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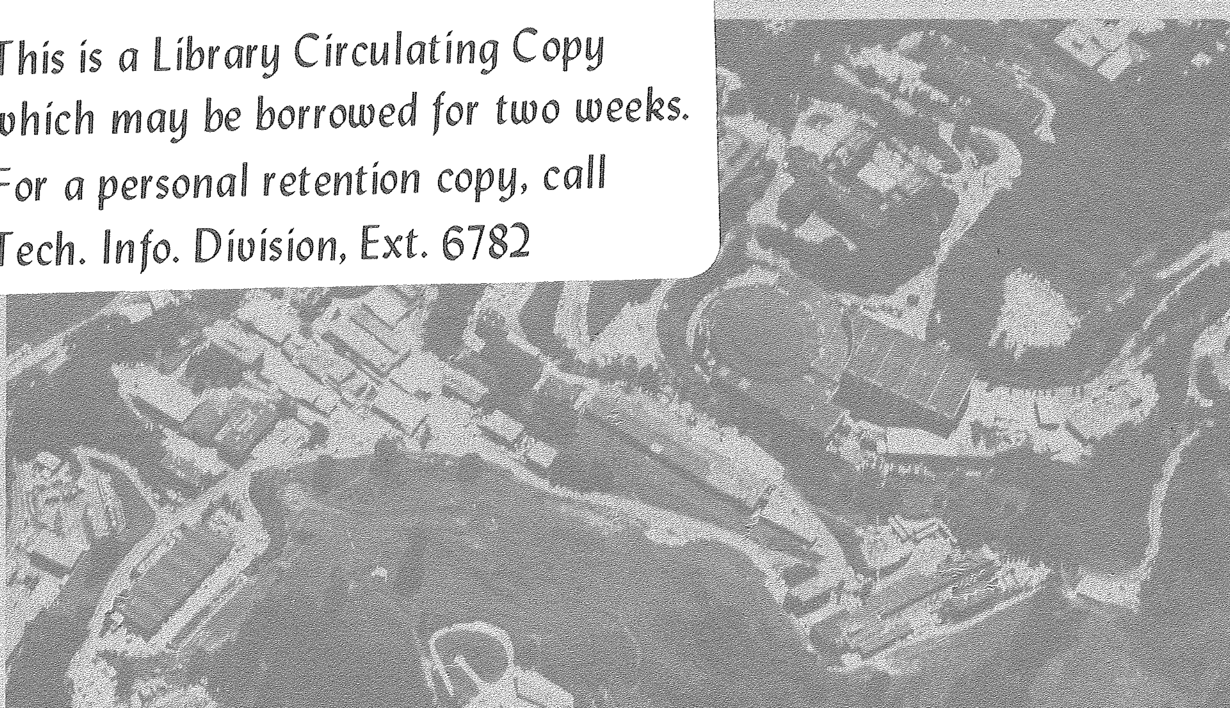

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DISCLAIMER

Search for quark effects in the d+^{4}He system

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ABSTRACT

It has been suggested that bags containing more than three interacting quarks may be formed in high energy collisions; these states would appear as narrow reasonances in the inelastic channels. We have measured the inclusive cross section d+^{4}He→p+X at E_{cm}=6.25 to 7.91 GeV in steps of 50 to 100 MeV to search for a eighteen quark bag resonance. Upper limits on the production cross section are presented.

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Central collisions between nuclei are expected to lead to the formation of hot and highly compressed nuclear matter.[1] The resulting dense matter may give rise to a transient quark state.[2-4] The model for a transition from nuclear to quark matter is based on the interaction between quarks as derived in the M.I.T. bag model.[5-8] At high nucleon density the quarks may come into such close contact with one another that they could lose their identity with any particular nucleon bag. A metastable state might exist in which the quarks from several nucleons are contained within one large bag. The energy difference between nuclear and quark phases has been estimated to be as low as a few hundred MeV per baryon number even near normal nuclear densities.[2,3,9,10]

It has been pointed out that in light nuclear systems resonances might exist due to a kind of quark shell effect.[2] In this picture the bag exerts a force (the bag pressure) on the quarks which is balanced by the repulsive quark-quark interactions. The strength of this interaction decreases as 1/r. Closed shells with a spherical geometry impose a greater proximity on the quarks than partially filled shells with a non-spherical or deformed geometry. Hence bags having unfilled shells are expected to have a lower energy per quark than that of a closed shell and thus be more stable. Such a configuration would probably be produced with high angular momentum An impact parameter of 0.5 fm yields angular momenta up to $10\hbar$ in the midrange of our measurements, so that high angular momentum is not at variance with good overlap of all nucleons.

