Title
REVIEW OF THE KN AND KN TOTAL CROSS SECTIONS BELOW 3-5 GeV/c

Author
Lynch, Gerald.

Publication Date
1970-06-01

Invited talk presented at the
Conference on Hyperon Resonances,
Duke University, North Carolina,
April 24-25, 1970.

UCRL-19844
Preprint

REVIEW OF THE KN AND $\bar{K}N$ TOTAL CROSS SECTIONS BELOW 3.5 GeV/c

Gerald Lynch

June 1970

AEC Contract No. W-7405-eng-48

UCRL-19844

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

REVIEW OF THE KN AND $\bar{K}$N TOTAL CROSS SECTIONS BELOW 3.5 GeV/c*

Gerald Lynch

Lawrence Radiation Laboratory

Berkeley, California 94720

INTRODUCTION

Accurate K^+ and K^- total cross-section measurements have been made in hydrogen and deuterium for kaon laboratory momenta from 400 MeV/c to 3.4 GeV/c. Many of the resonances that are presently tabulated in this region (including all of those with masses greater than 2.2 GeV) have these total cross-section data as their only evidence, and some other resonances depend greatly upon the total cross-section data for their determination. It is the purpose of this paper to present these total cross-section data and also present the derived cross sections in the I = 0 and I = 1 channels in such a way that one can get a feeling for how well the different experiments agree concerning various features of the data and to what extent some of the conclusions are placed in doubt by uncertainties that are introduced during the analysis.

K^+ CROSS-SECTION DATA

Figure 1 shows the K^+p total cross-section data. The most precise data come from three experimental groups: the Brookhaven group, the Rutherford group, and the Arizona group. The square symbols (◫ and ⊠) are for the two Brookhaven experiments of Abrams et al. and Cool et al.[1] The cross entries (⚹) represent the Rutherford experiment of Bugg et al.,[2] and the diamond points (⟠) are for the data of the Arizona group[3] that have been presented at this conference by Ed Jenkins. These data of the Arizona group are the only new data to be added in the past year and as yet they are unpublished. The points shown by the symbol ⍋ are those of Burrows et al.,[4] those denoted by ⍒ are from Cook et al.,[5] and the points shown by the double triangle (⧗) at low momentum are

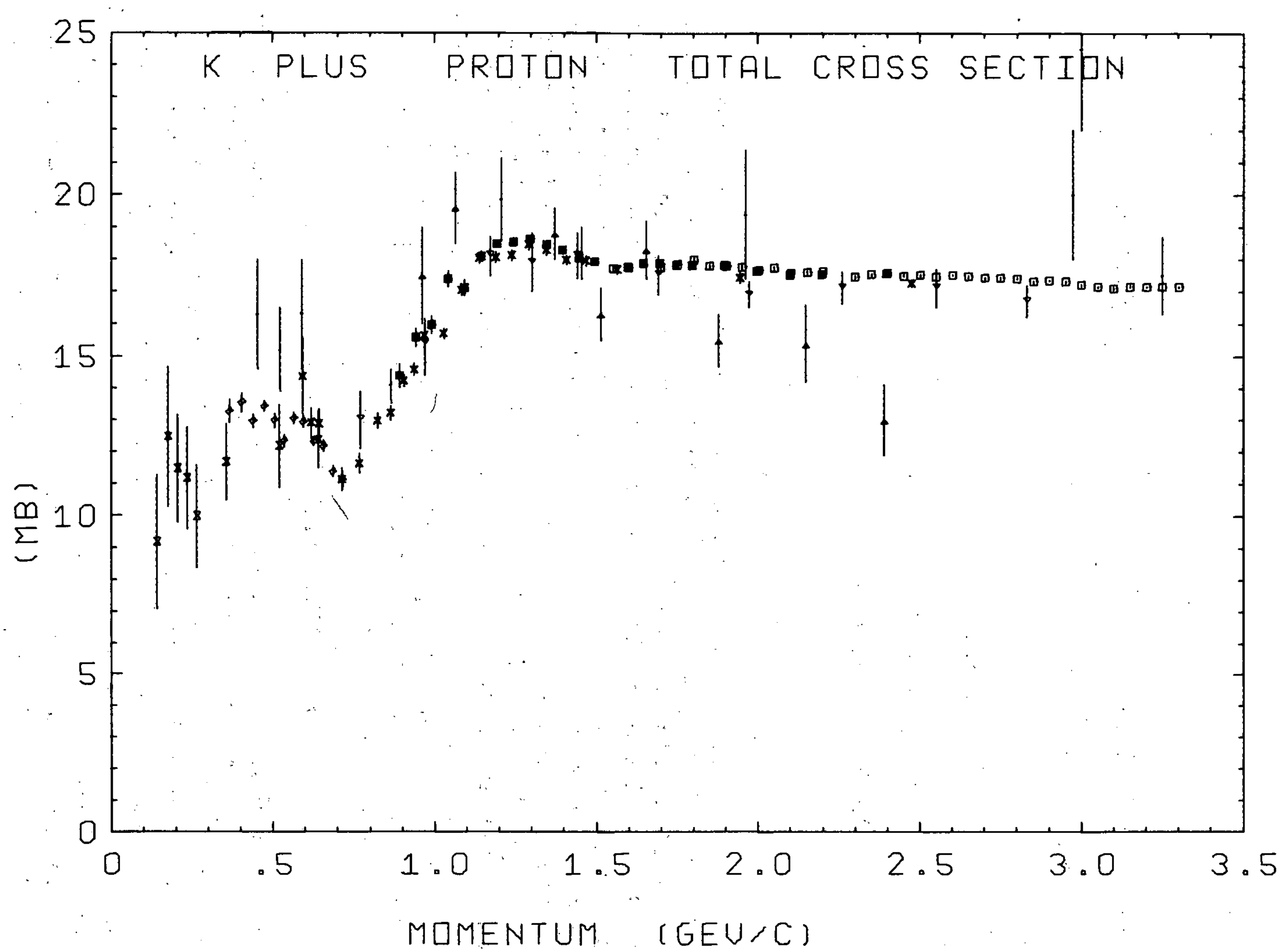

FIG. 1. The K^+p total cross-section data from 0 to 3.5 GeV/c.

those of Goldhaber et al.[6] The points denoted by + are from six other experiments, none of which covered a broad momentum range. Figures 2 and 3 show somewhat magnified representations of these data, with the less precise experiments omitted. The solid curve that is drawn here represents no model, but is merely a freehand curve drawn through the data. The purpose of this curve is not to prejudice the eye but rather to show what curve has been used for making corrections to the data, corrections for the Glauber effect, the finite momentum resolution of the experiments, and the effect of the internal momentum of the deuteron.

Since the K^+p system has I = 1, these figures (1 through 3) represent the I = 1 K-nucleon cross section. They show the peak at about 1.25 GeV/c (corresponding to a mass of 1.91 GeV) that has been called the Z_1^* since the time that it was first observed by Cool et al.,[1] in 1966. We can also see that the valley in the cross sections at 0.7 GeV/c that was indicated by the data of Bugg et al.[2] is confirmed by the data of the Arizona group. Figure 4 shows the difference between the measured values and the smooth curve. The absolute values of these differences merely reflect where I have chosen to draw the smooth curve. What is meaningful on this graph is the differences between different experiments. It should be pointed out that the errors shown on these plots are statistical errors only. This is the procedure that has been customary in presenting these total cross-section data. One should realize, however, that all of these experiments may have systematic errors of at least 1%, which is five times the statistical error on some of the higher-energy cross-section measurements. These systematic errors should not affect any local structure indicated by one experiment, but must be considered when comparing different experiments.

Figure 5 shows the K^+d total cross-section data. The symbols are the same as those used for the K^+p data. In the more magnified plot of these data shown in Fig. 6 one can see that there is a discrepancy of about 7% between the Arizona data and the Rutherford data in the region in which they overlap. This systematic error is a serious one. Since, as we shall see later, this same effect occurs in the K^- data, one is led to believe that somewhere there is a systematic error that affects the Kd data but not the Kp data. One possible contribution to this is that there is some uncertainty concerning the determination of the deuterium density. But since this uncertainty seems to be only about 1% and it is independent of the beam momentum it is probably not the main source of this discrepancy. There is another possible explanation for this effect; this arises from the difference in the extrapolation procedures used by the two groups. In any transmission-experiment measurement an extrapolation to zero angle must be made to account for those interactions resulting in particles produced at very small angles. This procedure is more straightforward for the Kp

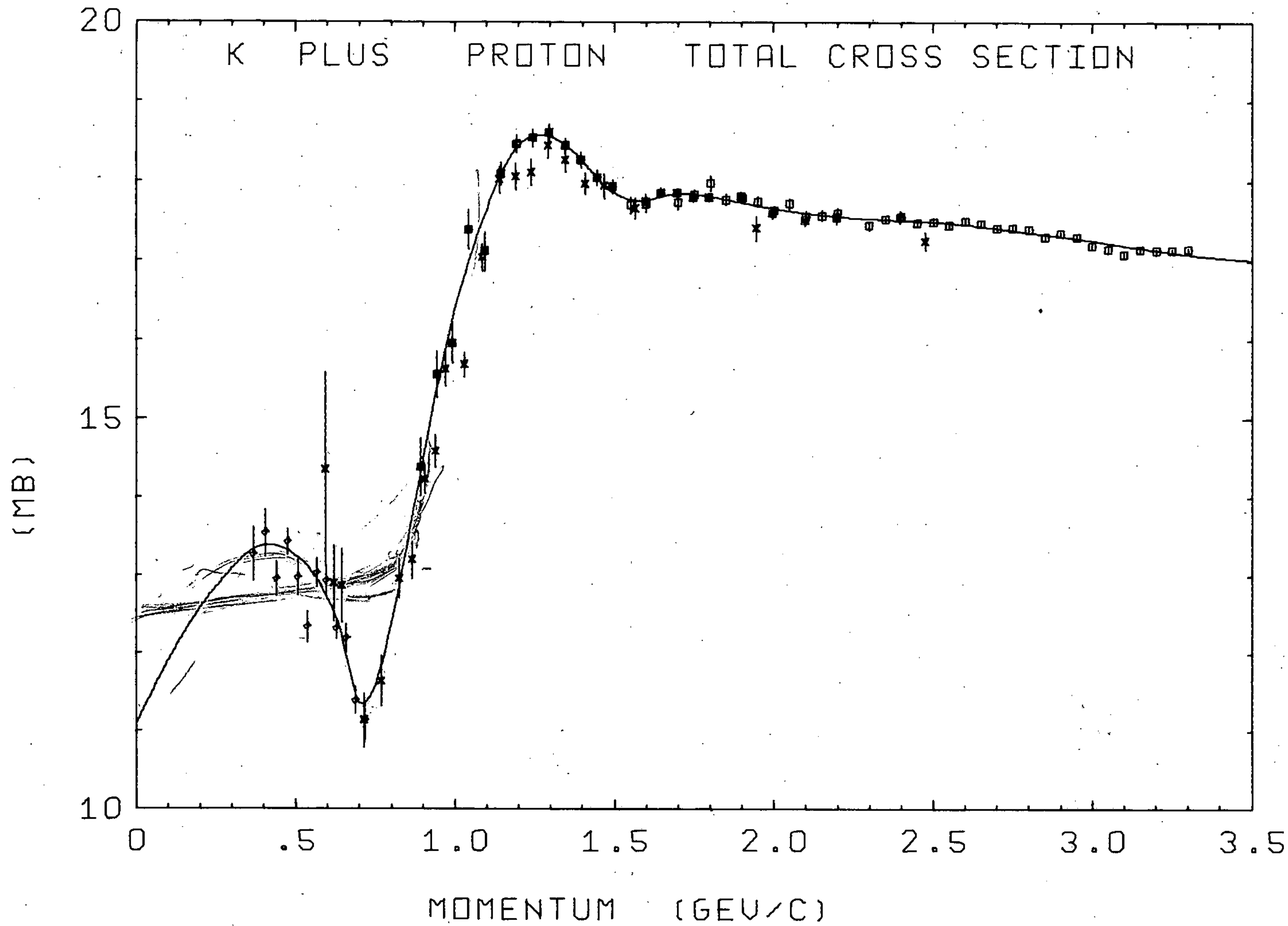

FIG. 2. The K^+p total cross-section data from 0 to 3.5 GeV/c with a smooth curve.

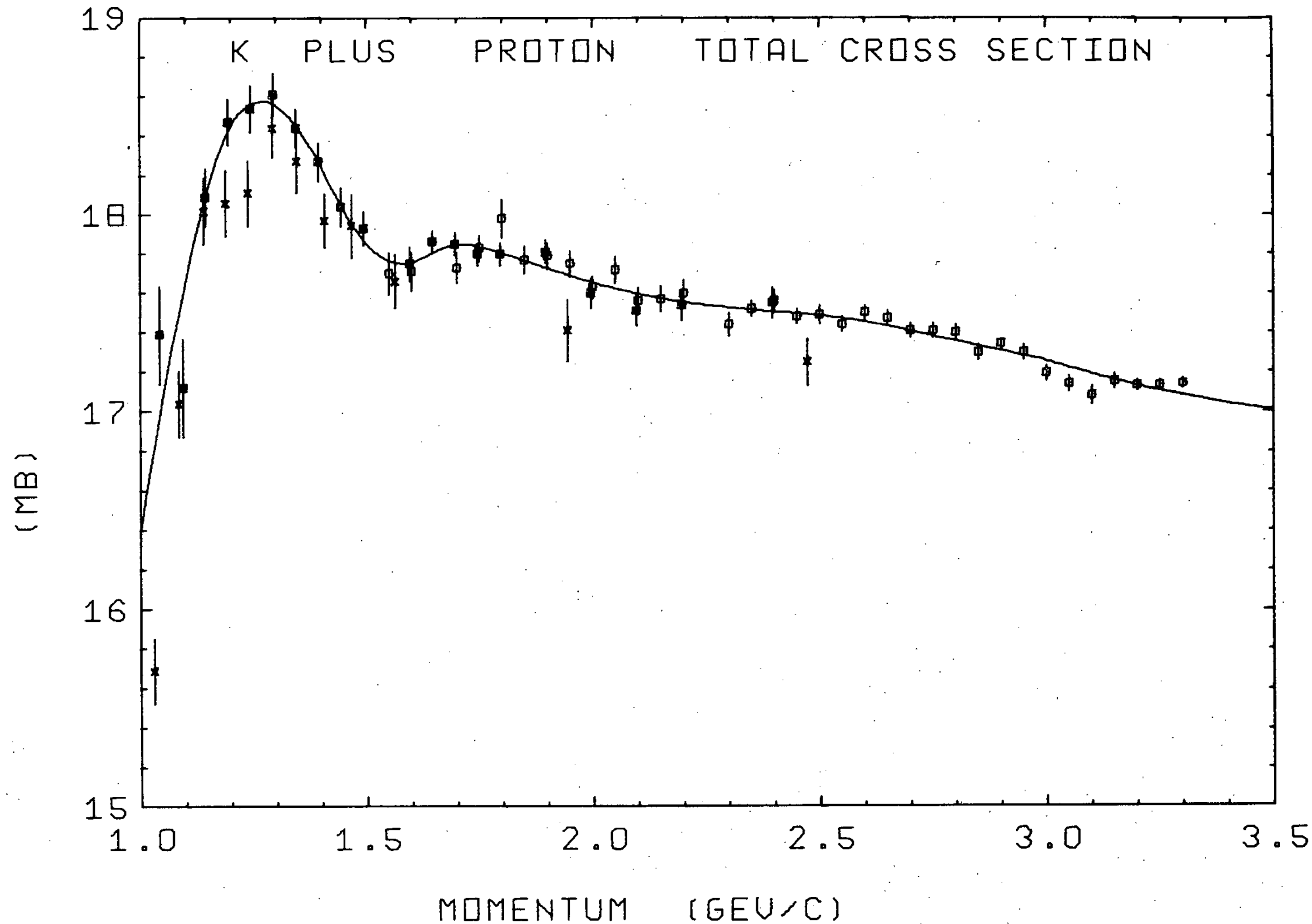

FIG. 3. The K^+p total cross-section data from 1.0 to 3.5 GeV/c with a smooth curve.

