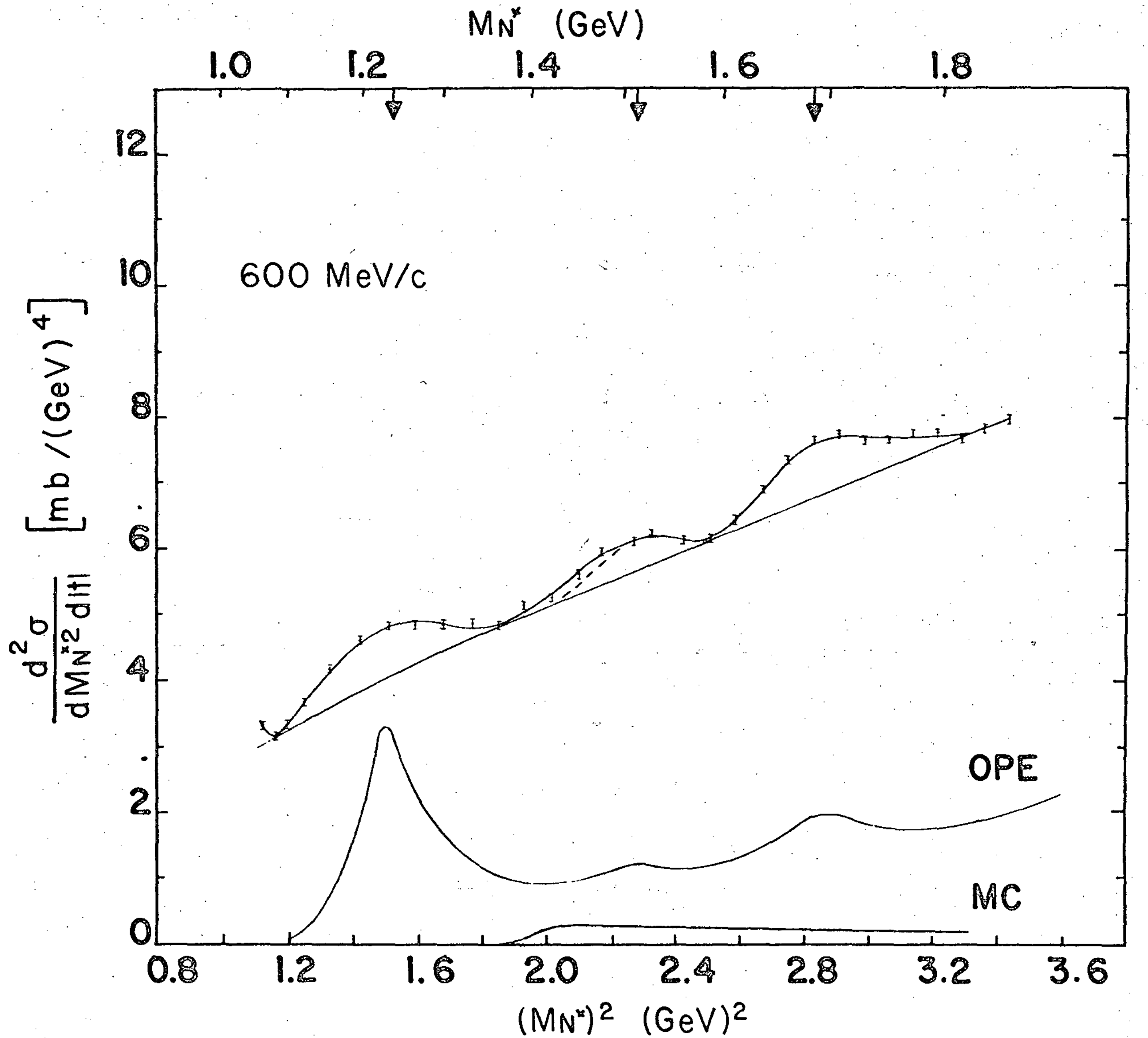
MUB-3386A

Fig. 1(b)