We have searched for quark bag resonances in the 18 quark system of d+^{4}He. The number of quarks n in this system lies between the expected closed quark shells of $S_{1/2}$(n=12) and $P_{3/2}$(n=36). Since the radii of the deuteron (2.0 fm) and ^{4}He (1.6 fm) are roughly the same, one would expect good geometrical overlap in a central collision. This enchances the likelihood of participation of all the quarks in the collision process. This choice of projectile and target seemed an optimum between the choices of lighter or heavier systems. It was suggested that for lighter systems such as p+p or p+d it might be too simple to decay back into the constituent nucleons with minor rearrangements of the quarks, resulting in a very broad resonance.[11] While higher densities may be achieved in a collision between heavier nuclei, one would expect to have difficulty in identifying any resonant production due to the large number of quarks involved.

The double differential cross section for the reaction of $d+{}^4He \rightarrow p+X$ was measured as a function of the incident deuteron momentum from 2.22 to 5.75 GeV/c corresponding to total center of mass energies E_{cm} of 6.2 to 7.9 GeV. The data extend to the highest bombarding energy for deuterons available at the Lawrence Berkeley Laboratory Bevatron. The proton was detected by a magnetic spectrometer positioned at 14.2 degrees with respect to the incident beam.[12] This was the largest angle accessable to the spectrometer and was chosen to minimize the non-resonant background.

The kinematics of the reaction were calculated using the assumptions that the bag decays only into nucleons; in this case no new quarks or anti-quarks need be created, and that the excitation energy of the bag will, on the average, be shared equally among the decaying nucleons as kinetic energy. Fig. 1 shows curves of constant T_p, the kinetic energy of the decay proton in the bag's rest frame, transformed to laboratory momentum P_{lab} as a function of incident deuteron momentum P_d.

Because the assumptions may not be strictly valid, we have made measurements spanning the range of T_p from 50 to 400 MeV at each incident momentum setting. The spectrometer had a momentum acceptance of approximately

±20%, necessitating two settings at each incident momentum to cover this range of T_p. The hatched areas of Fig. 1 indicate the momentum acceptance of the two spectrometer settings. The dashed curve illustrates the kinematics for p+p elastic scattering at half the deuteron beam momentum.

The data at each bombarding energy were sorted into 18 angle-momentum bins and the invariant cross section for each bin was extracted. Two major features of the data are shown in Fig. 2. The first is the broad peak in Fig. 2(a) at a bombarding momentum of 2.22 GeV/c. The peak is centered at the p+p elastic scattering momentum shown in Fig. 1 and seems to be associated with quasi-elastic scattering of the proton in the deuteron with target nucleons at half the beam momentum. Furthermore, this peak follows the p+p kinematics as the bombarding momentum is changed. This peaking of the cross section at the beam velocity has been seen before.[13-15] Secondly, once outside the rapidly varying cross section of the quasi-elastic region, the cross section is smooth as seen in Fig. 2(b) however a discontinuity is evident in the cross section where the two spectrometer settings join together at a given bombarding momentum. This is due to the fact that the highest momentum bin of the first spectrometer setting is approximately one degree different from the lowest momentum bin of the second spectrometer setting. Any angular dependence in the cross section would lead to a discontinuity at this match up point. This does not pose a problem in extracting a signal for resonant production of the quark bag. Such a signal is expected to be seen in the excitation function of a particular T_p bin. The way in which the data was taken insures that this always lies in the same spectrometer bin and hence never crosses the discontinuity.

A least squares fig was made to the 432 data points with a polynomial including terms up to third order in E_{cm} and P_{lab} so as to separate any narrow structure from a smoothly varying background and to estimate upper limits on the reaction cross section. In order to include the two effects mentioned previously, an additional term was added to fit the quasi-elastic peak. This amounted to a gaussian term centered at the p+p elastic scattering momentum with a fixed width of 100 MeV/c and a magnitude given by $e^{-6.32P_\perp}$. $P_\perp$ is the transverse momentum of the detected proton and the fall off parameter is consistent with previously measured values.[13] Note that this term contributes a negligible amount outside of the quasi-elastic region. Furthermore, in order to maintain the best fit with the fewest parameters, a different set of coefficients was used for each of the two spectrometer settings. This allowed us to use the same terms but avoid having to fit the instrumental break in the cross section at the match up point.

Fig. 3 illustrates the fit to the data and shows the traversal of the quasi-elastic peak through the region under investigation. The ridge passing through the center of the fit is the match up point of the two spectrometer settings. Except for the quasi-elastic region where the simplified parameterization leads to substantial differences between the data and the fit at high momentum as seen in Fig. 2, there are only two points outside of $\pm 3\sigma$ (statistical error) and they are uncorrelated in energy, and there are no points outside of $\pm 4\sigma$. Statistically one expects two points to be outside of 3σ for the number of points being fitted.

The upper limits we have placed on the cross section, based on the fit, for observing narrow resonant structure between center of mass energies of 6.7 and 7.9 GeV are 16 and 8 millibarns respectively, at the 99% confidence level. The unitarity condition for the S-wave formation of the eighteen quark bag, when taken with the assumptions of isotropic decay, and that the entire decay momentum width is contained within one T_p bin yields upper limits on the invariant cross section of 7 and 1 GeV-mb/sr-$(\mathrm{GeV/c})^3$ respectively. This would produce a signal comparable to our uncertainty in the non-resonant background. As mentioned earlier, however, we expect these states to be produced with high angular momentum implying a much increased theoretical limit on the cross section. These states were not exhibited, however, in the data.