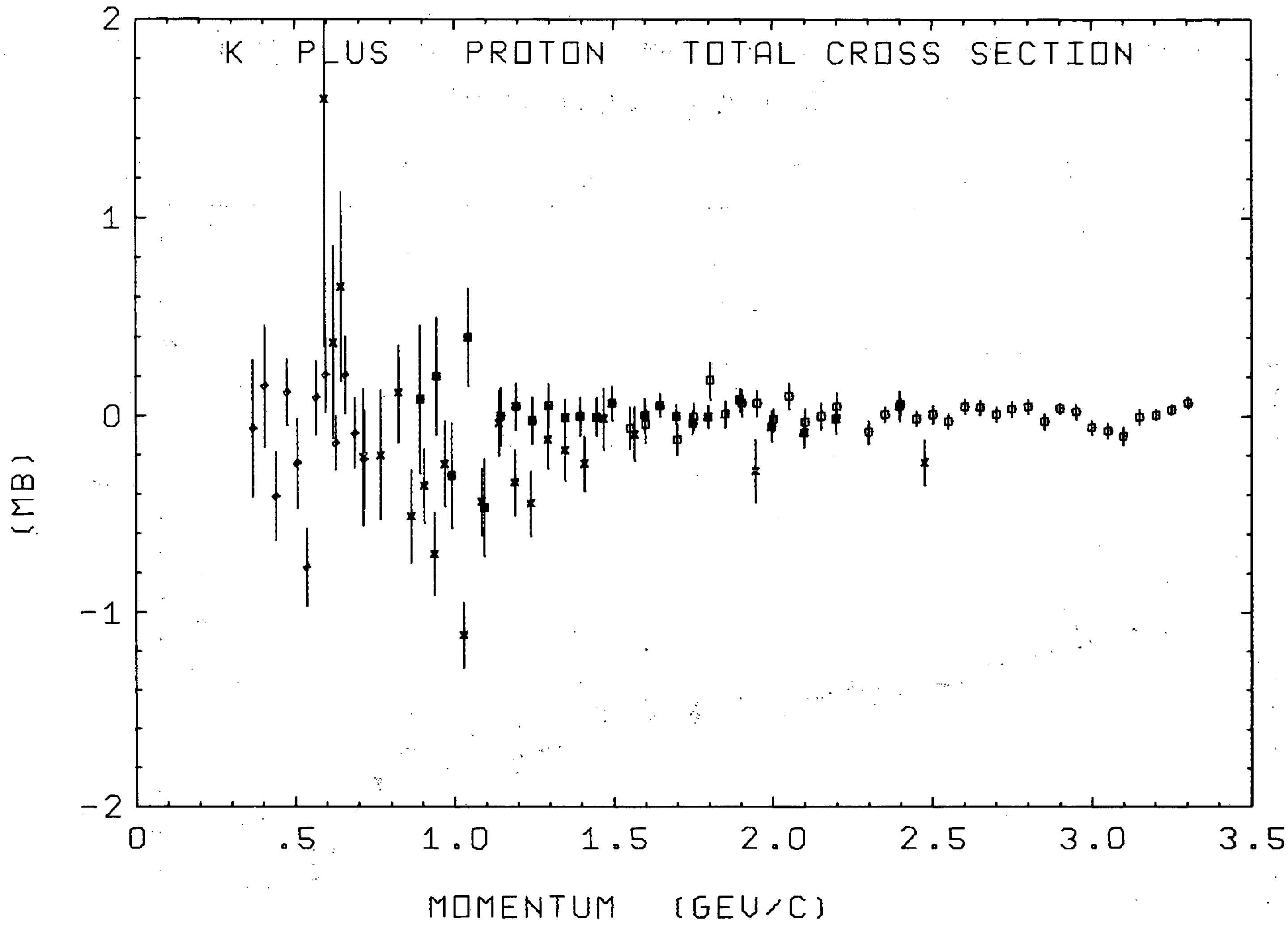

FIG. 4. The difference between the K^+p total cross-section data and a smooth curve.

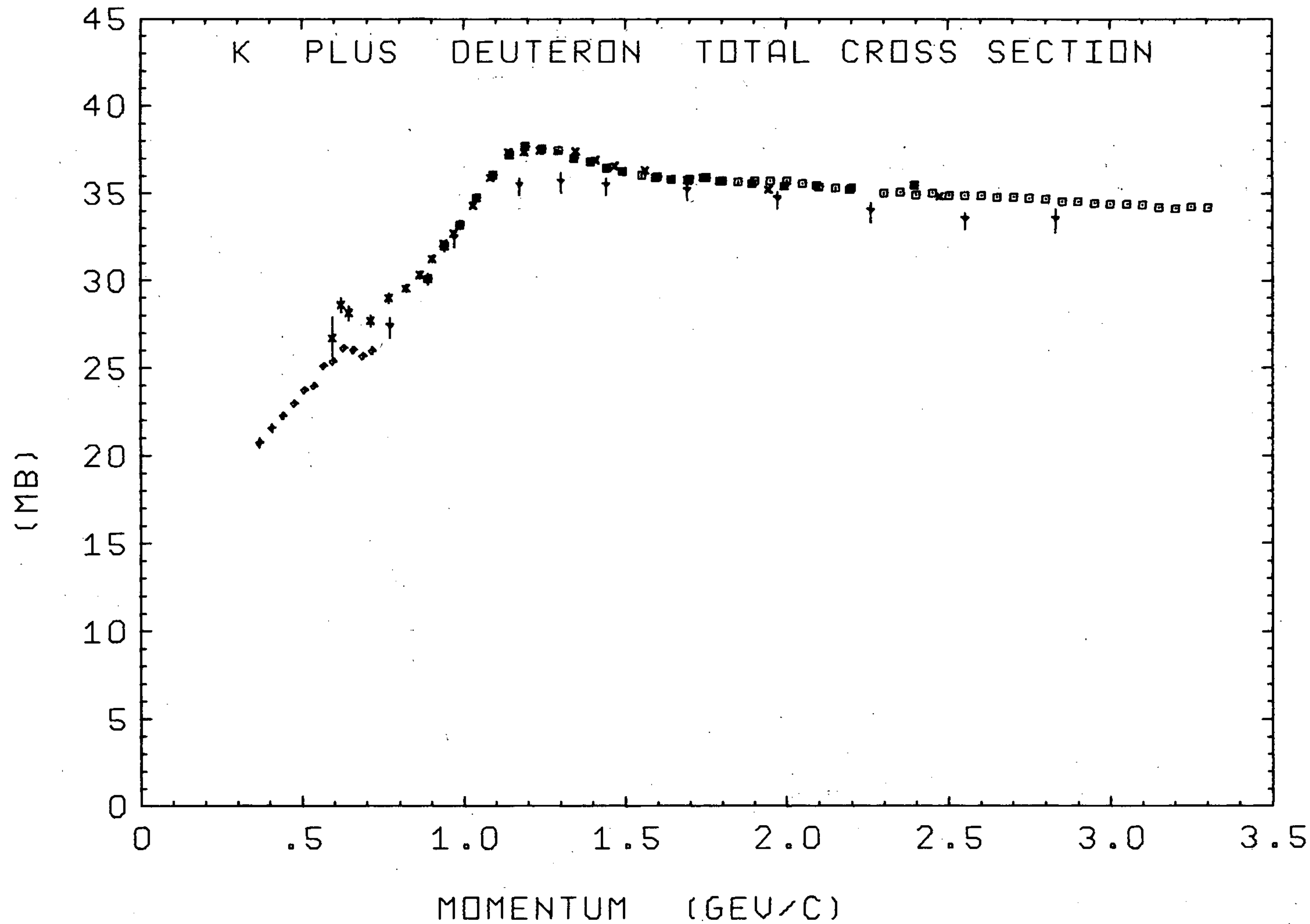

FIG. 5. The K^+d total cross-section data from 0 to 3.5 GeV/c.

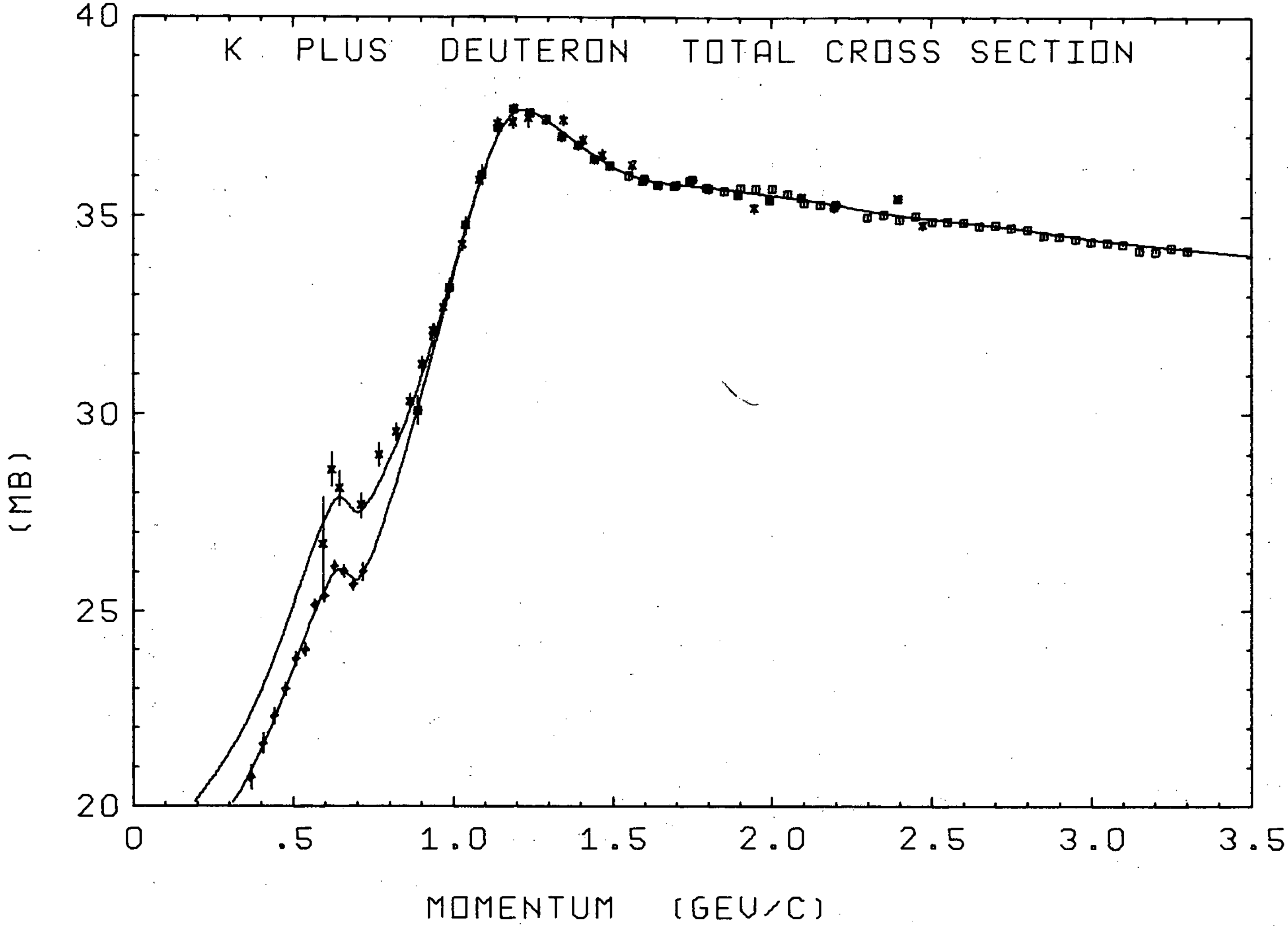

FIG. 6. The K^+d total cross section data from 0 to 3.5 GeV/c with smooth curves.

cross section where the elastic-scattering angular distribution is very nearly linear on a semilog plot than it is for the Kd cross section, for which the plot is not linear but has a peak at small angles due to coherent production. The Arizona group used a linear extrapolation whereas the Rutherford group used a quadratic extrapolation and found that the quadratic term is negligible for hydrogen but several standard deviations for deuterium. It would be worthwhile to investigate how much of the discrepancy can be explained by this effect.

Two smooth curves have been drawn in Fig. 6. The lower one connects the data of the Brookhaven group with those of the Arizona group, following the shape of the Rutherford data in between. The higher curve follows the data of the Rutherford group and is exactly 7% above the lower curve for all momenta less than 650 MeV/c. Another possible curve that can be drawn through these data is shown in Fig. 7, which was taken from an analysis of the K^+ data recently performed by Dowell.[8] This interpretation explains the disagreement between the two experiments in terms of poorly measured points by both experiments in the region in which they overlap, rather than in terms of a systematic difference between the experiments.

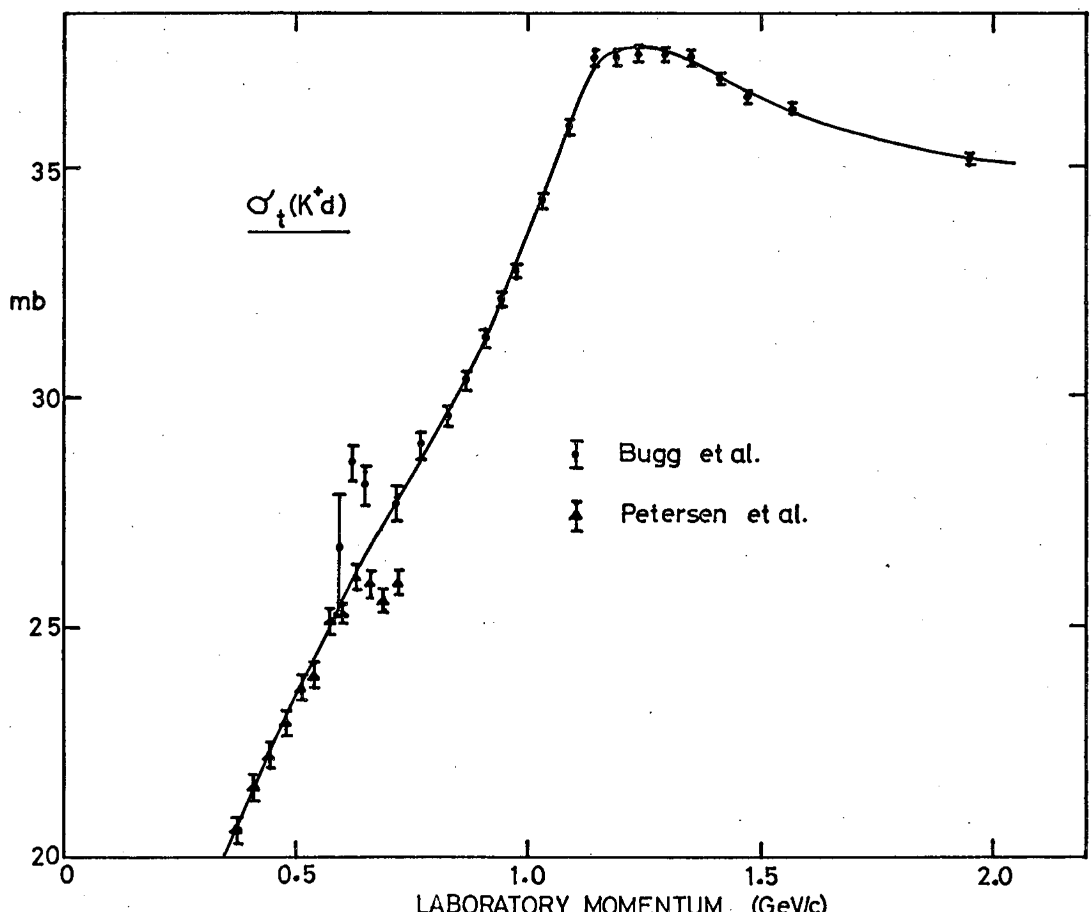

FIG. 7. An alternative smooth curve for the K^+d total cross-section data.

Figure 8 is a magnified plot of the K^+d data above 1 GeV/c, and Fig. 9 shows the differences between the data points and the lower curve of Fig. 6. Again let me emphasize that the fact that some of the points deviate from zero is no reflection on that experiment but rather a reflection of my somewhat arbitrary choice of where to draw the smooth curve.

K^- CROSS SECTION DATA

The K^- total cross-section data are shown in Fig. 10. The symbols on this plot are the same as those on the previous plots except that the double triangle symbol (⧗) represents the data of the CHS (CERN-Heidelberg-Saclay) collaboration.[9] These CHS data, along with the data of the Arizona group, are the results that are new in the past year. The first three points in Fig. 10 show the peak in the cross section caused by the $Y^*(1520)$.

In Figs. 11 and 12 one can see the other structure in the K^-p cross section. In particular, the small but significant peak at 800 MeV/c shows up here and its detection does not depend upon the K^-d data. Figure 13 shows how well the experiments agree. Around 1.1 GeV/c the Brookhaven data are higher than the Rutherford data. This seems to be due to a small disagreement in the momentum determination. At the low-momentum end, the Arizona data are systematically higher than the CHS data.

