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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 Bev/c protons incident on a liquid-hydrogen target. Scintillation counters detected the scattered 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 5 $(\text{Bev/c})^2$. For low momentum transfer, the spectrum has additional structure at a mass of about 1430 Mev. The $T = \frac{1}{2}$ isobar production cross sections at $-t = 5\ (\text{Bev/c})^2$ are comparable with the elastic-scattering cross section.

PRODUCTION OF NUCLEON ISOBARS BY 7 BEV/C PROTONS[†δ]

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We have measured momentum and angular spectra of protons resulting from inelastic proton-proton collisions at 7.1 BeV/c. A liquid hydrogen target was located in the Bevatron's external proton beam; 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 includes a more complete description of the setup. The results obtained with the two momentum spectrometers will be discussed separately.

Measurements at Low Momentum Transfer

In the low momentum channel, the angular spectrum was measured at large angles for fixed recoil momenta of 300, 400, 500, and 600 MeV/c, corresponding to fixed invariant momentum transfers of 0.088, 0.153, 0.234, and 0.329 $(BeV)^2$ respectively. The spectrometer accepted a momentum interval $\Delta p/p$ of 4.1%; the momenta were checked by range measurements.

Fig. 1 shows the angular spectra obtained. In each case there is a large elastic scattering peak (not shown), the size of which is consistent with

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published data.[1] At smaller angles, there is an inelastic continuum with peaks superimposed.

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

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

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 isobar. 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[3], 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 extraction of isobar production cross sections from the data is subject to considerable ambiguity due to the large background. In the present work, production cross sections for the 1238 and 1688 MeV isobars

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(1) See, for example, the references on pp elastic cross sections cited by Cocconi, et al. (2).

(2) G. B. Chadwick, G. B. Collins, P. J. Duke, T. Fujii, N. C. Hien, M.A.R. Kemp and F. Turkot, Phys. Rev. 128, 1823 (1962).

G. Cocconi, 1962 CERN Conf., p 883.

A. N. Diddens, E. Lillethun, G. Manning, A. E. Taylor, T. G. Walker and A. M. Wetherell, Phys. Rev. Letters 9, 32 (1962).

A. N. Diddens, 1962 CERN Conf., p 576.

G. Cocconi, E. Lillethun, J. P. Scanlon, C. A. Stahlbrandt, C. C. Ting, J. Walters and A. M. Wetherell, Physics Letters 8, 134 (1964).

(3) E. Ferrari and F. Selleri, Nuovo Cimento Suppl. 24, 453 (1962).

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 line. The production cross sections so obtained are shown in Fig. 2.

To obtain the full widths Γ of the isobars, the experimental 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 experimental resolution, the average full widths of the peaks (at half-max. 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 $|t| = 0.088\ (\mathrm{Bev})^2$ to about 100 MeV at $|t| = 0.329\ (\mathrm{Bev})^2$.

Several interpretations of the unexpected behavior in the neighborhood of the 1512 MeV isobar were considered. 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; an examination of the kinematics shows that at 7.1 BeV/c incident momentum, the kinematic limit for the decay protons, where the effect would probably occur, is around a missing mass of 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[4] have indicated a resonance near this energy.

However, even if a resonance occurs in pion-nucleon scattering, the absence of a peak at this energy indicates, on the one pion exchange model, that there would correspondingly be no peak in the inelastic proton spectra. Moreover, it is possible to understand the effect in the inelastic proton

(4) P. Bareyre, C. Bricman, G. Valladas, G. Villet, J. Bizard, and J. Seguinot, Physics Letters 8, 137 (1964).

L. David Roper, Phys. Rev. Letters 12, 340 (1964).

spectra without invoking a new isobar. The peak or ledge may be caused by decay protons from the reaction

$$p + p \rightarrow N_{33}^{*} + N_{33}^{*}, \quad N_{33}^{*} \rightarrow N + \pi, \quad N_{33}^{*} \rightarrow N + \pi \tag{2}$$

To examine this possibility, a Monte Carlo calculation of the decay proton spectra from reaction (2) was undertaken.

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 BeV/c to 1430 MeV at p_{inc} = 7.1 BeV/c and the rapid disappearance of the effect with increasing momentum transfer are explained naturally. The following reasonable assumptions on reaction (2) were made in the Monte Carlo program:

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 $\delta_{33} = 90^0$ around 1238 MeV.[5]

2. The angular distribution of the N_{33}^*'s is sharply peaked forward and backward in the center of mass system. This assumption is justified by the one pion exchange model and by other experiments.[6,7] The shape of the calculated spectra is insensitive to the exact form of this distribution.

