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OBSERVATION OF A DIP-BUMP STRUCTURE IN DIFFERENTIAL CROSS-SECTION FOR $\bar{p}p \to \bar{n}n$ IN THE 700-760 MEV/C MOMENTUM RANGE

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ABSTRACT

Based on a sample of about 3500 events, we have measured the total and differential cross-sections of $\bar{p}p \to \bar{n}n$ in the 700-760 MeV/c incident momentum region. It is found that σ_{CE} = 10.7 ± 0.2 mb at the average momentum of 730 MeV/c. The differential angular distribution is characterised by a sharp peak and a dip in the forward direction followed by a secondary maximum. The position of the dip corresponds to $|t| \sim m_\pi^2$. These results are compared with the predictions of the model of Bryan-Phillips. On the other hand, this dip-bump structure can be well understood on a simple picture involving a π exchange and a constant background (for $|t| \lesssim 3\ m_\pi^2$).

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The clarification of our understanding of low energy nucleon interactions necessitates the knowledge of the charge exchange process $\bar{p}p \to \bar{n}n$. It is related to the elastic scattering $\bar{p}p \to \bar{p}p$ through isospin amplitudes and to the charge exchange $np \to pn$ through line reversal. One may therefore expect some similarities between the two charge exchange processes. In particular, it is of interest to see if the sharp forward spike observed in $np \to pn$ [1] is also present in $\bar{p}p \to \bar{n}n$. The differential cross-section for the charge exchange reaction $\bar{p}p \to \bar{n}n$ has been measured previously at p_{lab} = 0.3 - 0.6 GeV/c [2], at 1.13 GeV/c [3], 1.8 GeV/c [4], 7.76 GeV/c [5] and 40.0 GeV/c [6,7]. We present here the results of the measurement of the total and differential cross-sections of the charge exchange reaction $\bar{p}p \to \bar{n}n$ in the region of 700 - 760 MeV/c incident momentum. Preliminary results from this investigation have been presented earlier [8]. The present results based on increased statistics confirm our earlier observation of a sharp forward peak followed by a dip and a second maximum.

Two exposures of the Saclay 81 cm hydrogen bubble chamber to an antiproton beam of 720 MeV/c and 780 MeV/c were made at CERN, producing respectively about 1500 and 2000 charge exchange events useful for our analysis. Since no significant difference was observed between the two sets of results, we present the combined results which correspond to an average incident momentum, at the charge exchange vertex, of 730 MeV/c (FWHM = 150 MeV/c).

The signature of a charge exchange event in the bubble chamber is the occurrence of a vertex with an odd number of charged prongs due to an $\bar{n}p$ annihilation associated with an upstream zero prong $\bar{p}p$ vertex. We scanned for $\bar{n}p$ annihilations with vertices having > 3 charged prongs so as not to have the difficulty of identifying single prong $\bar{n}p$ annihilations from background of stray tracks. A double scan gave an efficiency of 97 % for the detection of these events.

Various selection criteria were introduced to reduce inefficiencies and contaminations to a negligible level compared to statistical errors.

The incident particle was identified by ionisation and its momentum was required to lie between 600 and 900 MeV/c. A cut at L_{min} = 1 cm was imposed on the distance between the $\bar{p}p$ and the $\bar{n}p$ vertices to avoid low detection efficiencies. The contamination to the 3 prong "$\bar{n}p$ annihilation" due to π-p elastic scattering which may have crept into the sample were eliminated by a coplanarity test (10 % of the total sample). Accidental coincidence of non-associated $\bar{p}p$ and $\bar{n}p$ vertices occurring on the same frame was estimated to be of the order of 8 %, using the known number of isolated $\bar{n}p$ and $\bar{p}p$ vertices. It is relatively important at large angles but does not affect the structure observed in the forward direction. We estimate that 3 % of the total sample of $\bar{n}$ may have suffered an unseen forward elastic scattering before annihilating, with little consequence on the apparent charge exchange angular distribution.