The K^-d cross-section data are shown in Figs. 14, 15, and 16. The smooth curves in Fig. 15 were chosen in the same way that the curves for the K^+d data were chosen, with the upper curve 7% above the lower one for momenta less than 650 MeV/c. In Fig. 17 one can see that there are quite a few systematic differences between the experiments for the K^-d cross-section data.

DERIVED CROSS SECTIONS

The purpose of measuring both the Kp and Kd cross sections is to obtain from them the cross sections for I = 0 and I = 1. If the deuteron were merely composed of a proton and a neutron at rest, then we could calculate these cross sections from the deuteron and proton cross sections as follows:

for K^+, $\quad \sigma_1 = \sigma_p,$
$\quad\quad\quad\quad \sigma_0 = 2\sigma_d - 3\sigma_p,$

and for K^-, $\quad \sigma_1 = \sigma_d - \sigma_p,$
$\quad\quad\quad\quad \sigma_0 = 3\sigma_p = \sigma_d.$

There are a number of corrections to be made to these relations. One correction is the shadowing correction, often called the Glauber correction.[10] One replaces σ_d in the above formulas by $\sigma_d + \sigma_g$, where the correction term σ_g is approximately equal to $\langle r^{-2} \rangle \sigma_n \sigma_p / 4\pi \approx \sigma_n \sigma_p / 400$ mb, where $\langle r^{-2} \rangle$ is the average inverse square of the neutron-proton separation in the deuteron ground state.

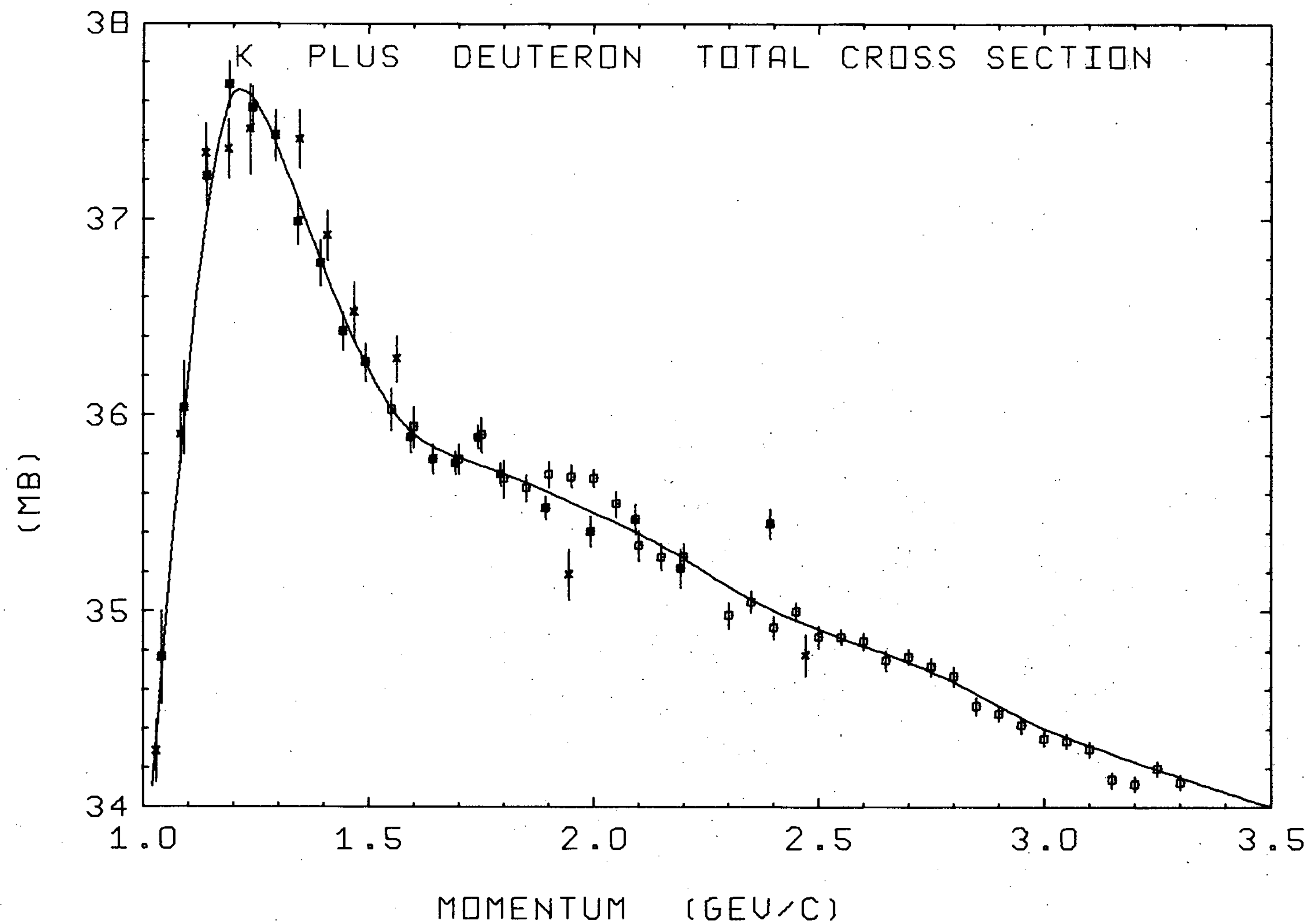

FIG. 8. The K^+d total cross-section data from 1.0 to 3.5 GeV/c with a smooth curve.

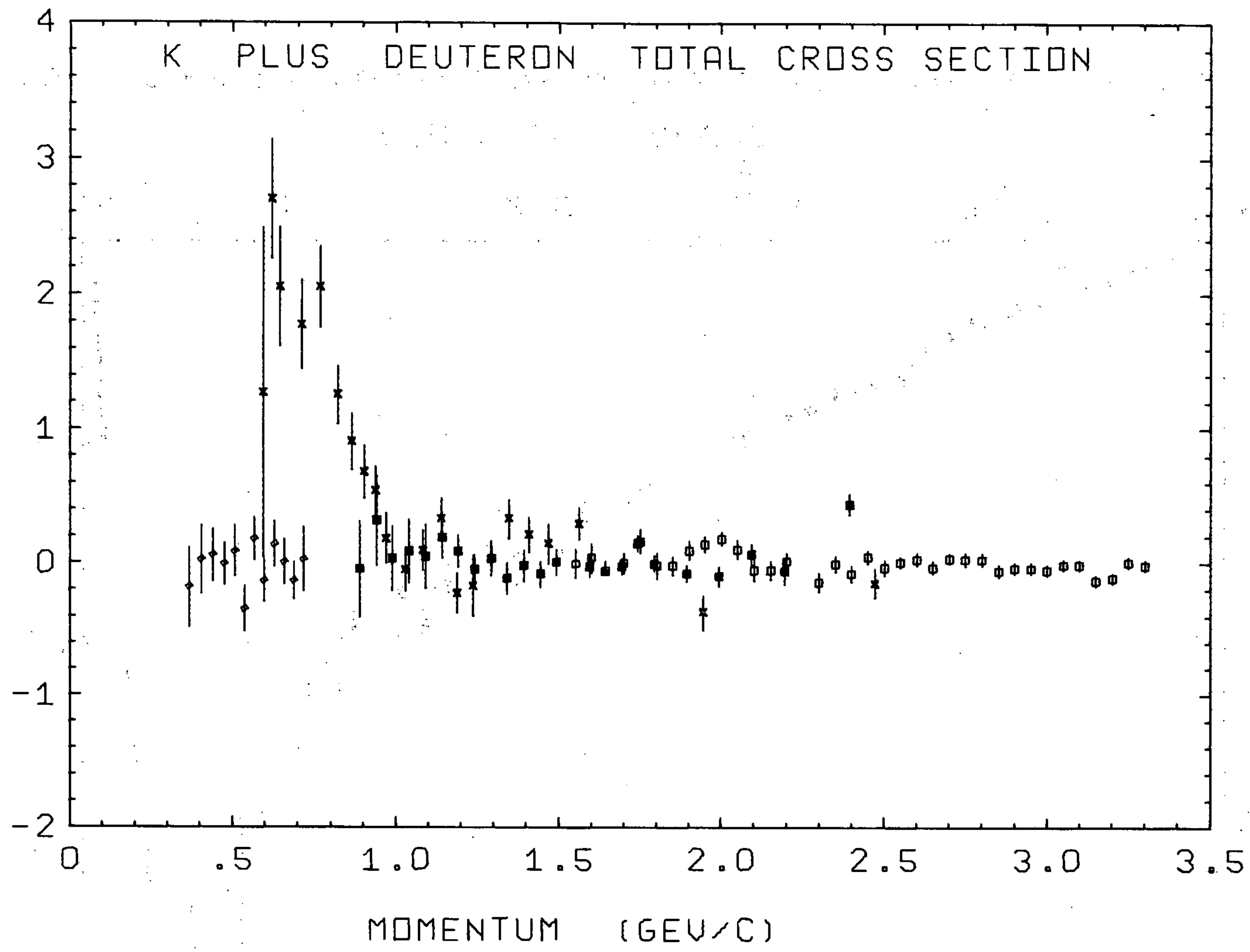

FIG. 9. The difference between the K^+d total cross-section data and the lower smooth curve.

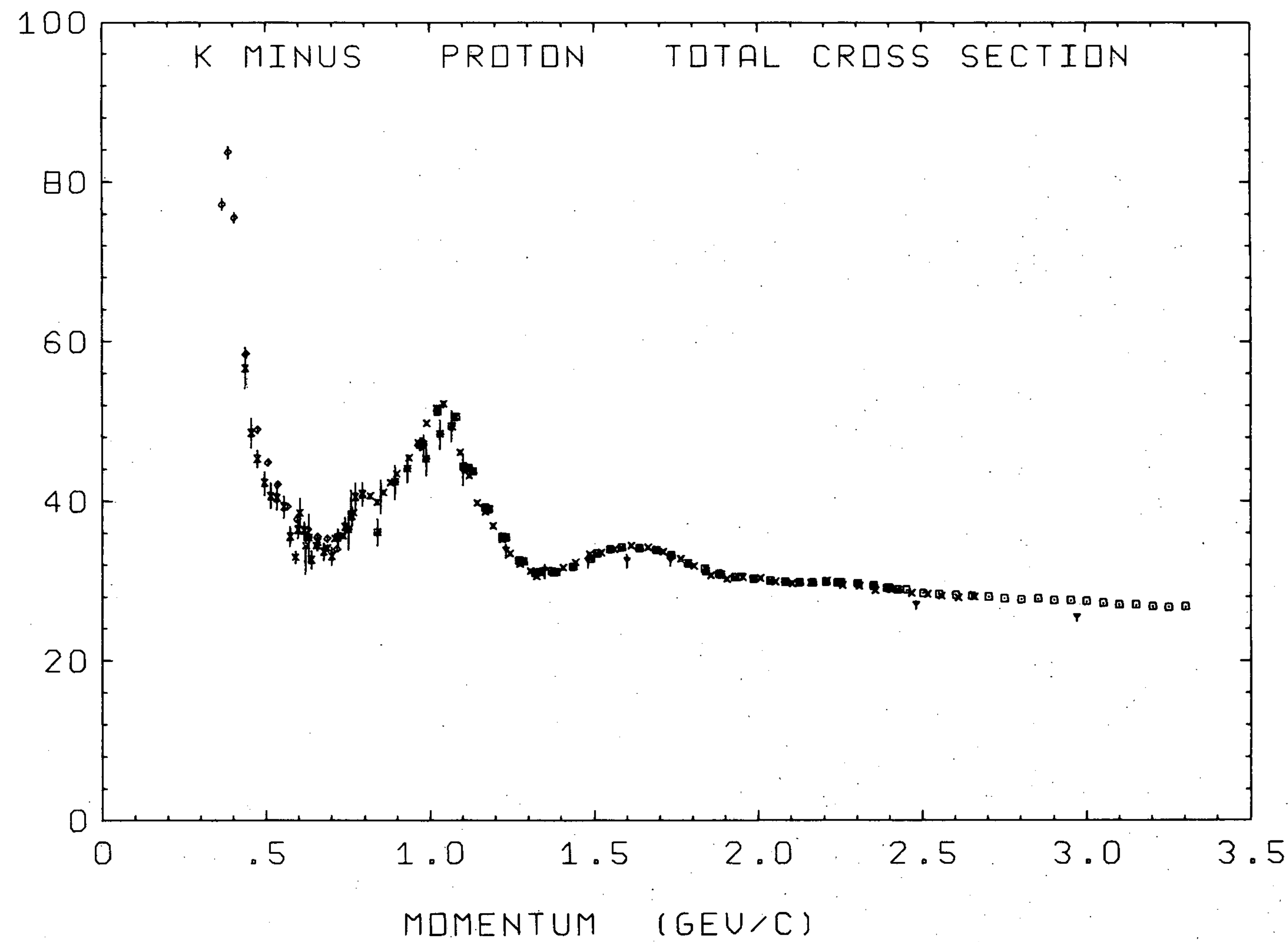

FIG. 10. The K^-p total cross-section data from 0 to 3.5 GeV/c.

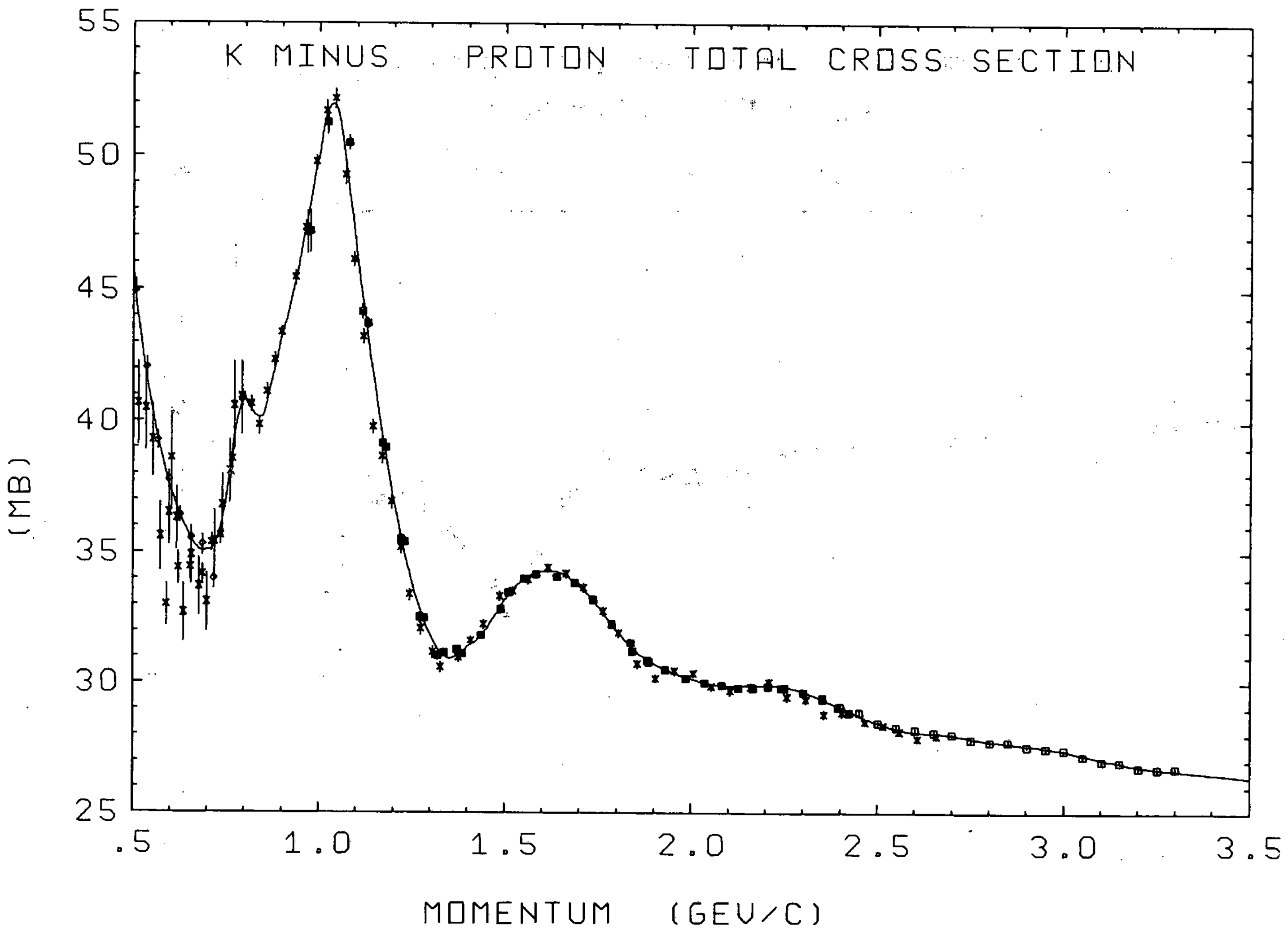

FIG. 11. The K^-p total cross-section data from 0.5 to 3.5 GeV/c with a smooth curve.