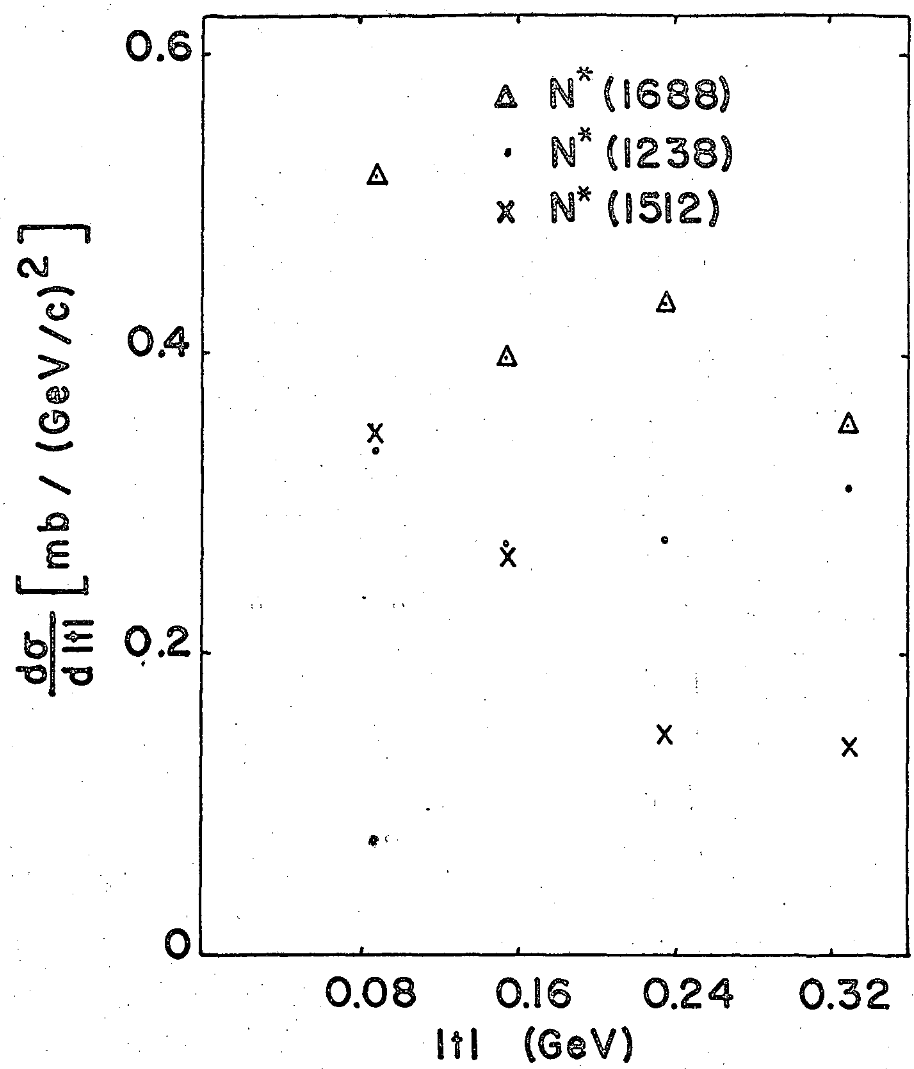
MUB-3387A

Fig. 1(c)