Because of the mass difference between the proton and the neutron, there is ambiguity in the choice of the antineutron momentum since there are two possible solutions. We have used the high momentum solution for the following reasons. A few events gave a 1C fit with the low momentum solution ($\bar{n}$ momentum of 4 to 50 MeV/c) but path length of the antineutron in these events is rather large ; if these fits were real, the path lengths of the antineutrons should have been considerably smaller because of the large $\bar{n}p$ annihilation cross-section at low momenta. When a multivertex 4C fit was possible (8 % of the total sample) the low momentum solution was never chosen by the fit. This sets an upper limit of 0.3 % for a possible validity of the low momentum solution.

Each $\bar{n}p$ event was weighted by the inverse of its detection probability within the fiducial volume. For this purpose one needs to know the total $\bar{n}p$ annihilation cross-section giving rise to three or more prongs. We have used the empirical formula

$$\sigma_{ann} (> 3 \text{ prongs}) = 747 / \sqrt{T} \text{ mb} \qquad (1)$$

given by Bizzarri et al., [9] for the charge symmetric $\bar{p}n$ annihilations (T is the kinetic energy of $\bar{n}$ in MeV). The average weight for an event turns out to be approximately 24.

We determine the total $\bar{p}p$ charge exchange cross-section (σ_{CEX}) as (10.8 ± 0.3) mb and (10.6 ± 0.2) mb at 700 and 760 MeV/c respectively, giving an average value of

$$\sigma_{CEX}\ (730\ \text{MeV/c}) = 10.7 \pm 0.2\ \text{mb} \tag{2}$$

We estimate a possible systematic error of 5 % due to the use of the empirical formula (1). This result is compared in Fig. 1 with other measurements of σ_{CEX} below 1 GeV/c [2,10,11]. The value obtained by Kohno et al. [12] is not shown as their data forms a part of the data of this investigation.

The differential angular and t (momentum transfer squared) distributions are shown in Fig. 2. The errors shown are statistical only. The most significant feature of the distributions shown in Fig. 2 is the sharp forward peak followed by a dip at $\cos\Theta^* \sim 0.875$ and a second maximum at $\cos\Theta^* \sim 0.80$ (corresponding to $\sqrt{|t|} = 0.150$ and 0.190 GeV respectively). It may be noted that the dip corresponds to $|t| \sim m_\pi^2$. Thus, the present results based on increased statistics confirm our earlier observation [8] on the presence of a dip in the charge exchange reactions $\bar{p}p \to \bar{n}n$ at 730 MeV/c.

The forward spike is very similar, within errors to that observed by Mischke et al., [1a] in the charge exchange reaction $np \to pn$ at 741 MeV/c. The $np \to pn$ data [1a] indicates that the slope of the forward spike increases with increasing p_{lab} till 750 - 800 MeV/c (i.e. near the one-pion threshold), after which the slope decreases, attaining a minimum value at ~ 1.8 GeV/c. Beyond 1.8 GeV/c, the slope seems to once again show a tendency to increase with p_{lab}. Although the $\bar{p}p \to \bar{n}n$ data are not of comparable quality (and do not go down to low enough $|t|$), they also seem to indicate a tendency for the slope of the forward spike to decrease with p_{lab} as the p_{lab} increases from 0.73 GeV/c (our data) to 1.8 GeV/c [3,4]. The 5.0 and 7.76 GeV/c data [5] indicate that the slope has once again begun to increase with p_{lab} reaching a rather high value at 40 GeV/c [6,7]. It may also be noted that the forward spike in $\bar{p}p \to \bar{n}n$ at 40 GeV/c seems to be very similar to the forward spike in $np \to pn$ at 42.5 GeV/c [13,7].

The $np \to pn$ data however do not indicate any dip-bump structure. The dip-bump structure observed in $\bar{p}p \to \bar{n}n$ seems to indicate a complicated dependence on p_{lab}, somewhat similar to that of the slope of the forward spike. The dip-bump structure, which is fairly clear at 0.73 GeV/c in our data, is not observed at 1.13 GeV/c [3] or at 1.8 GeV/c [4]. At higher energy, the 5.0 GeV/c data [5] shows it fairly clearly and it is considerably more pronounced at 40.0 GeV/c [6,7]. These features seem to suggest a fairly complicated behaviour of the coherent background which interferes with the pion exchange.