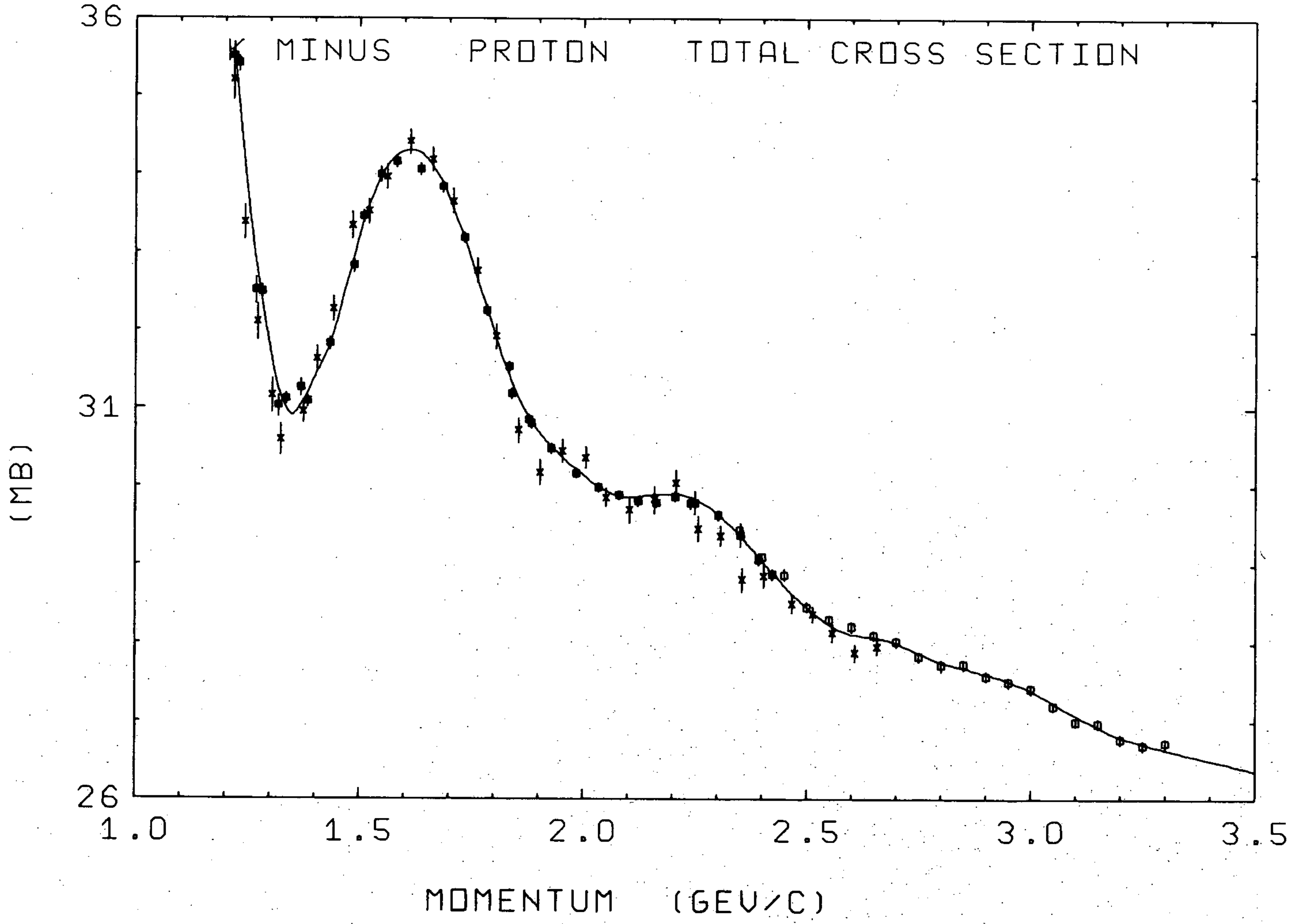

FIG. 12. The K^-p total cross-section data from 1.0 to 3.5 GeV/c with a smooth curve.

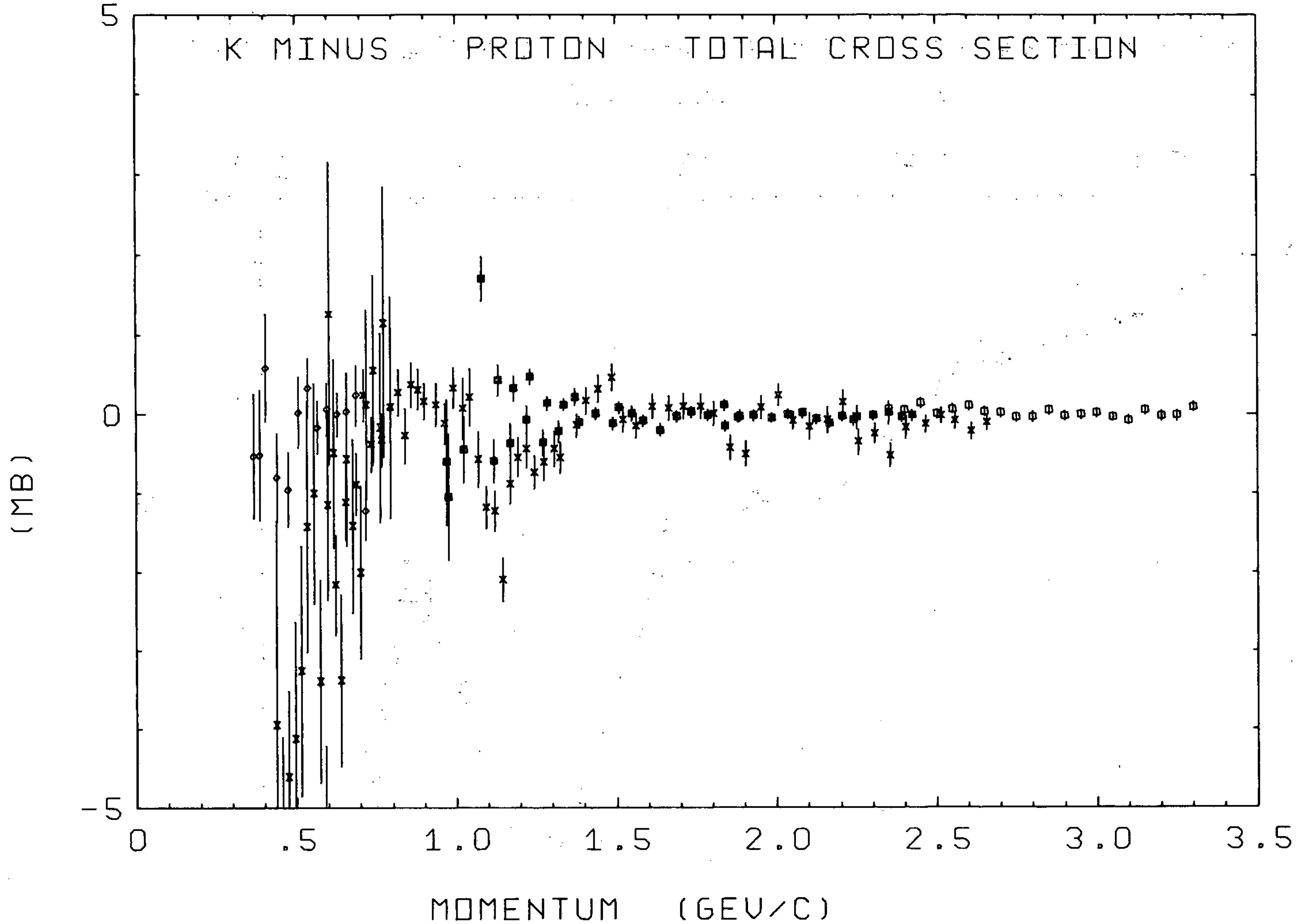

FIG. 13. The difference between the K^-p total cross-section data and the smooth curve.

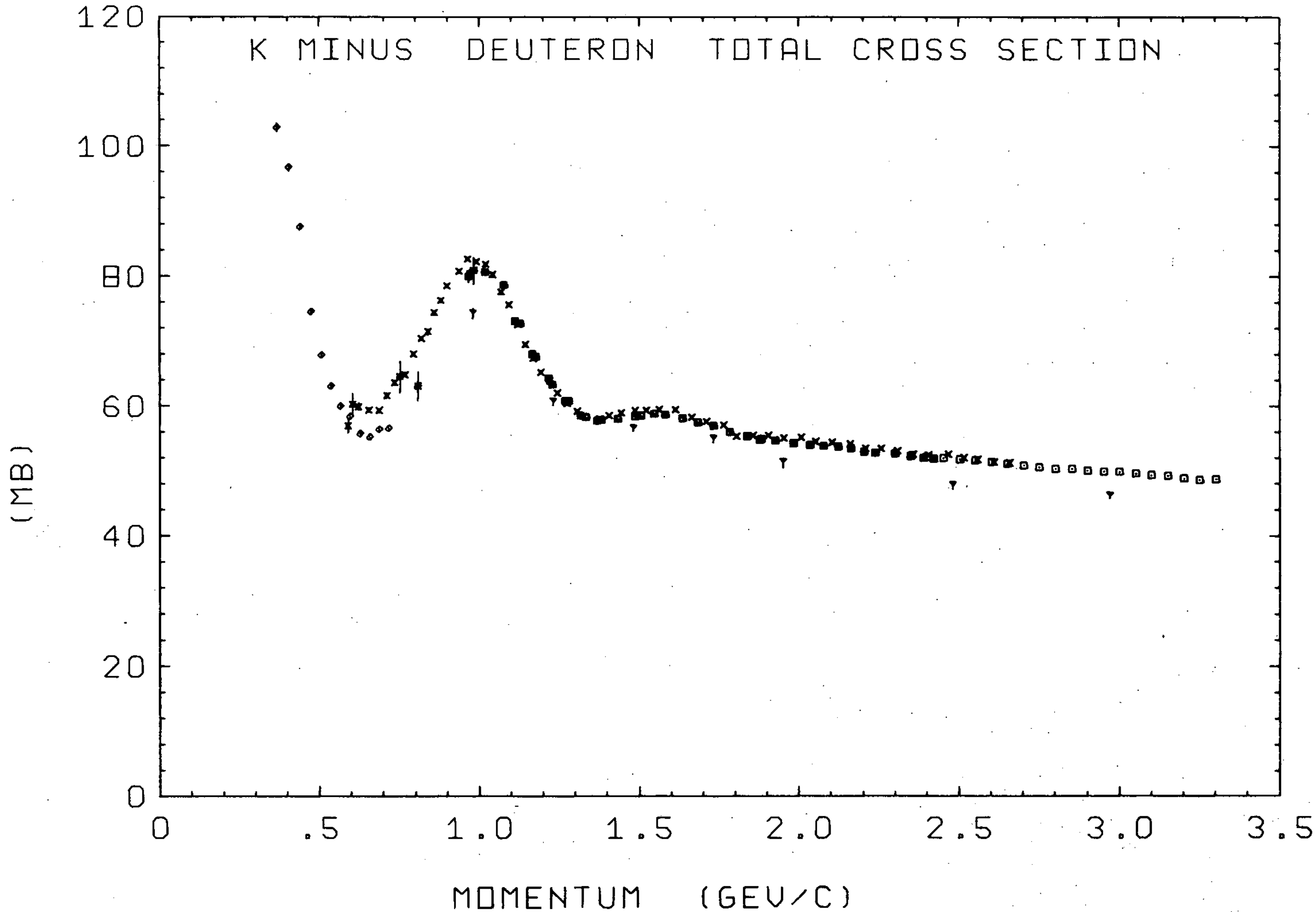

FIG. 14. The K^-d total cross-section data from 0 to 3.5 GeV/c.

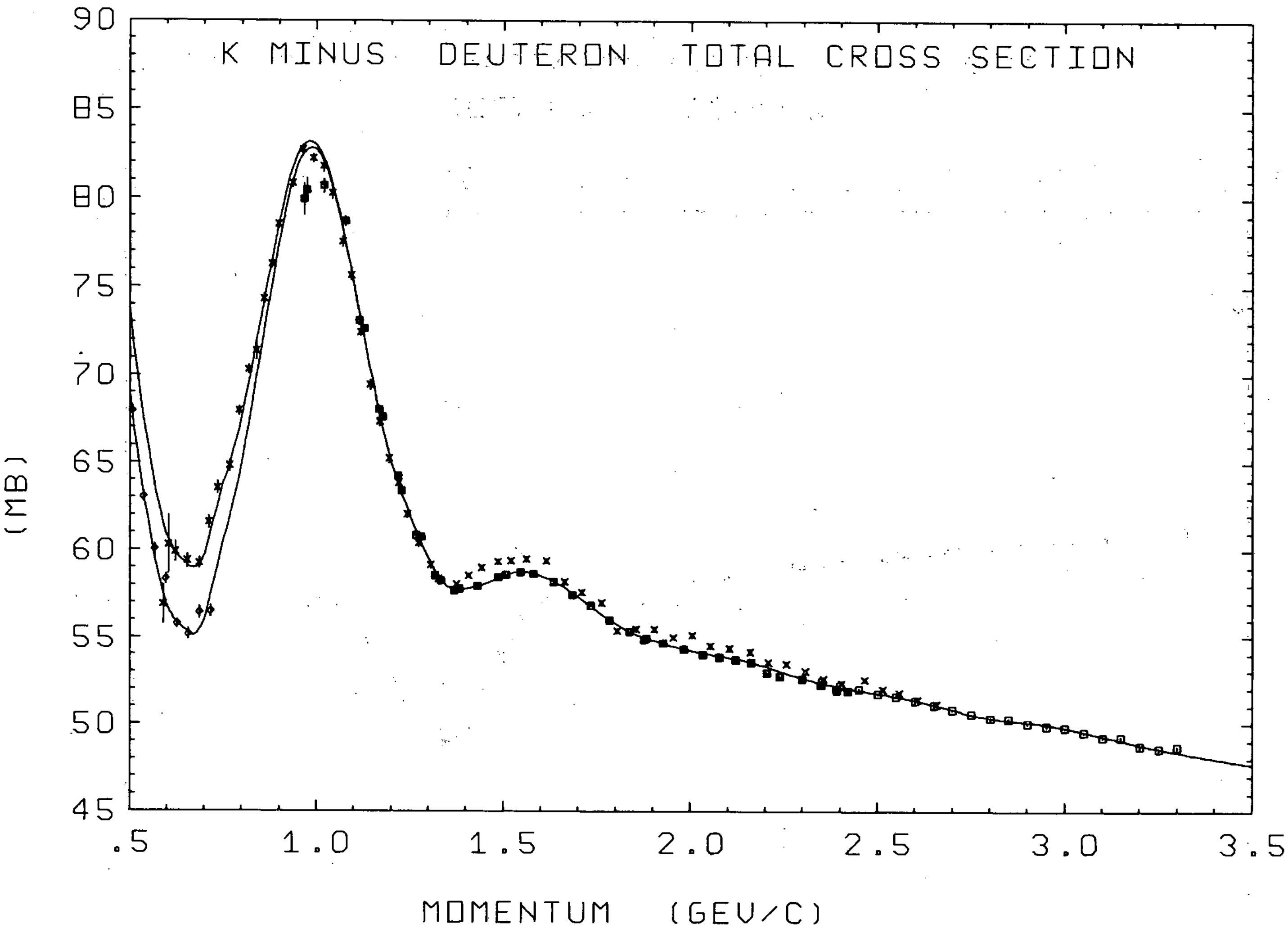

FIG. 15. The K^-d total cross-section data from 0.5 to 3.5 GeV/c with a smooth curve.