3. The decay protons are distributed according to $(1 + 3 \cos^2\theta_p)$ in the N_{33}^* rest system. This form is also suggested by the one pion exchange model.

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(5) This difference is pointed out by G. Goldhaber on pp 22–23 of the Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, ed. by B. A. Munir and L. J. Gallaher (1963).

(6) E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. 125, 2091 (1962).

(7) E. L. Hart, R. I. Louttit, D. Luers, T. W. Morris, W. J. Willis, and S. S. Yamamoto, Phys. Rev. 126, 747 (1962).

Experience with the Monte Carlo results indicates that similar assumptions would give equally good agreement with the observed spectra; the effect is mainly of kinematical origin.

The Monte Carlo spectra of Figs. 1 and 3 were normalized by assuming that the total cross section for reaction (2) is 1.6 mb at 3.6 BeV/c, 1.4 mb at 7.1 BeV/c. These values depend rather critically on the assumed form of the angular distributions. For comparison, previous estimates include 4.22 or 5.40 mb at 2.8 BeV/c[(6)] and 2.9 mb at 9.9 BeV/c.[(8)]

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 $(BeV)^2$. 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 scattering 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.

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(8) I. M. Dremin and D. S. Chernavskii, JETP 11, 167 (1960).

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.

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

Mass (MeV)	$(d\sigma/dt)/(d\sigma/dt)_{elastic}$	$\lvert t\rvert\ (\text{BeV})^2$
1238	0.2 ± 100%	5.06
1512	2.5 ± 50%	4.59
1688	1.3 ± 50%	4.24

The errors are estimated; the main contribution comes from the critical dependence of the cross section on the fitted width of the peak. The large uncertainty of the 1238 MeV cross section reflects the marginal possibility of fitting the data without the 1238 peak. For reference, a determination of the elastic cross section by other methods yields a preliminary value of $1\ \mu b/(\text{BeV})^2$ at $|t| = 5.44\ (\text{BeV})^2$.

Several empirical observations may be in order:

1. The 1512 and 1688 MeV isobar production cross sections are comparable to the elastic.

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.