Since our data is at relatively low energy we have attempted to compare it in Fig. 2 with the predictions of the model of Bryan and Phillips [14], which is a non-relativistic model. This model uses one boson exchange potential and a phenomenological imaginary potential à la Woods-Saxon to take care of the strong absorption in the $\bar{N}N$ case with no spin and isospin dependence. The one boson exchange potentials are obtained by fitting the NN data and then applying the results to the $\bar{N}N$ case, having changed the sign of the contributions of the mesons with odd G-parity. It is clear from Fig. 2 that this model is able to simulate the dip-bump structures observed in the forward $\bar{p}p$ charge exchange data, but its predictions fall short of the data considerably. Within this frame, the sharp forward peak can be interpreted as a manifestation of the pion exchange contribution. However, as pointed out by Ohsugi et al. [15], the predictions of this model are not correct for the polarisation observed in the $\bar{p}p$ elastic scattering. Also, as can be seen from Fig. 2 this model underestimates the total charge exchange cross section. This has also been pointed out by Alston-Garnjost et al. [11].

Recently, in an attempt to understand the t distribution of the charge exchange reaction $\bar{p}p \to \bar{n}n$ at 40 GeV/c [6] Leader [16] has suggested, for low $|t|$ region, a simple parameterisation of the form

$$\frac{d\sigma}{dt} = \frac{\pi}{2\,M^2\,p_{lab}^2}\left(\frac{g^2}{4\pi}\right)^2\left[\left(\frac{t}{t-\mu^2} - B\right)^2 + \left(\frac{t}{t-\mu^2}\right)^2 + I^2\right] \qquad (3)$$

where M is the proton mass, p_{lab} is the momentum of the $\bar{p}$ in the laboratory system, $(g^2/4\pi) \sim 14.8$, B represents the coherent background which interferes with the pion exchange term and I^2 represents the incoherent background. Eq. (3) is based on the assumption that in the low $|t|$ region, say $|t| \lesssim 3\, m_\pi^2$, only the π-exchange term varies significantly with t and that all other contributions can be taken to be effectively constant. Eq. (3) can be rewritten in a simpler form as

$$\frac{d\sigma}{dt} = \frac{\pi}{M^2\, p_{lab}^2} \left(\frac{g^2}{4\pi}\right)^2 \left[\left(\frac{\tau}{\tau+1} - \frac{B}{2}\right)^2 + J^2\right] \qquad (4)$$

where $\tau = -\, t/m_\pi^2$ and $J^2 = (B^2 + 2\, I^2)/4$.

It appears that at high energies such as 40 GeV/c, the above assumption may not be valid since the contribution from the interference of ρ-pole and the Pomeron (ρ - $\mathbb{P}$ cut) may vary significantly even in the low $|t|$ region. However, at low energies such as ours, this assumption is expected to be reasonably good.

We have carried out a fit based on eq. (4) to our data for $\tau \lesssim 2.5$, keeping $(g^2/4\pi)$ fixed at 14.8. This fit is shown in Fig. 3. The values of the parameters obtained are $B = 0.97 \pm 0.03$ and $J = 0.112 \pm 0.004$. The parameter B is related to the position of the minimum as $\tau_{min} = B/(2-B)$. As can be seen from Fig. 3 the fit is quite good. However, the fit (not shown) becomes even better if we vary $(g^2/4\pi)$ also and the values obtained are $(g^2/4\pi) = 11.2$, $B = 1.00$ and $J = 0.218$. Thus, we conclude that the dip-bump structure observed in $\bar{p}p \rightarrow \bar{n}n$ at 0.730 GeV/c can be well understood on a simple picture involving a π exchange and a constant background with the usual value of the coupling constant, namely $(g^2/4\pi) \sim 14.8$.

A systematic analysis of the entire available data on $\bar{p}p \rightarrow \bar{n}n$ is being carried out and the results would be published elsewhere.