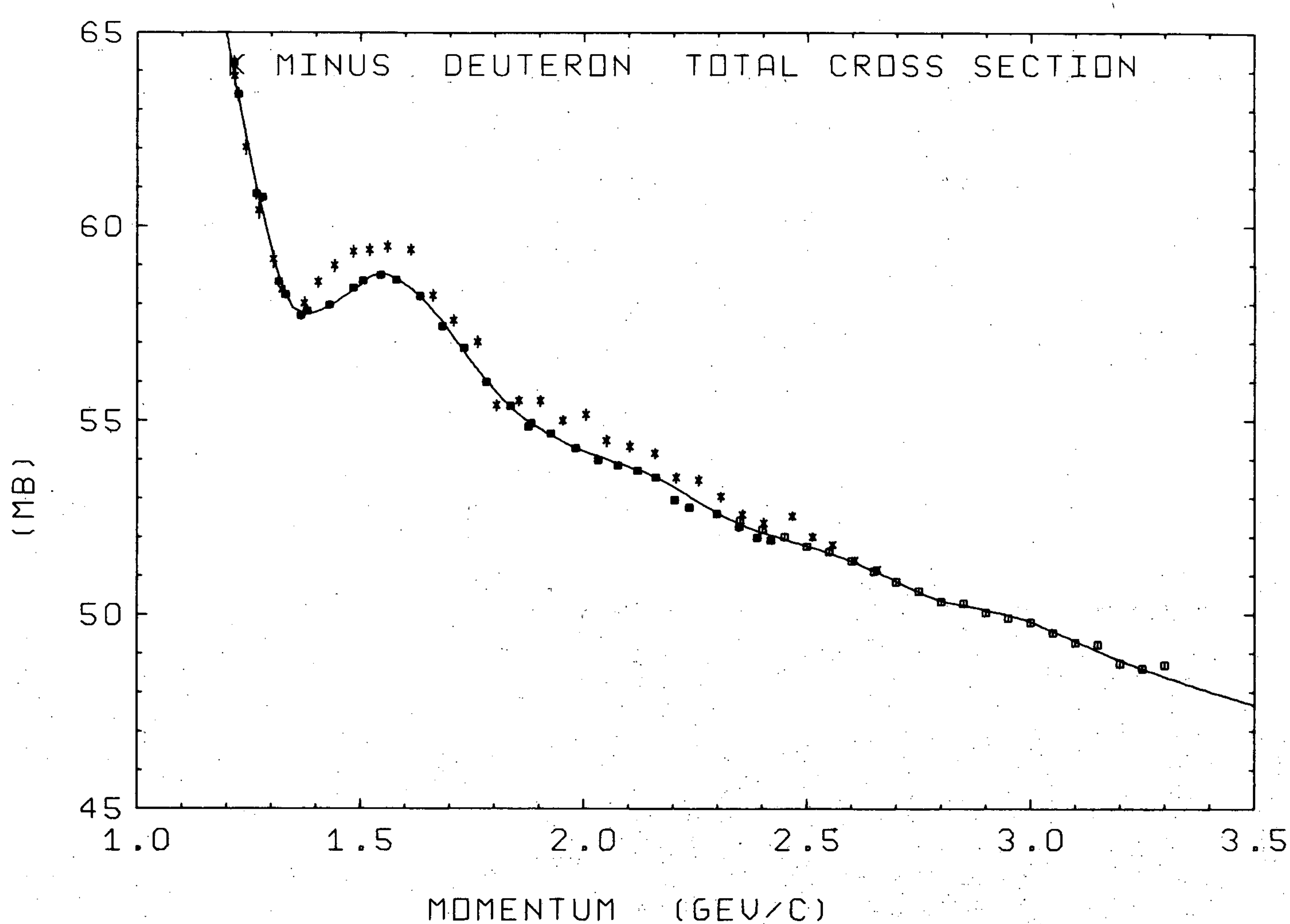

FIG. 16. The K^-d total cross-section data from 1.0 to 3.5 GeV/c with a smooth curve.

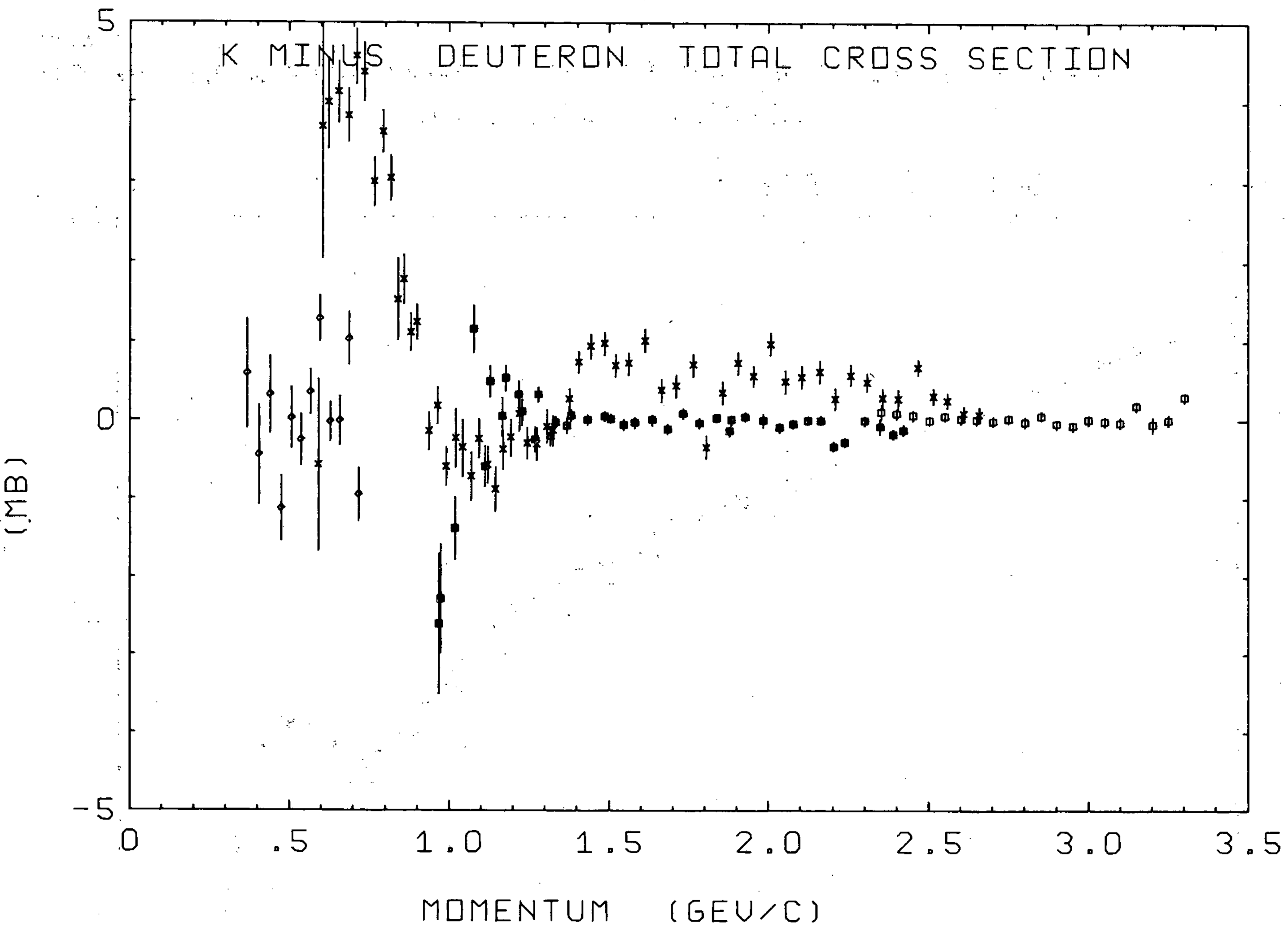

FIG. 17. The difference between the K^-d total cross-section data and the lower smooth curve.

In practice a more complicated form for σ_g has been used that makes it satisfy charge independence and tries to take into account the real parts of the scattering amplitudes.[11]

A second correction is the correction for the effect of the internal momentum of the nucleons in the deuteron. To make this correction one must "unfold" the deuteron cross section; that is, find that neutron cross section which, when added to the proton cross section, smeared out by the internal momentum of the deuteron, and corrected for the Glauber correction produces the observed deuteron cross section. As long as the nucleon cross sections have no fine structure this process is straightforward and adds no significant additional errors to the final result. However, if there is structure with widths on the order of the effect of the smearing caused by the deuteron internal momentum, then the process of unfolding does add additional uncertainties. The full width at half height of the effective resolution caused by this smearing is about 28 MeV in center-of-mass energy at a beam momentum of 500 MeV/c and 46 MeV/c at 1000 MeV/c, and 82 MeV at 2.5 GeV/c.

There is a third correction that has been made to these data, a correction for the finite momentum resolution of the experiments. This correction is very small for the K^+ data, and for the K^- data is significant only at the lowest momenta. It affects both the proton and the deuteron cross sections. In order to make the corrections to the data to obtain σ_0 and σ_1, calculations were made using the smooth curves that were drawn through the data. But in order to present a result that is nearly independent of the smooth curve that was used, one can present the individual data points modified by this correction. This procedure is facilitated by the fact that each of these experiments has measured the hydrogen and deuterium cross sections at the same, or very nearly the same, momenta.

THE I = 0 KN CROSS SECTION

The data points for σ_0 for the KN system are shown Fig. 18. Clearly there is a broad peak from 700 to 1200 MeV. It is unclear whether this broad peak is separated into two distinct peaks, and this determination depends upon which data points are correct in this region. The next graph (Fig. 19) shows these same data points along with the smooth curve that resulted from the original smooth curves assumed, which in the case of the deuteron data was a curve that is exactly midway between the two smooth curves shown in Fig. 6. This smooth curve in Fig. 19 should not be favored over any other smooth curve that could be drawn through these data. Indeed it does not seem like a very natural curve to draw in this case. What is important is that the position of the points on Figs. 18 and 19 would differ very little from those shown if the corrections had been made using any reasonably smooth curve drawn through the raw data.

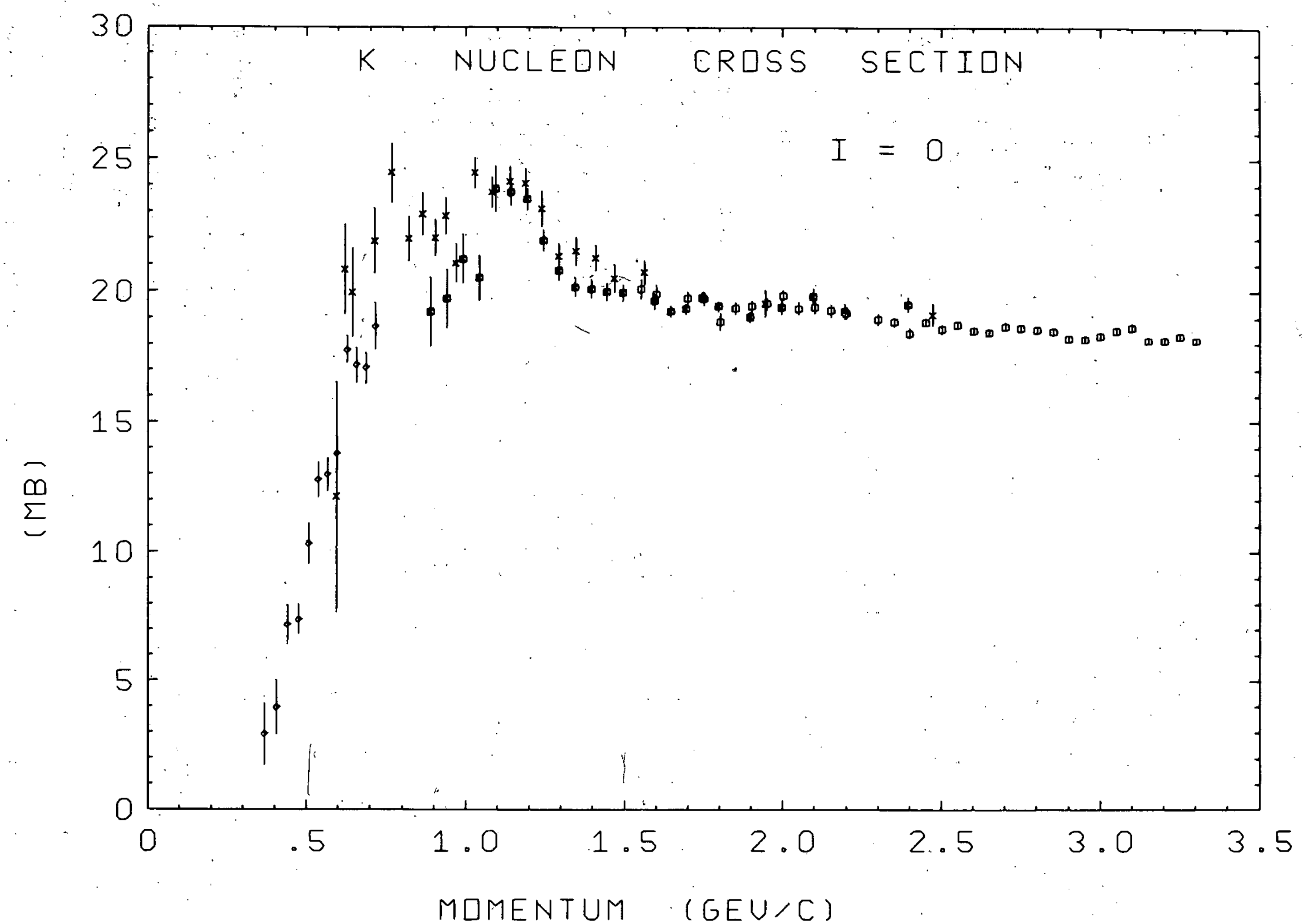

FIG. 18. The data points for the I = 0 KN cross section.

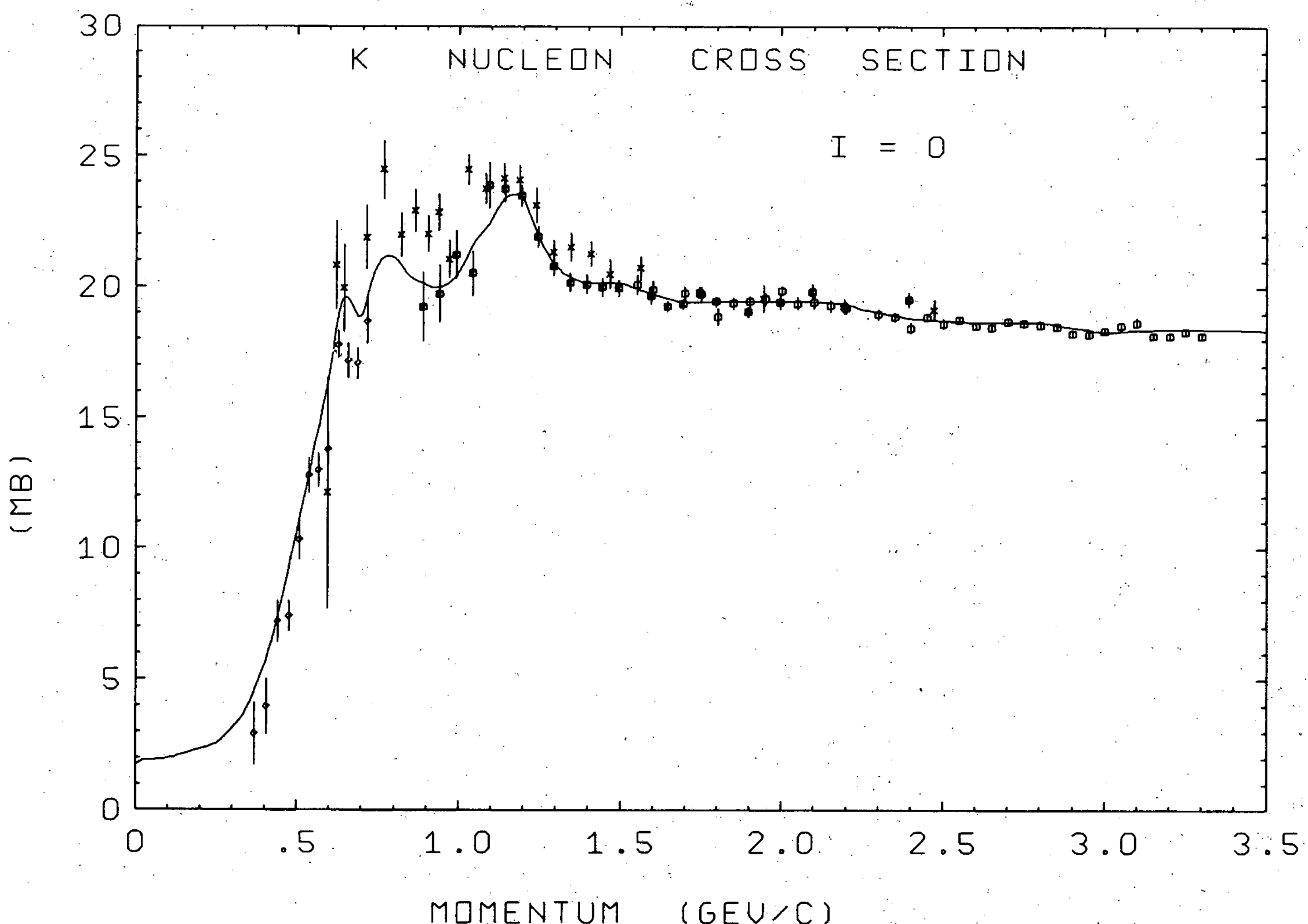

FIG. 19. The data points and smooth curve for the I = 0 KN cross section.