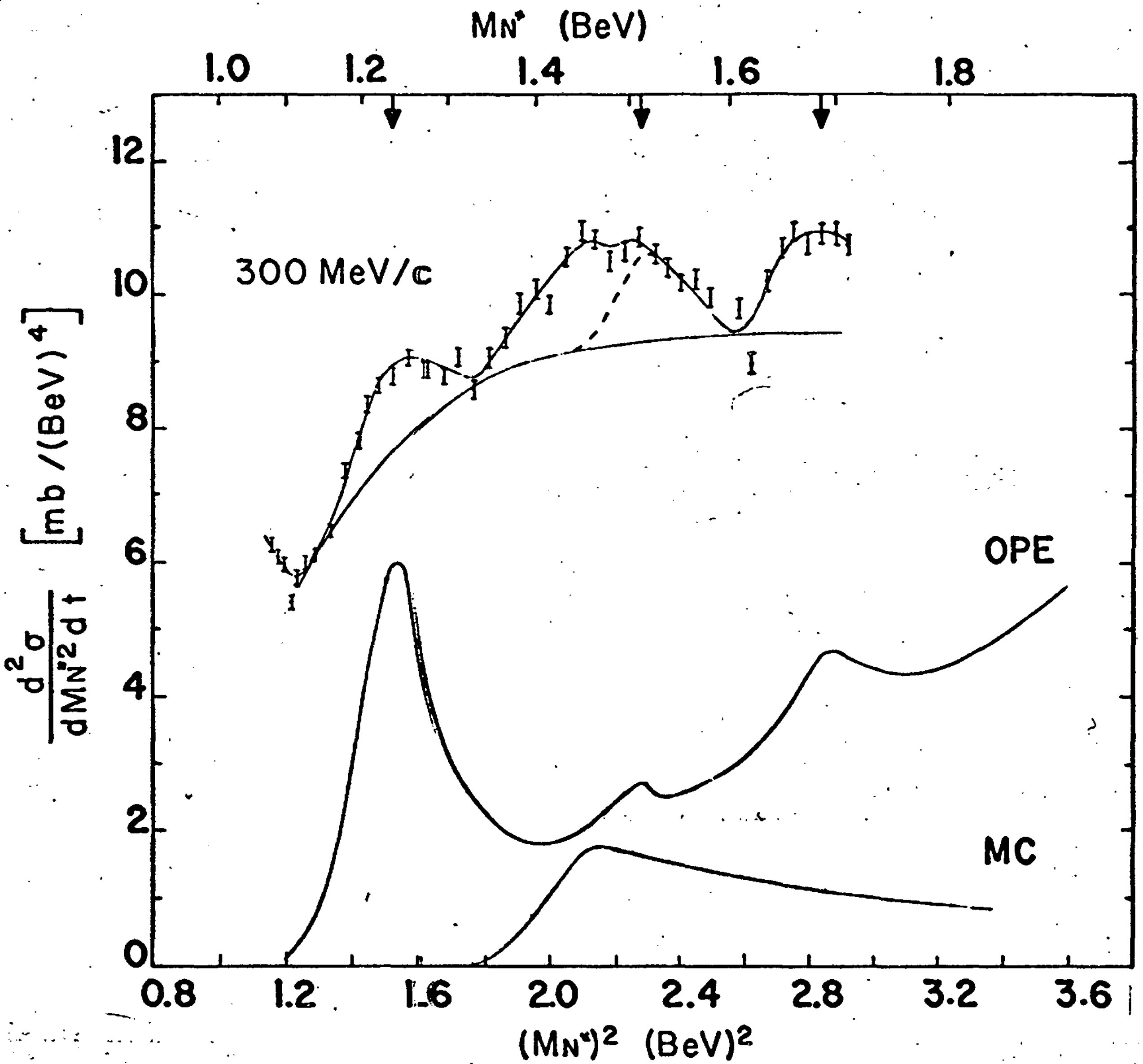
FIGURE LEGENDS

Fig. 1 Spectra of recoil protons produced in inelastic proton-proton collisions at 7.1 BeV/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 curves associated with the data show how the production cross sections for the nucleon isobars were defined. 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 $p + p \rightarrow N_{33}^* + N_{33}^*$ (MC).

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

Fig. 3 Another example of the agreement between the experimental effect around 1400 MeV and the proton spectrum from the reaction $p + p \rightarrow N_{33}^* + N_{33}^*$. The experimental data are taken from Cocconi, et al.[2]; the spectrum from double isobar production is calculated by the Monte Carlo Method.

Fig. 4 The difference of normalized counting rates of two counters having different momentum resolutions, plotted vs. missing mass squared. Each peak has been fitted by a form representing the effect of a Breit-Wigner peak on the difference function. For further explanation, see the text.



MUB-3385

Fig.1(a)