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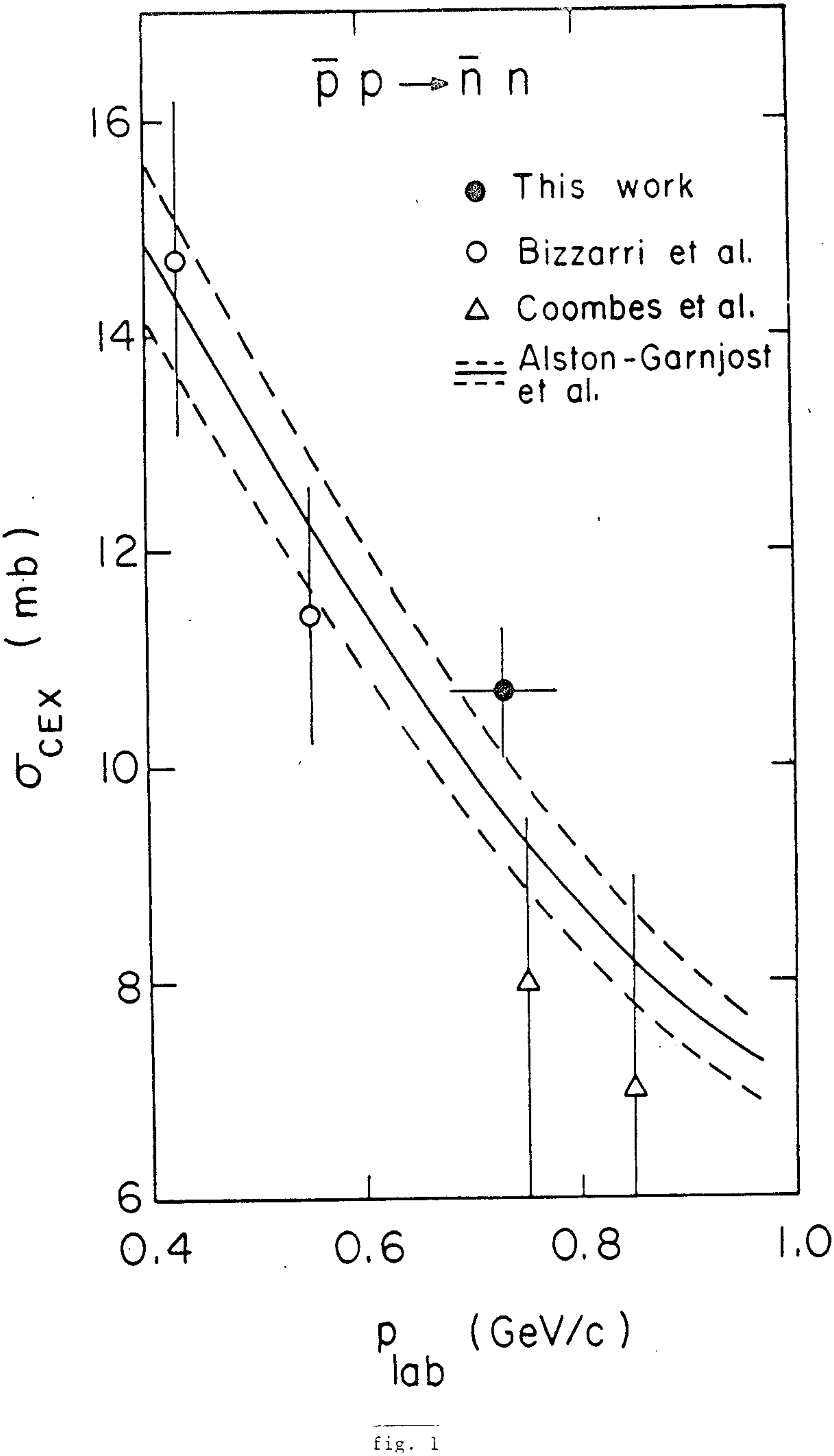
FIGURE CAPTIONS

Fig. 1 The total cross-section for the charge exchange reaction $\bar{p}p \rightarrow \bar{n}n$ as a function of p_{lab}. A 5 % systematic uncertainty is included in our data point. The solid line represents the data of a recent counter experiment of Alston-Ganjost et al. [11] and the dashed lines indicate their systematic uncertainty.

Fig. 2 (a) The differential cross-section per unit solid angle for the reaction $\bar{p}p \rightarrow \bar{n}n$ as a function of $\cos\theta^*$, where θ^* is the c.m. angle. The curve BP shows the predictions of the Bryan and Phillips model.

(b) The differential cross-section as a function of t. The distribution is presented up to $t = -0.35$ GeV^2. Higher $|t|$ values are not shown because of the spread in the incident beam momentum.

Fig. 3 $d\sigma/dt$ as a function of $\tau = -t/m^2$ for $\tau \lesssim 2.5$. The curve represents a fit based on a simple model (eq. 4) involving a π exchange and a constant background (valid for $\tau \lesssim 2.5$).