The next few figures are presented in an attempt to give one a feeling for the effect of various factors involved in the calculation of σ_0. Figure 20 compares the same solid curve that is in Fig. 19 with the result obtained if the internal momentum of the deuteron is ignored or if a different deuteron wave function is used. In doing the calculation a two-parameter Moravcsik deuteron wave function[12] was used. Here we see that the result is negligibly different if the Hulthén wave function is used. We can see that the unfolding process accentuates the structure that is there but for the K^+ data does not make the structure qualitatively different.

The effect of the Glauber correction is illustrated in Fig. 21. Clearly this Glauber correction has a considerable effect on the magnitude of the cross section but has essentially no effect on its structure. As I said before, the Glauber-correction formula involves the real part of the KN scattering amplitude. Figure 21 shows that whether or not this effect is included is unimportant. Actually the form of the Glauber correction used is derived from a high energy approximation that may be violated at the lower energies of this experiment. Above one GeV/c it is probably very good.

The methods used to do the unfolding and the Glauber correction have been checked for the pion-nucleon data by both the Brookhaven and Rutherford groups.[13] Since the I = 1/2 pion-nucleon cross section can be calculated from π^-p and π^+p cross sections as well as from π^-p and π^-d cross sections, the method can be checked. The Brookhaven group found that above 900 MeV/c this method checks very well. But the Rutherford group found that at lower momenta the self-consistency is much poorer, to the extent that the Glauber correction seems to have the wrong sign. It is very difficult to estimate how much uncertainty is placed into the final derived cross sections owing to the inadequacy of the assumptions made: that one can use an impulse approximation to calculate the effect of the internal momentum of the nucleons in the deuteron, and that one can use at low momenta the Glauber correction that is valid in the diffraction region.

Previous attempts at unfolding the cross sections have neglected the flux-factor effect that arises from the fact that the measured rate depends upon not only the cross section but the relative velocities of the beam and the target. The result of neglecting this effect, as well as the result of neglecting the binding energy of the dueteron, is shown in Fig. 22. Each of these effects causes a slight shifting of the positions of peaks, but the magnitude of the effect is not important at the present level of accuracy.

THE I = 0 AND I = 1 $\bar{K}N$ CROSS SECTIONS

Before I present the results for the $\bar{K}N$ cross sections in the form of data points, let us look at how the results in this case

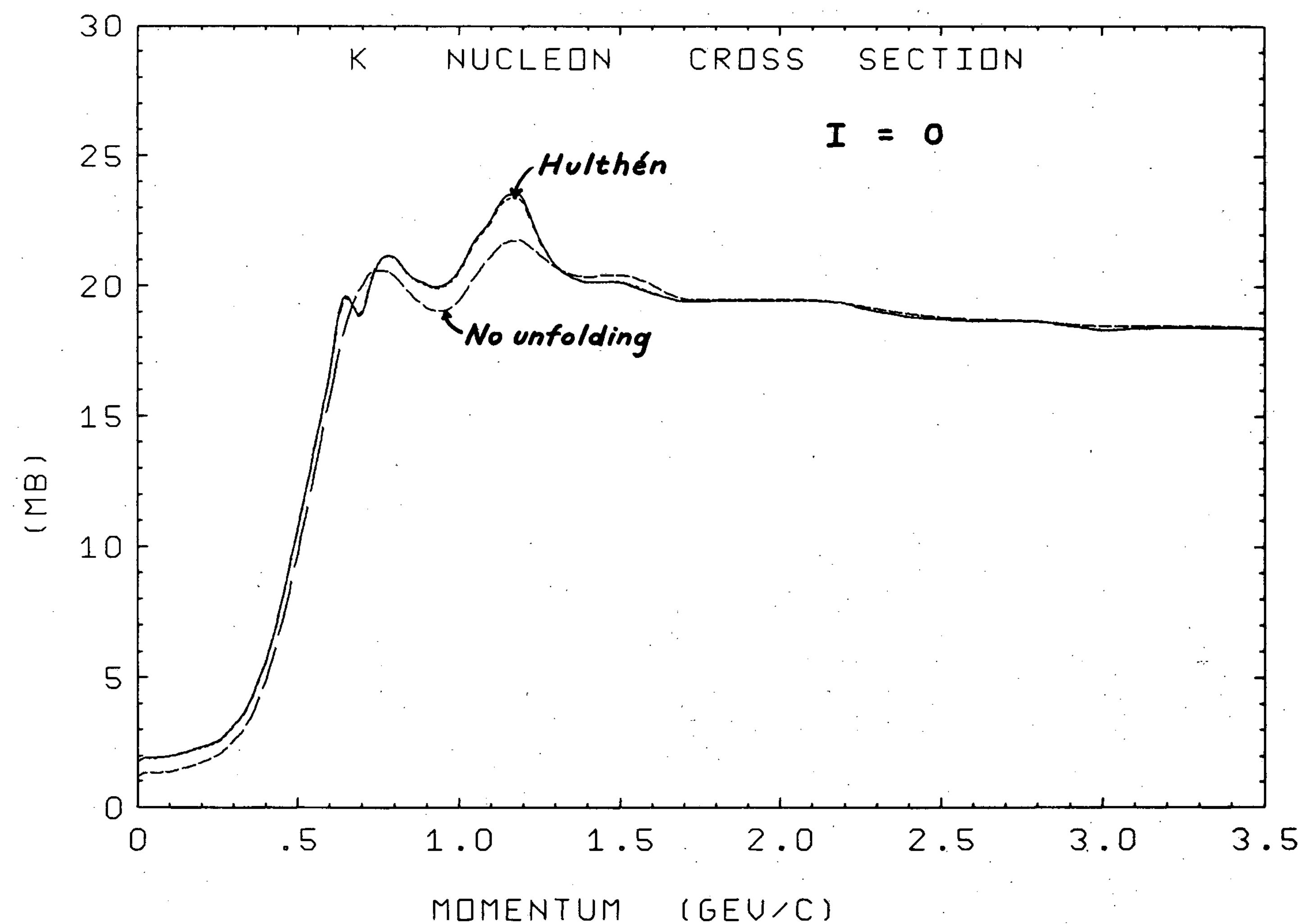

FIG. 20. The effect on σ_0 of neglecting unfolding and of using a the Hulthén wave function.

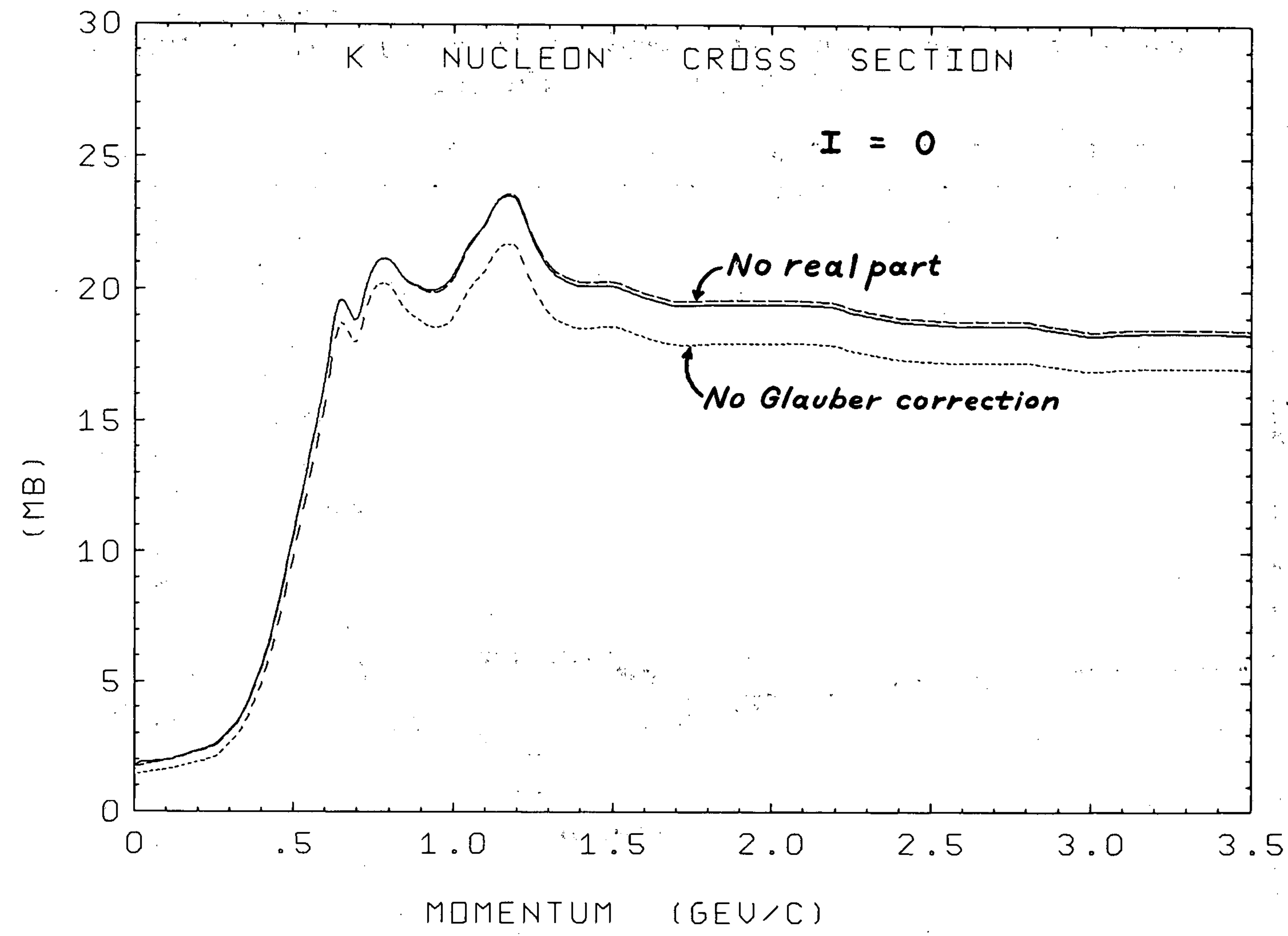

FIG. 21. The effect on σ_0 of neglecting or modifying the Glauber correction.

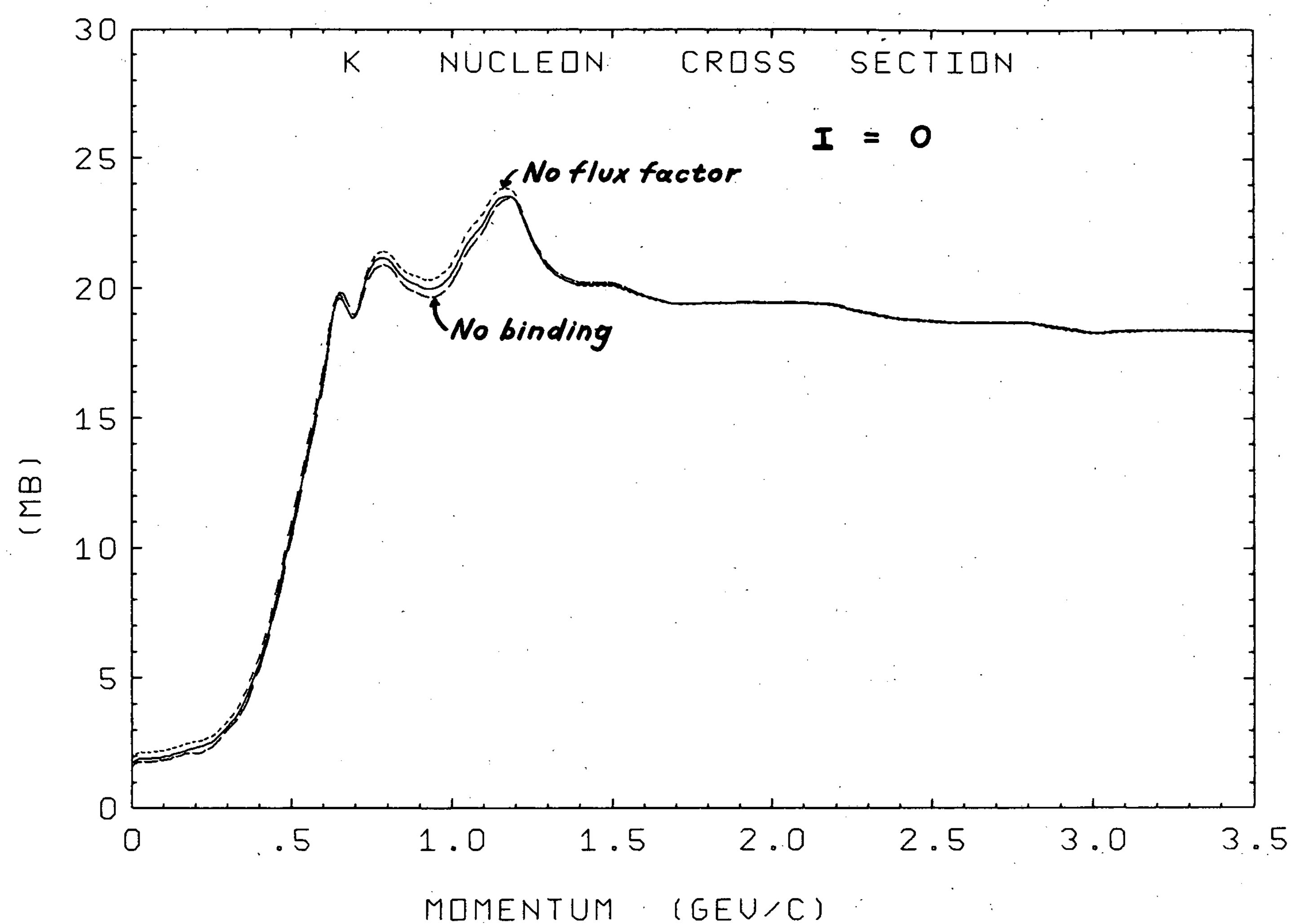

FIG. 22. The effect on σ_0 of neglecting the flux factor or the deuteron binding energy.

depend upon various things. The effect of the Glauber correction is shown in Fig. 23, and Fig. 24 shows the effect of neglecting the unfolding altogether. One can see that many of the features in the I=1 cross section are not visible, or are hardly present before the unfolding is done. In particular the peak at 1.26 GeV/c, which has been often been identified as the recurrence of the Σ, is not present before unfolding is done. These features of the derived cross section are suspect since in this case, in contrast to the K^+ case, there are non-negligible errors introduced by the unfolding process itself, because there are resonances such as the $Y_0^*(1520)$ and the $Y_0^*(1815)$ that are narrow enough compared with the effect of the internal momentum to complicate the unfolding. There are many different schemes that have been used to do the unfolding. One rather elegant scheme is to write down a set of linear equations that express how each measured data point depends upon the unknown unfolded cross-section points. Then one obtains the answer by solving this set of simultaneous equations. A difficulty with this method is that there is no way of imposing smoothness on the final answer; it may give an answer that has high frequency fluctuations. Therefore most attempts at unfolding have used an iterative method. By starting with a guess of the unfolded cross section and correcting this by the amount that the resulting folded cross section disagrees with the measured data, one can iterate toward an answer. Usually this process does not converge but first approaches a self-consistent result and then develops instabilities that cause it to diverge. To avoid this trouble the Brookhaven group stopped after three iterations. My approach was to smooth each new guess by setting each point to the value of the best-fit parabola through the five points centered about that point (for a point spacing of 20 MeV/c). This method converged to a very self-consistent solution in four interactions for the K^+d data, but took about 10 iterations to converge to a not nearly so self-consistent result for the K^-d data. This latter method produced results that have slightly more pronounced structure than the results of the former method, but the differences are so small that on graphs such as the ones that I have been presenting here the differences are difficult to see above 500 MeV/c.

Since the solution is not very self-consistent, one is tempted to use points every 10 MeV/c rather than every 20 MeV/c. This amounts to relaxing the smoothness criterion. The result of doing this is shown in Fig. 25. We see that this solution has considerably more exaggerated structure than the solution using 20-MeV/c intervals. Thus the solutions that we get are somewhat sensitive to the extent to which the solutions are forced not to have fine structure. The differences between the two curves in Fig. 25 is a fair measure of the size of the systematic error due to this effect above 500 MeV/c. Below 500 MeV/c the systematic errors are larger because of the presence of the large narrow $Y^*(1520)$ and because this region is strongly influenced by the poorly known but large and rapidly varying cross section below 360 MeV/c.