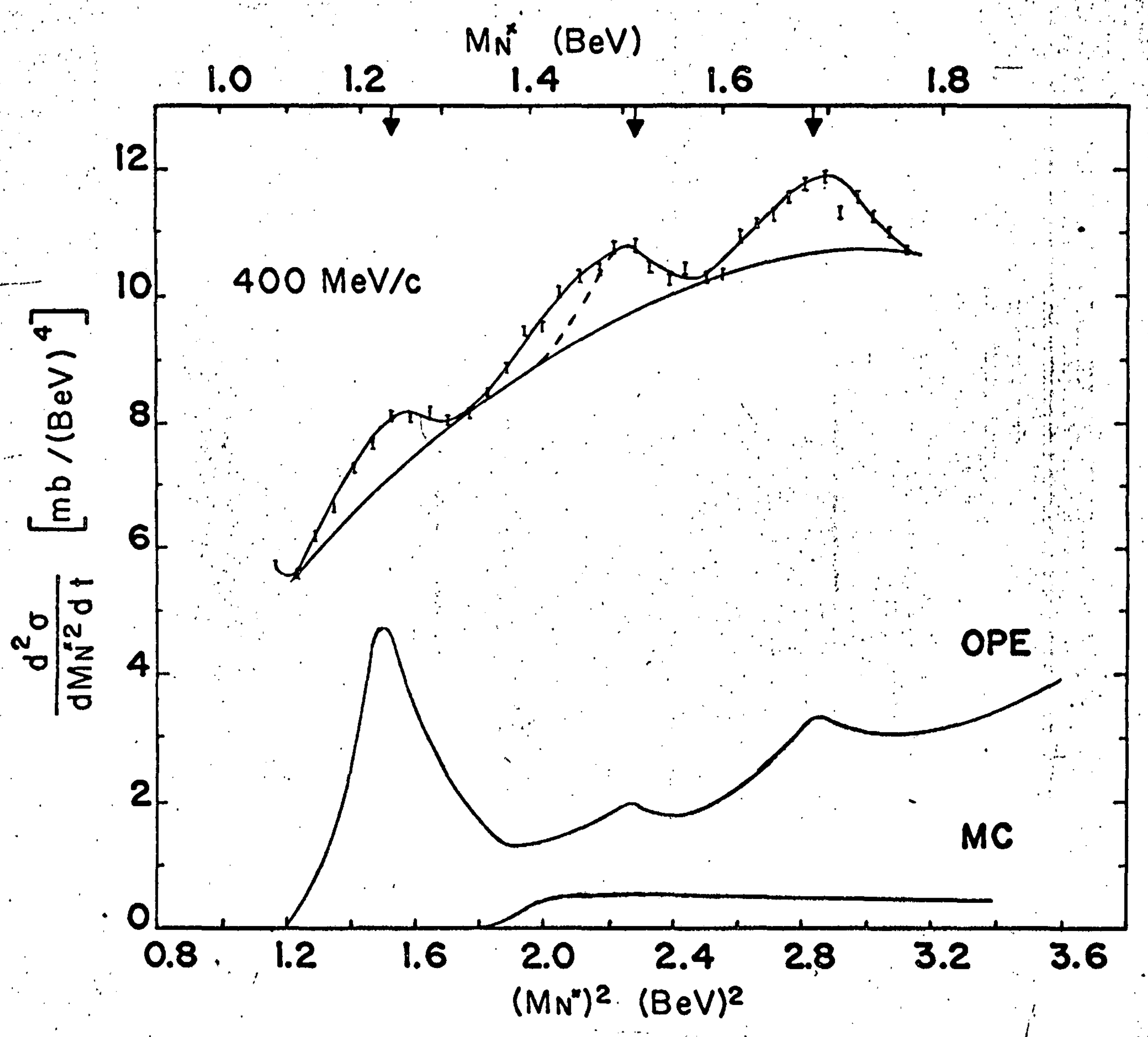
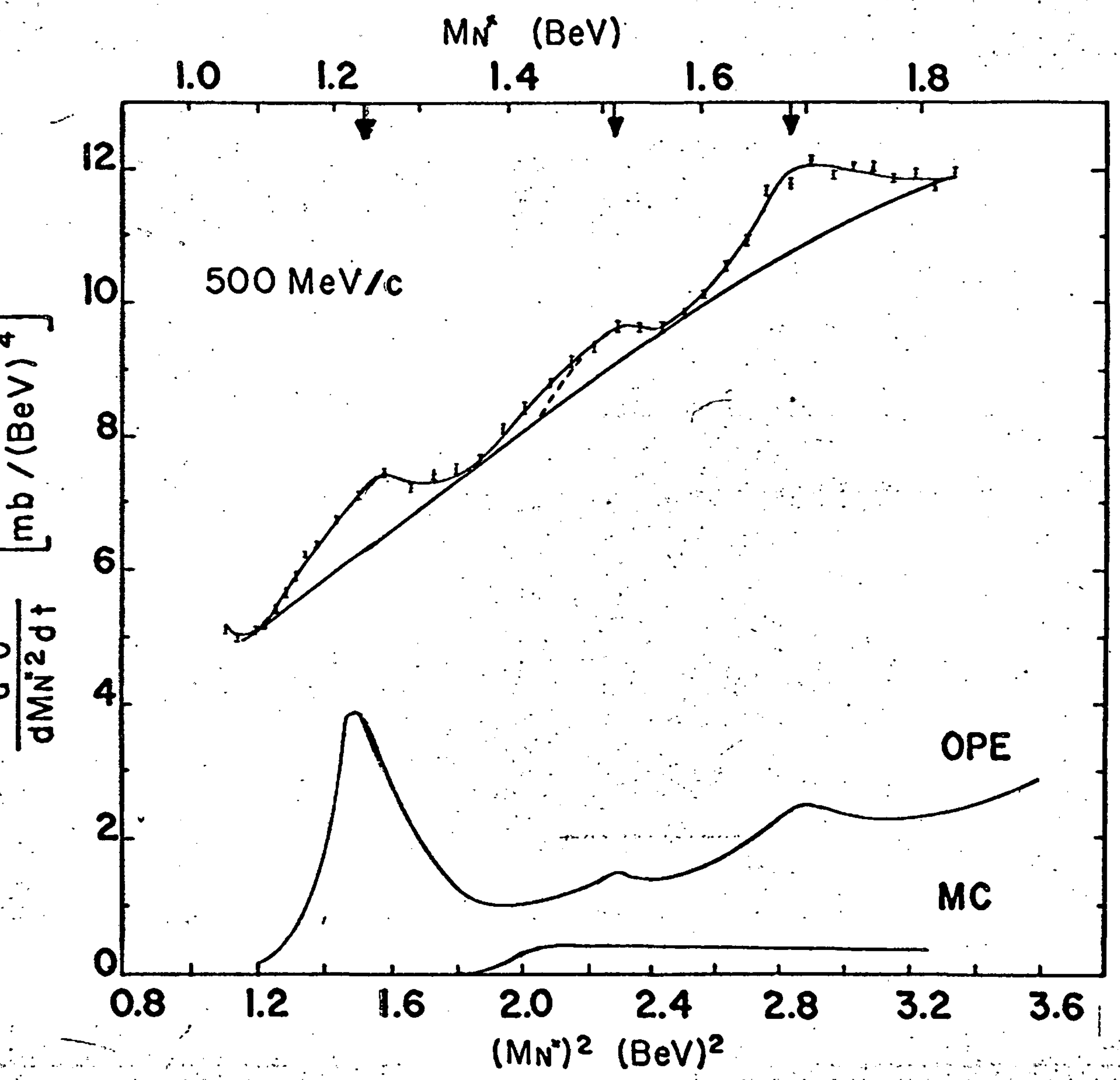