$\bar{p}p \rightarrow \bar{n}n$
This work
Bizzarri et al.
Coombes et al.
Alston-Garnjost et al.
σ_{CEX} (mb)
p_{lab} (GeV/c)
16
14
12
10
8
6
0.4
0.6
0.8
1.0

fig. 1

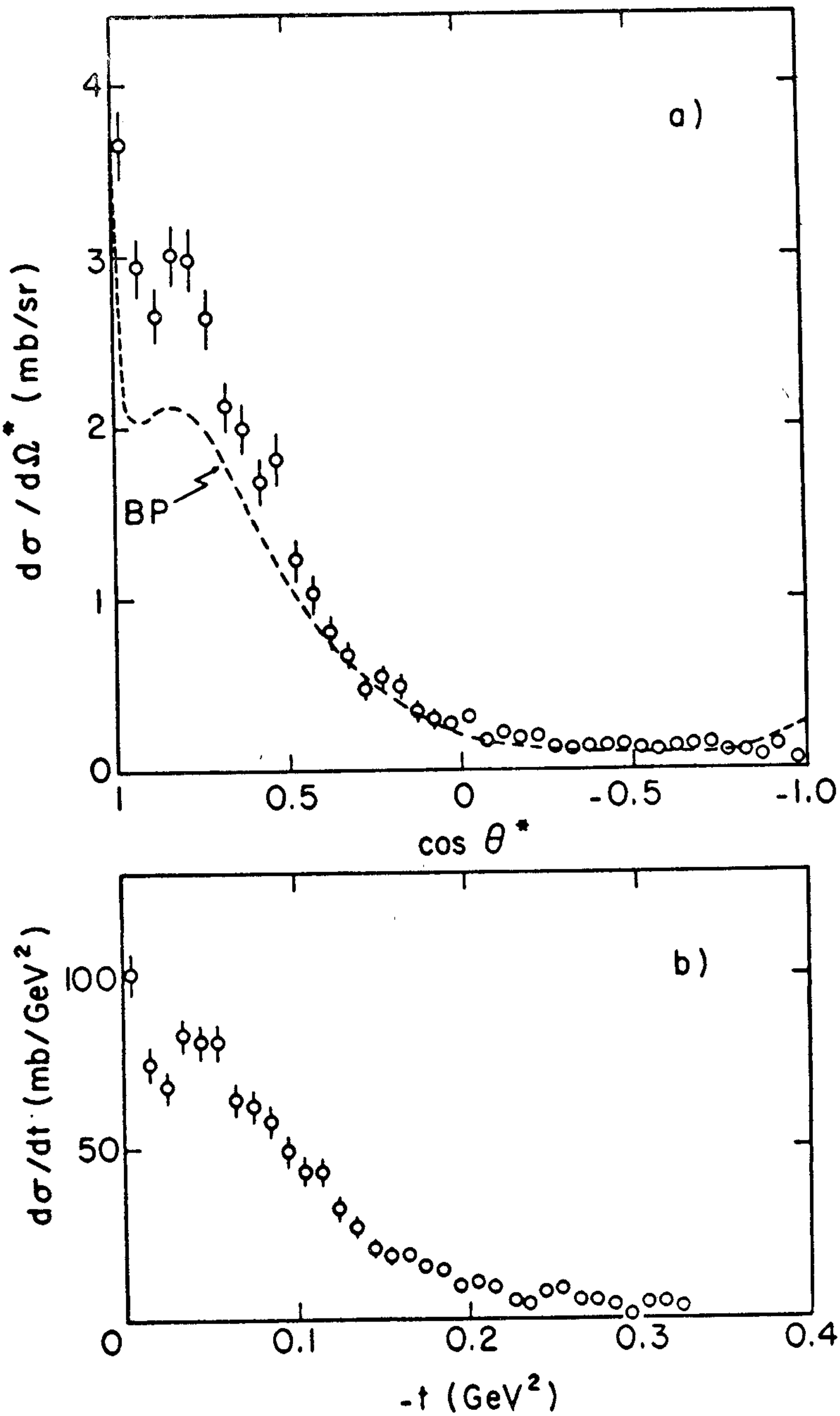

a)
BP
4
3
2
1
0
1
0.5
0
-0.5
-1.0
cos θ*
dσ / dΩ* (mb/sr)
b)
100
50
0
0.1
0.2
0.3
0.4
-t (GeV²)
dσ/dt (mb/GeV²)