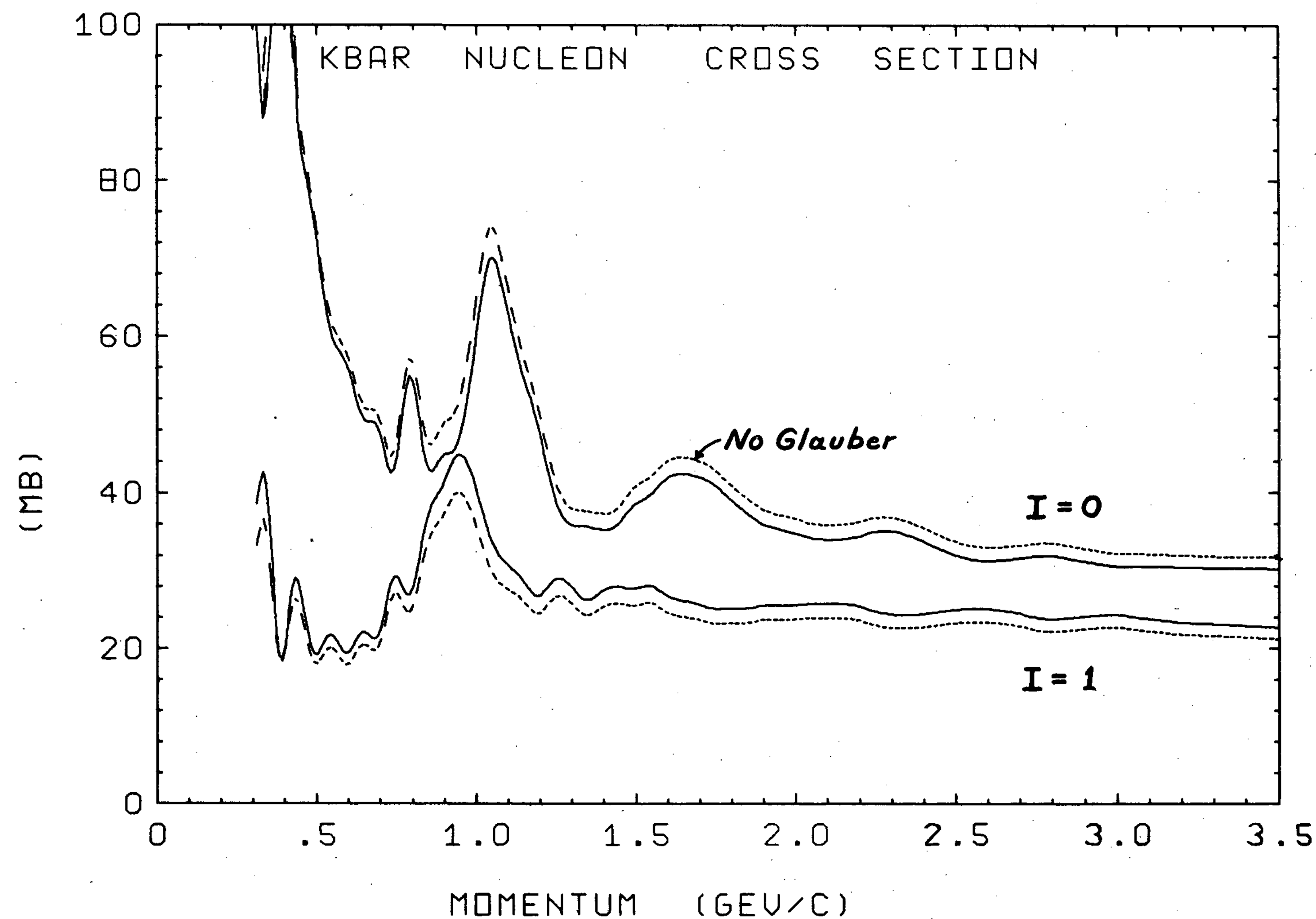

FIG. 23. Effect of neglecting the Glauber correction on the derived $\bar{K}N$ total cross sections.

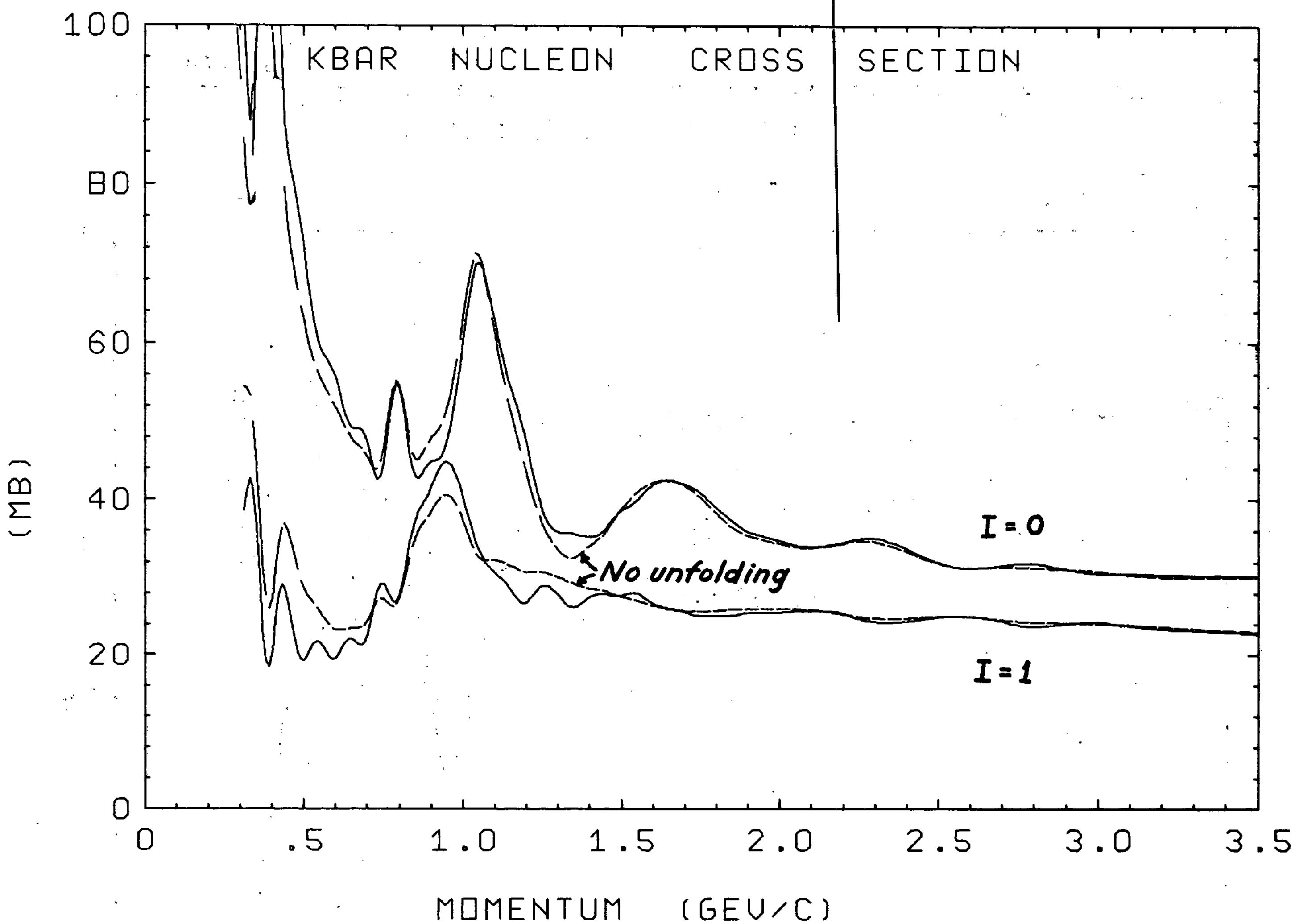

FIG. 24. The effect of neglecting unfolding on the derived $\bar{K}N$ total cross sections.

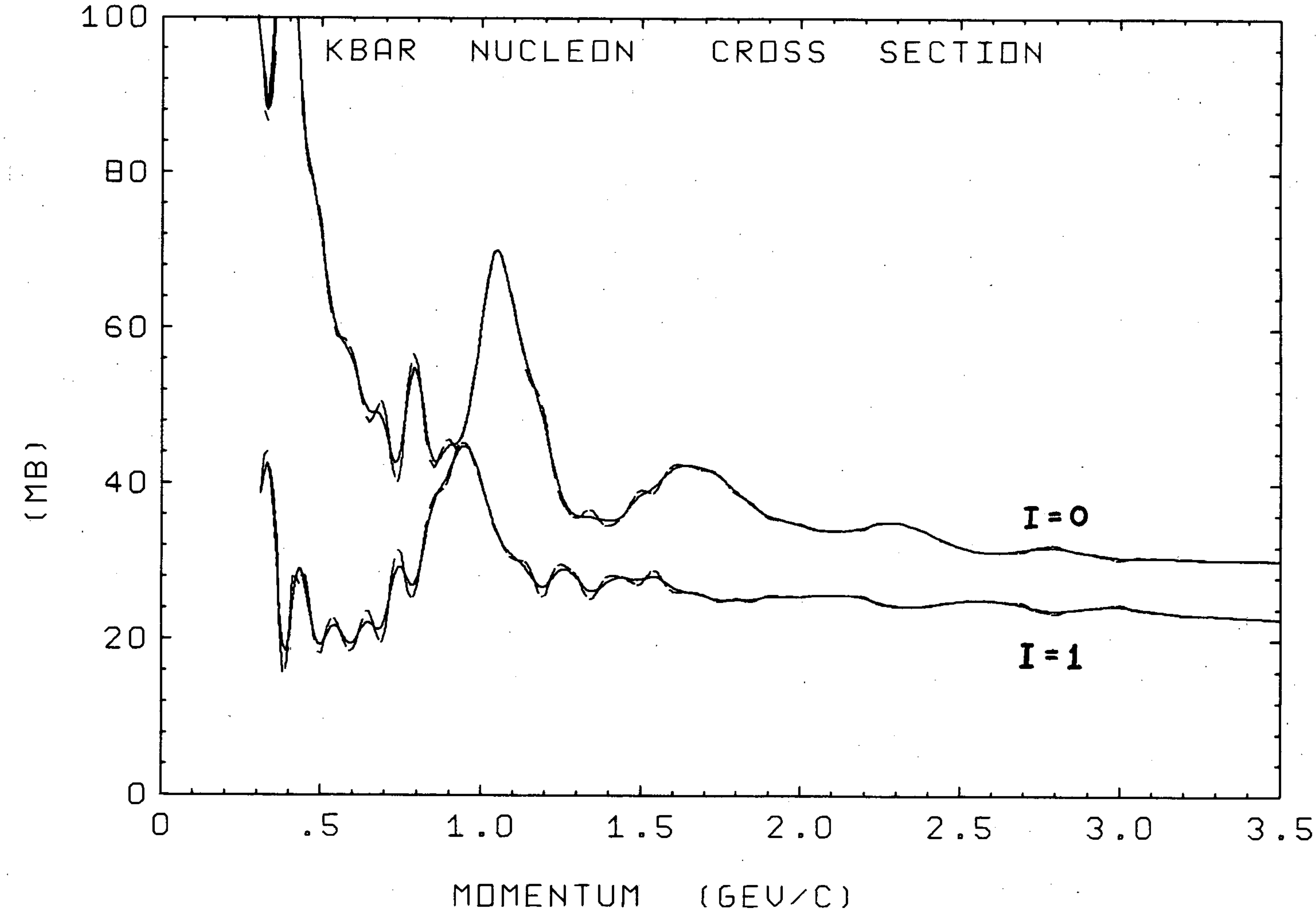

FIG. 25. Effect of using 10- rather than 20-MeV/c intervals on the derived $\bar{K}N$ total cross sections.

The sensitivity to the amount of smoothing is much greater than the sensitivity to other reasonable modifications, such as changing the deuteron wave function, neglecting the real part of the scattering amplitude, or neglecting the flux factor. It also makes little difference whether one finds the neutron cross section by substracting the proton cross section from the unfolded deuteron cross section (which I did) or if one unfolds the difference between the deuteron cross section and the folded proton cross section (which the Brookhaven group did).

The data points for the I = 0 cross section are shown in Figs. 26 and 27. As we have seen, the statistical errors do not reflect the entire uncertainties in this cross section. Nevertheless all of the peaks in this plot are unquestionably correct, including the $Y^*(1520)$ at 390 MeV/c, the $Y^*(1690)$ at 800 MeV/c, the $Y^*(1815)$ at 1050 MeV/c, the $Y^*(2100)$ at 1700 MeV/c, and the bump at 2300 MeV/c.

The situation for I = 1, as seen in Figs. 28 and 29, is much less clear. The apparent peak at 440 MeV/c is almost surely not real, but is a result of the inability to adequately unfold the $Y^*(1520)$ peak in the K^-d cross section. The structure in the smooth curve between 500 and 800 MeV/c is not demanded by the data. The Y^* (1765) is clearly visible at 950 MeV/c. The $Y^*(1915)$ at 1260 MeV/c is, as we have seen, entirely a product of the unfolding, and because of this must be considered as much more suspect than the resonances indicated in the I = 0 state. Nevertheless the $Y^*(1915)$ emerges from the unfolding no matter what plausible method is used. The $Y^*(2030)$ shows up here at 1500 MeV/c. Its magnitude is not as great as the magnitude indicated by the analyses of the charge-exchange data[14] in this region. There is a hint here that this object is a double rather than a single structure.

CONCLUSION

The I = 0 cross section for the KN system can be calculated in a way that depends very little upon the method of analysis that is chosen. The greatest uncertainty in these results comes from the disagreement between the different experiments. Yet another experiment will be needed before the detailed shape of the cross section will be known in the region from 700 MeV/c to 1 GeV/c.

For the K^- data the uncertainties introduced by the unfolding are more serious than the disagreement between the experiments, and the derived cross sections should not be taken as accurate cross sections for the purpose of testing models. The total cross-section data are very precise data and should be used in phase-shift analyses. But it is my advice that anyone who does phase-shift analyses should use the raw data themselves rather than the derived cross section, that is, he should fold and correct his assumed solutions to compare with the measured Kd cross section rather than compare his solution with an unfolded corrected derived cross section.

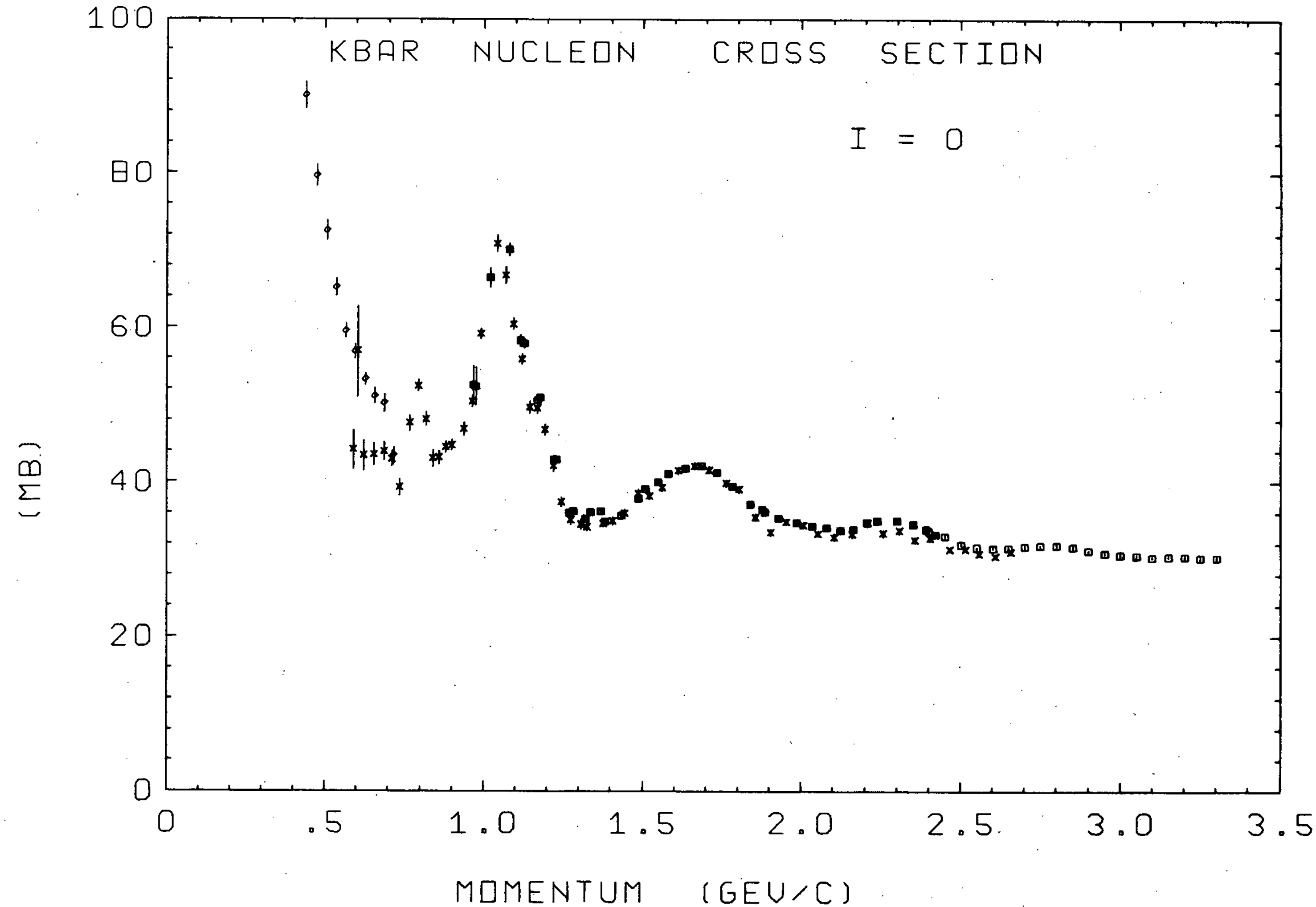

FIG. 26. The data points for the I = 0 $\overline{K}N$ cross sections.