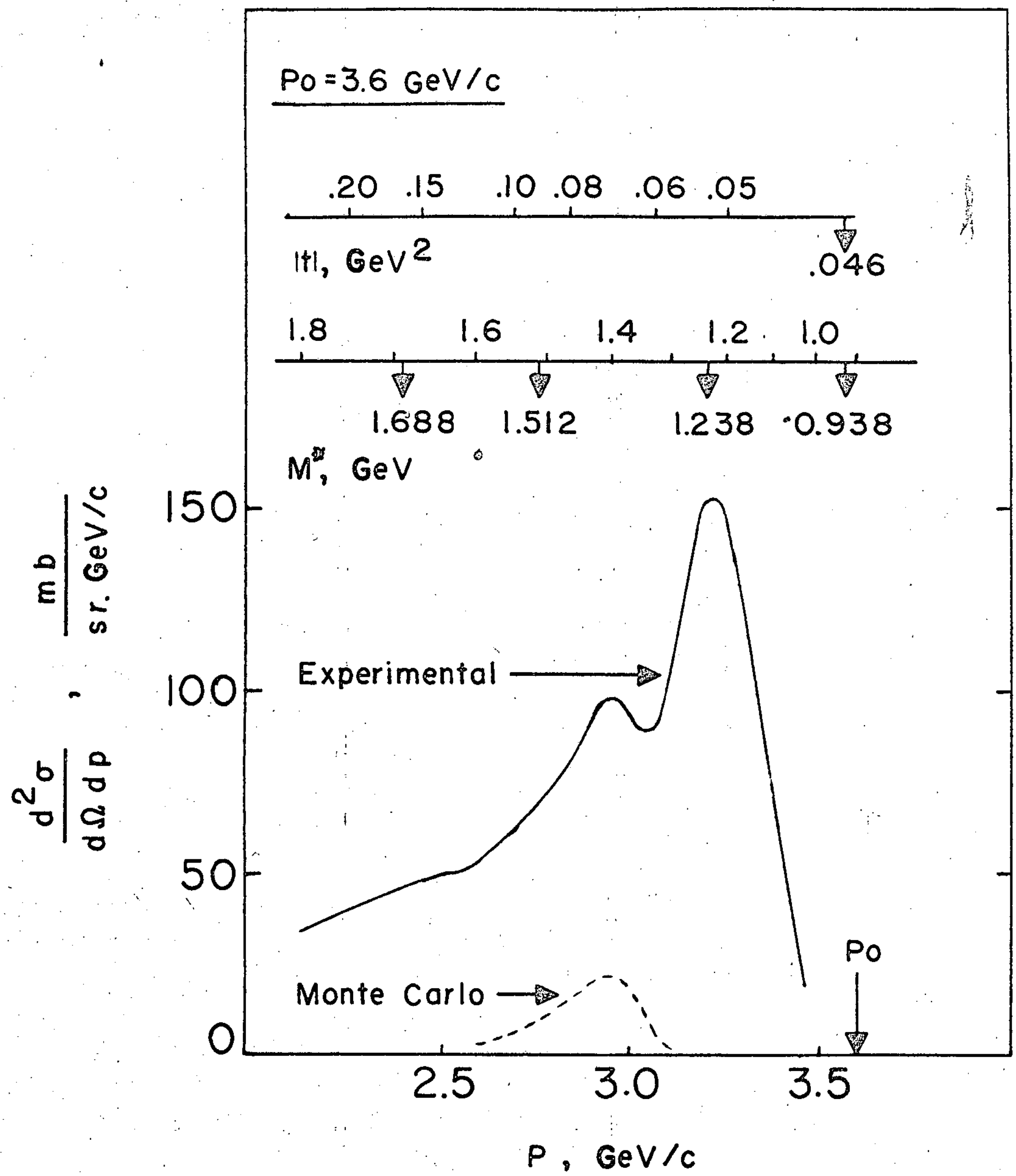
MUB-3388A

Fig. 1(d)