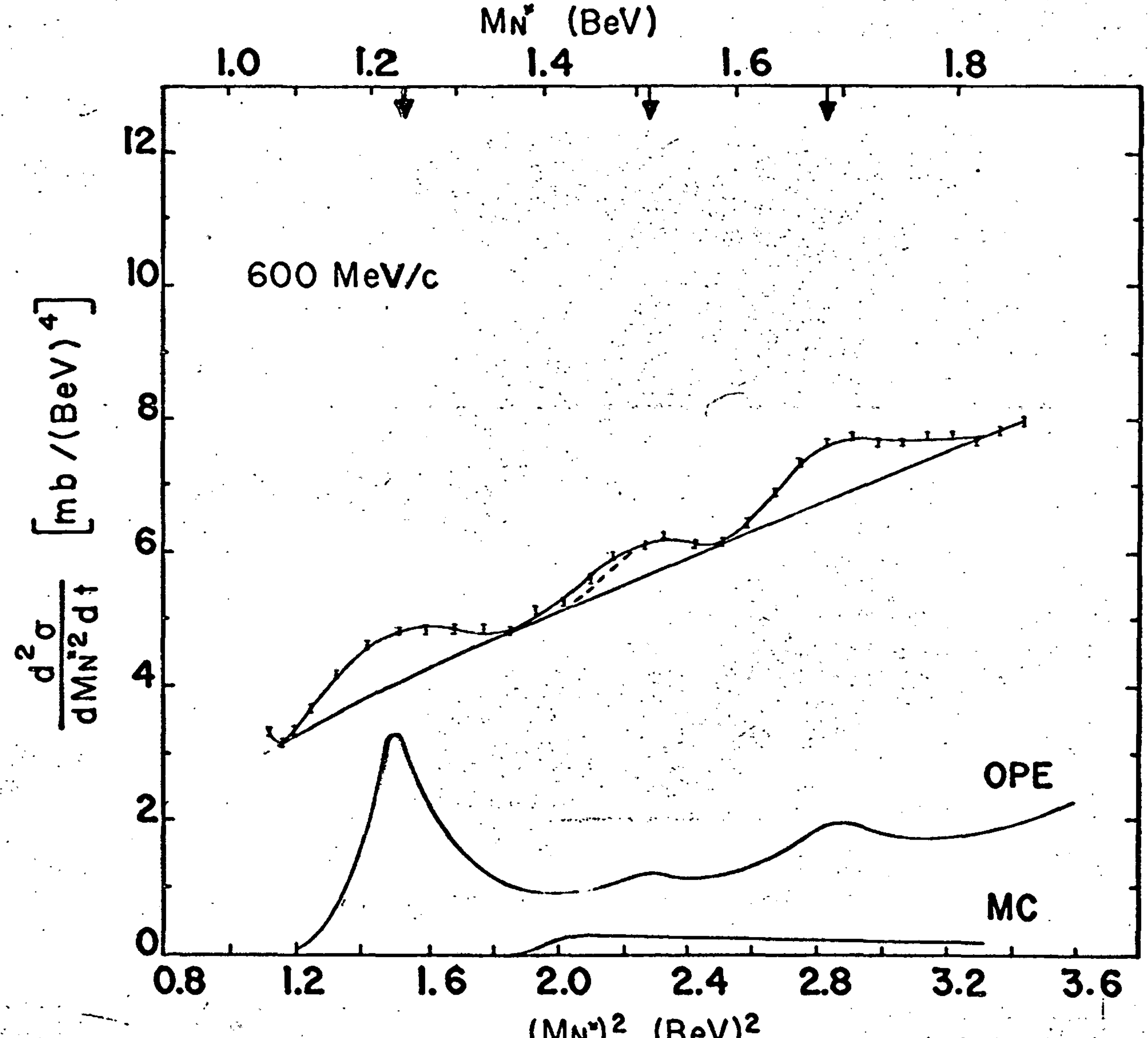
Fig. 1(b)