fig. 2

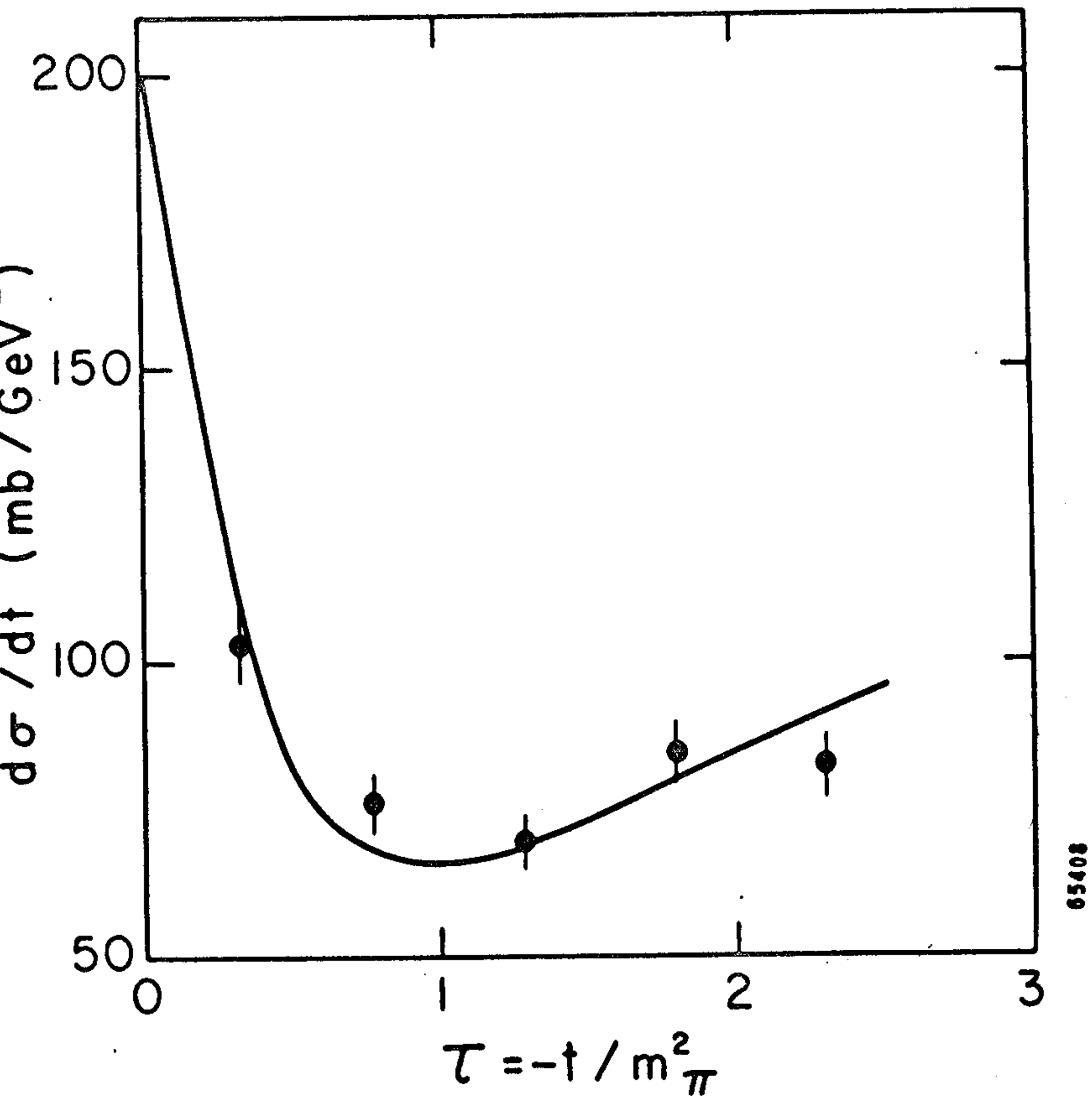


fig. 3