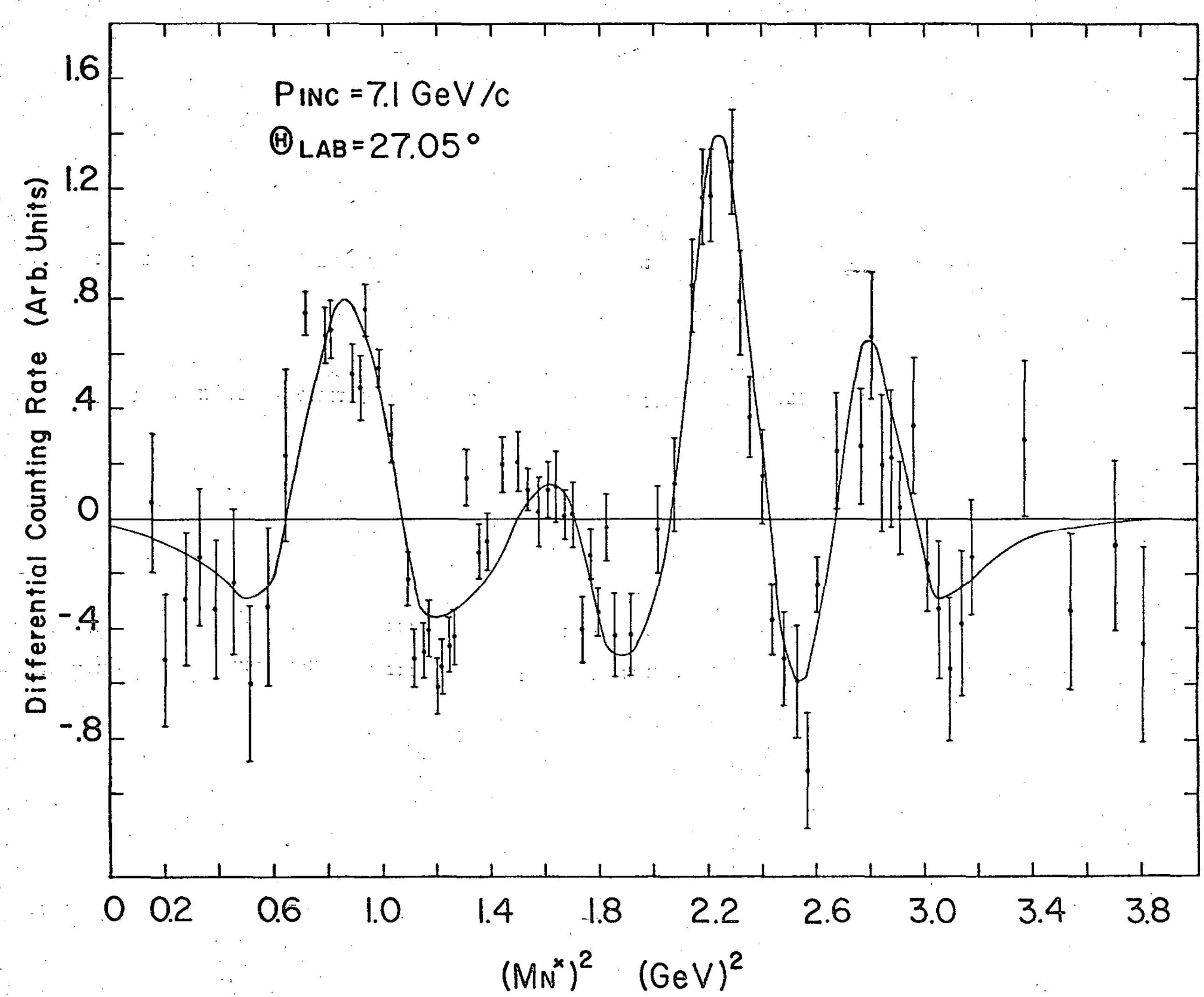
MUB-3389A

Fig. 2



MUB-3390A

Fig. 3



PINC = 7.1 GeV/c
ΘLAB = 27.05°
Differential Counting Rate (Arb. Units)
1.6
1.2
.8
.4
0
-.4
-.8
0
0.2
0.6
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
(MN*)² (GeV)²

Fig. 4