MUB-3386



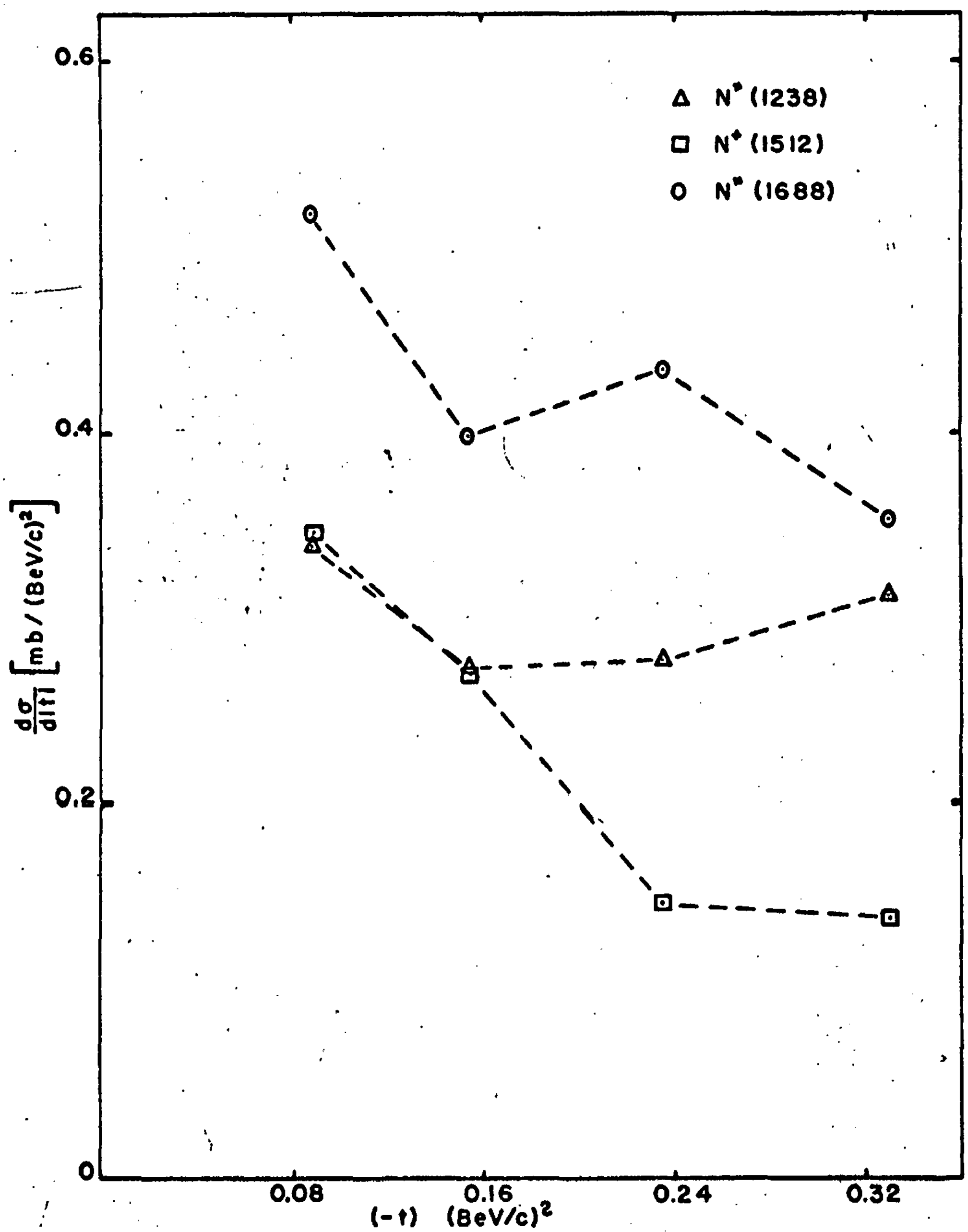
MUB-3387

Fig. 1(c)