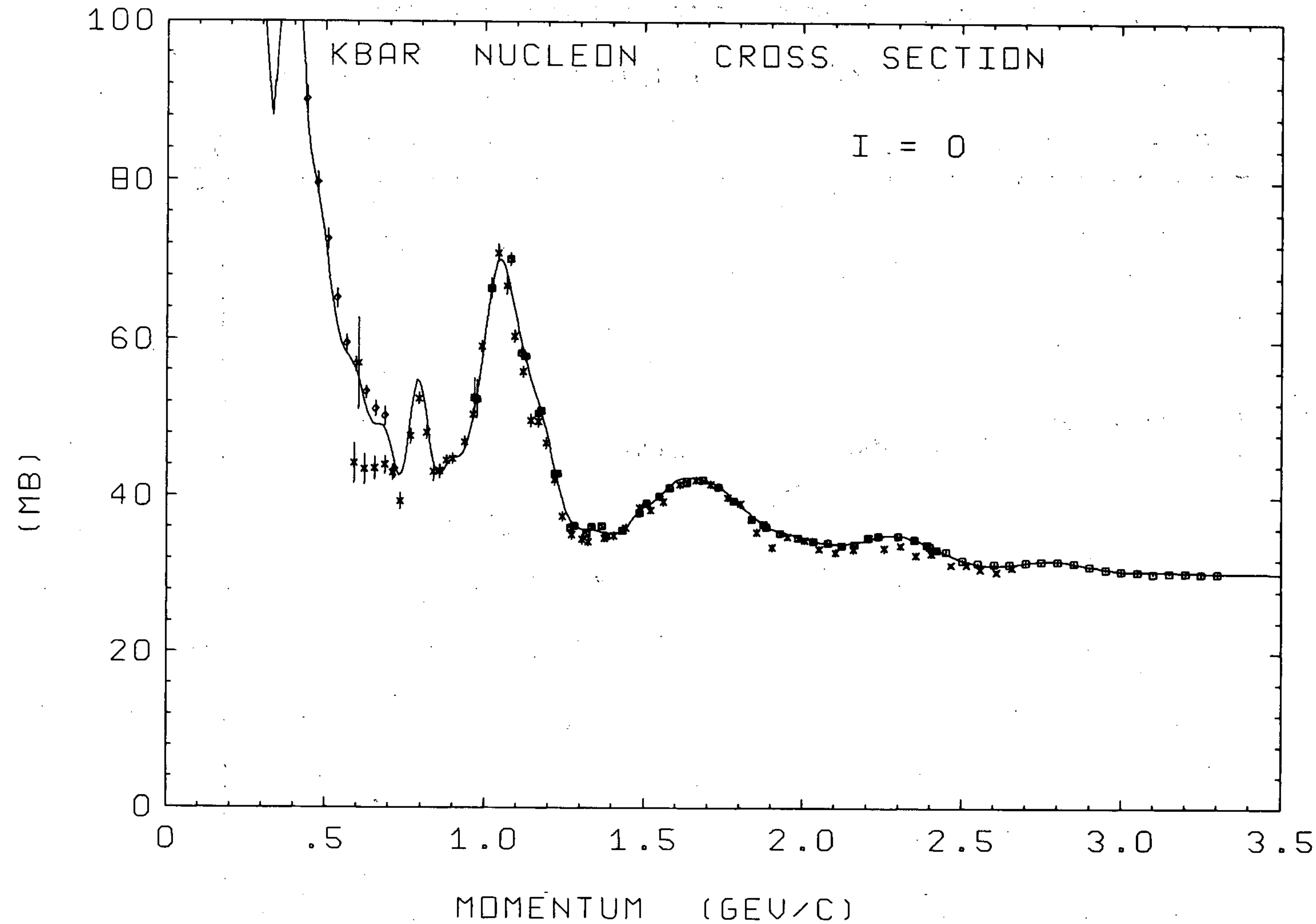

FIG. 27. The data points and smooth curve for the I = 0 $\bar{K}N$ cross section.

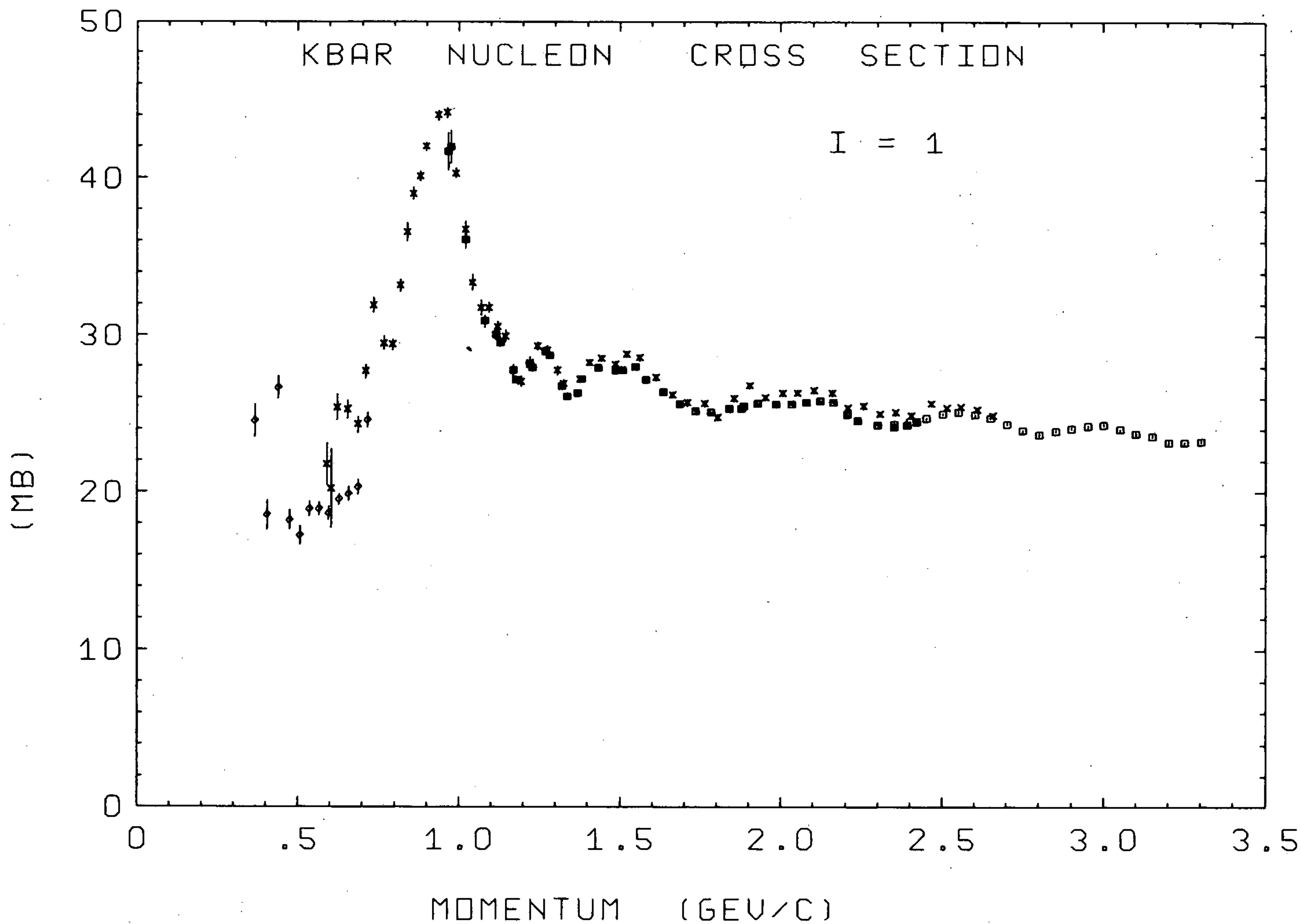

FIG. 28. The data points for the $I = 1$ $\overline{K}N$ cross section.

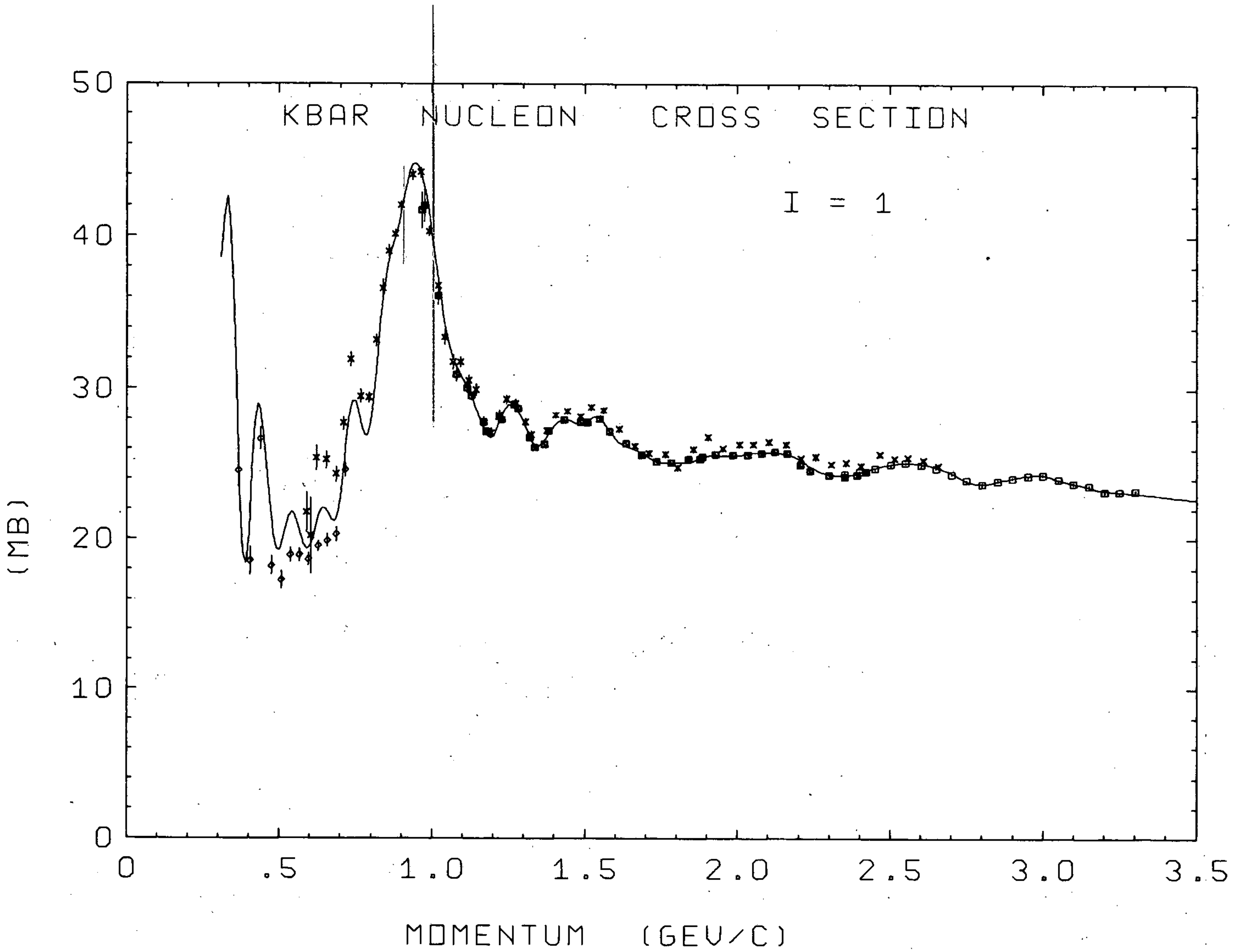

Fig. 29. The data points and smooth curve for the I = 1 $\overline{K}N$ cross section.

FOOTNOTE AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, and D. N. Michael, Phys. Rev. Letters 18, 1209 (1967); 19, 259 (1967) and 19, 678 (1967). An article by the same authors has been submitted to the Physical Review [BNL 14046 (1969)].
   R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, A. Lundby, and J. Teiger, Phys. Rev. Letters 16, 1228 (1966); 17, 102 (1966). An article by the same authors plus C. Wilkin has been submitted to the Physical Review [BNL 14047 (1969)].
2. D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. N. Wilson, J. D. Davies, J. D. Powell, P. M. Hattersley, R. J. Homer, A. W. O'Dell, A. A. Carter, R. J. Tapper, and K. F. Riley, Phys. Rev. 168, 1466 (1968).
3. E. Jenkins (private communication) and D. V. Petersen, Ph.D. Thesis, University of Arizona.
4. H. C. Burrows, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, and R. A. Schluter, Phys. Rev. Letters 2, 117 (1952).
5. V. Cook, D. Keefe, L. T. Kerth, P. G. Murphy, W. A. Wenzel, and T. F. Zipf, Phys. Rev. Letters 7, 182 (1961).
   V. Cook, B. Cork, T. F. Koang, D. Keefe, L. T. Kerth, W. A. Wenzel, and T. F. Zipf, Phys. Rev. 123, 320 (1961).
6. S. Goldhaber, W. Chinowsky, G. Goldhaber, W. Lee, T. O'Halloran, T. F. Stubbs, G. M. Pjerrou, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters 9, 135 (1962).
7. T. F. Kycia, L. T. Kerth, and R. G. Baender, Phys. Rev. 118, 553 (1960).
   R. W. Bland et al., Lawrence Radiation Report UCRL-18758 (1969).
   W. F. Baker, R. L. Cook, E. W. Jenkins, T. F. Kycia, R. H. Phillips, and A. L. Read, Phys. Rev. 129, 2285 (1963).
   G. von Dardel, D. H. Frisch, R. Mermod, R. H. Milburn, P.A. Piroue, M. Kivargent, G. Weber, and K. Winter, Phys. Rev. Letters 5, 333 (1960).
   A. Bettini, M. Cresti, S. Limentani, L. Peruzzo, R. Santangelo, D. Locke, D. J. Crennell, W. T. Davies, and P. B. Jones, Physics Letters 16, 83 (1965).
   W. Chinowsky, G. Goldhaber, S. Goldhaber, T. O'Halloran, and B. Schwarzchild, Phys. Rev. 139B, 1411 (1965).
   P. Sällström, G. Otter, and G. Ekspong, Nuovo Cimento, 49A, 348 (1967).
   O. Chamberlain, K. M. Crowe, D. Keefe, L. T. Kerth, A. Lemonick, Tin Maung, and T. F. Zipf, Phys. Rev. 125, 1696 (1962).

P. L. Bastien and J. P. Berge, Phys. Rev. Letters 10, 188 (1963).
A. N. Diddens, E. W. Jenkins, T. F. Kycia, and K. F. Riley, Phys. Rev. 132, 2721 (1963).
8. J. D. Dowell, Isotopic Spin Analysis of K^+p and K^+d Total Cross Sections (to be published).
9. R. Armenteros et al., (to be submitted to Nuclear Physics B.
10. R. J. Glauber, Phys. Rev. 100, 242 (1955).
R. J. Glauber and V. Franco, Phys. Rev. 142, 1195 (1966).
11. The formulation is that of C. Wilkin, Phys. Rev. Letters 17, 561 (1966).
12. M. Moravcsik, Nuclear Physics 7, 113 (1958).
13. A. A. Carter, K. F. Riley, R. J. Tapper, D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. Wilson, J. D. Davies, J. D. Dowell, P. M. Hattersley, R. J. Homer, and A. W. O'Dell, Phys. Rev. 168, 1457 (1968).
14. C. W. Wohl, F. T. Solmitz, and M. L. Stevenson, Phys. Rev. Letters 17, 107 (1966).

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720