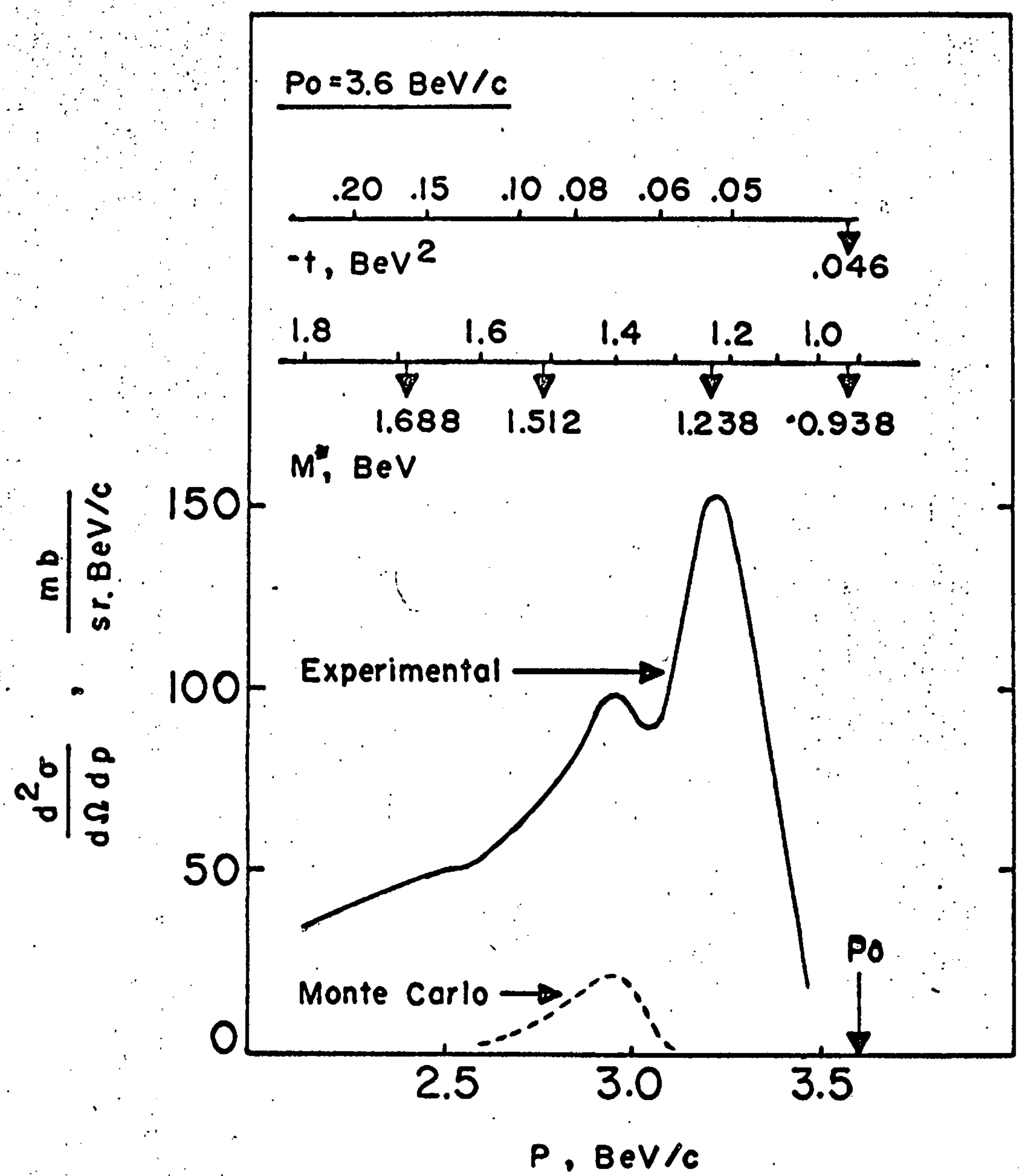
MUB-3388

Fig. 1(d)



MUB-3389

Fig. 2



MUB-3390

Fig. 3

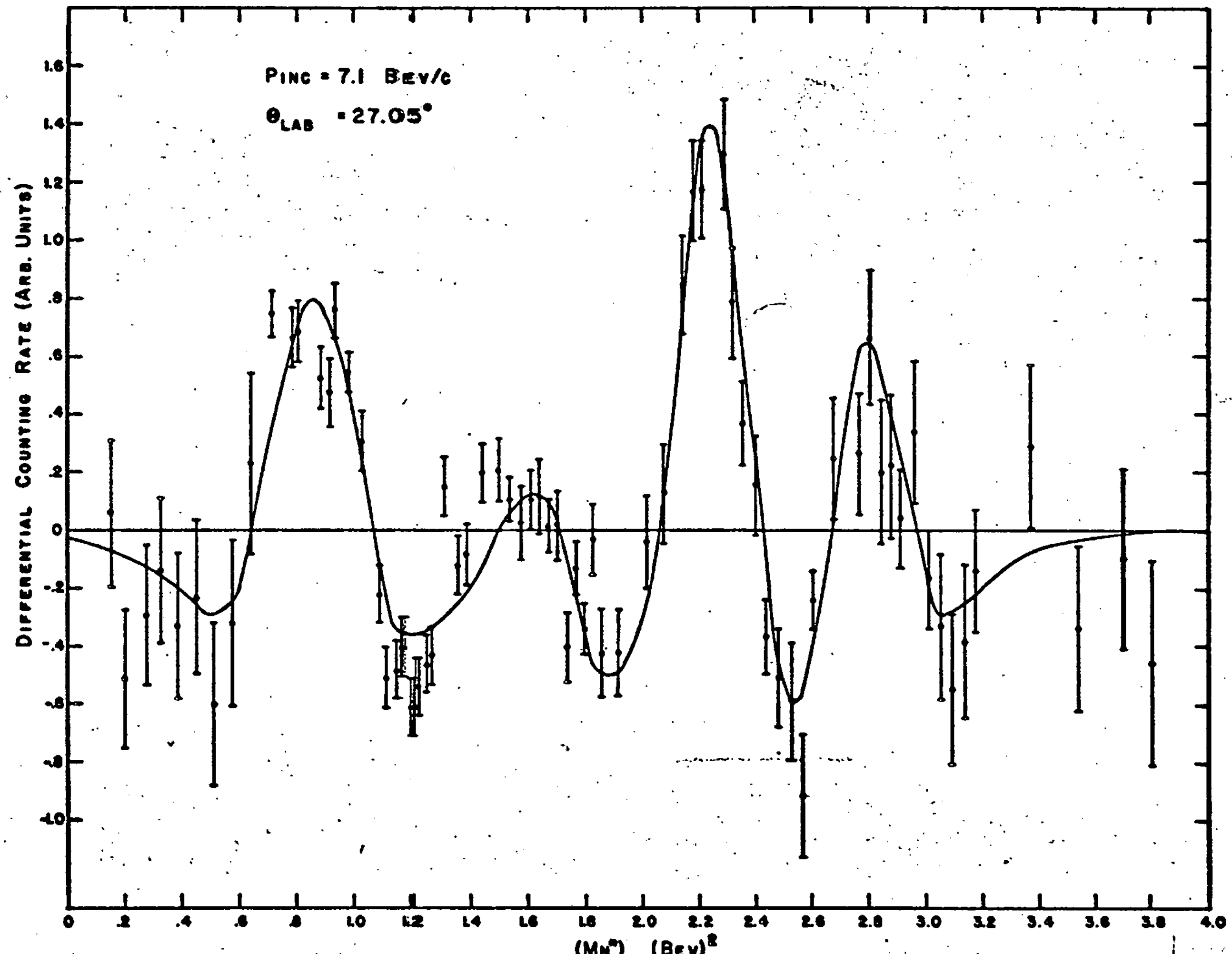

PINC = 7.1 BEV/C
ΘLAB = 27.05°
DIFFERENTIAL COUNTING RATE (ARB. UNITS)
(MN²) (BEV)²
MUB-3410

Fig. 4