To summarize, in the region of phase space investigated, no narrow resonant-like behavior is observed in the inclusive proton spectra. The experimentally determined upper limit of the cross section for producing an eighteen quark bag resonance depends on the mass, width, and on the assumptions made in determining the region of phase space in which to make the measurement. Within the assumptions made in this experiment and described in this letter, the upper limit we have set on the reaction cross section between E_{cm}=6.7 and 7.9 GeV is 16 and 8 millibarns respectively at the 99% confidence level.

We wish to thank the Bevatron cres for their cooperation in the operation of the accelerator in the unusual mode needed for stepping the energy through such a broad range. We thank A.K. Kerman for suggestions in the planning of this experiment, and C.W. Wong and C.A. Whitten, Jr. for helpful discussions.

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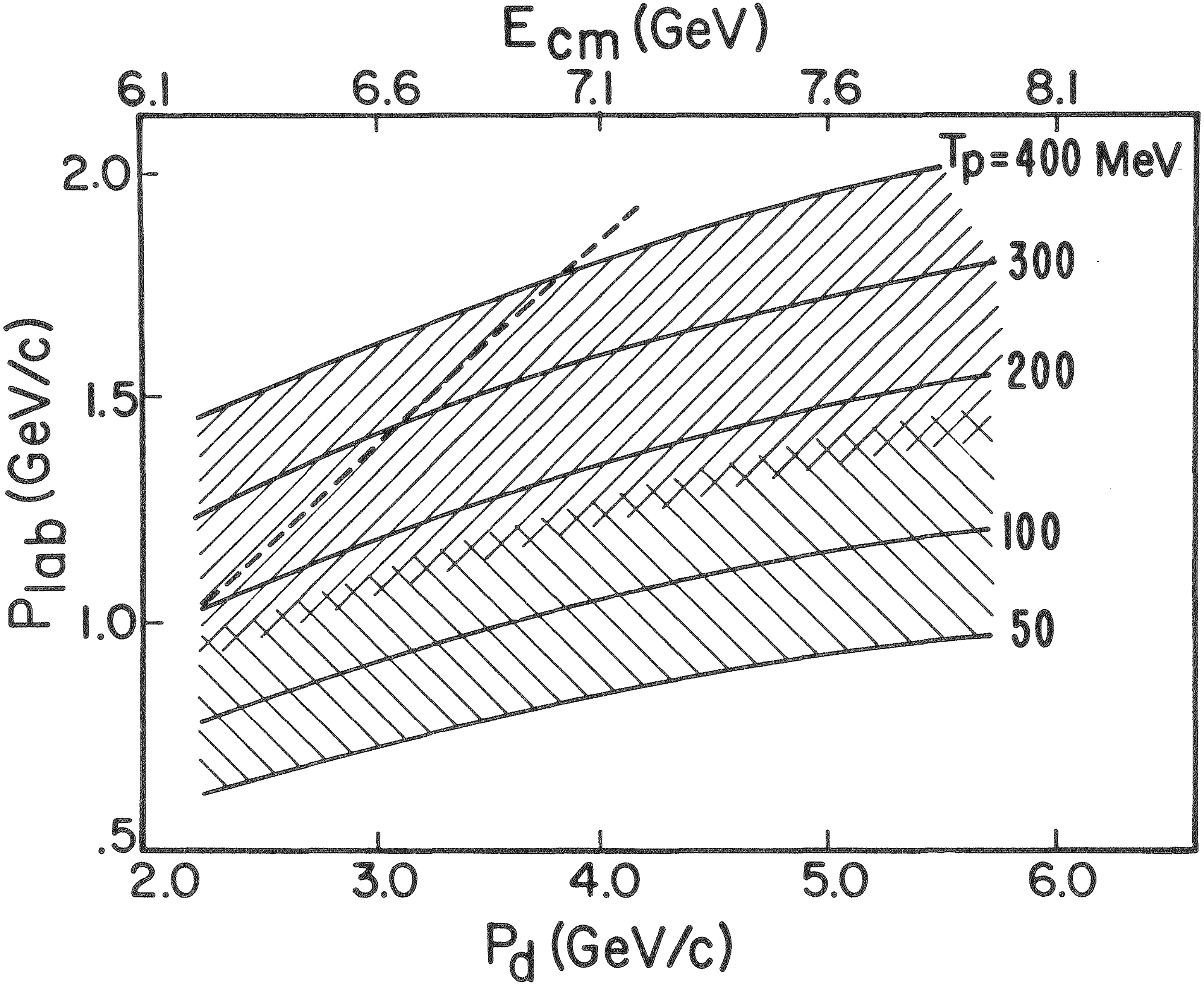
FIGURE CAPTIONS

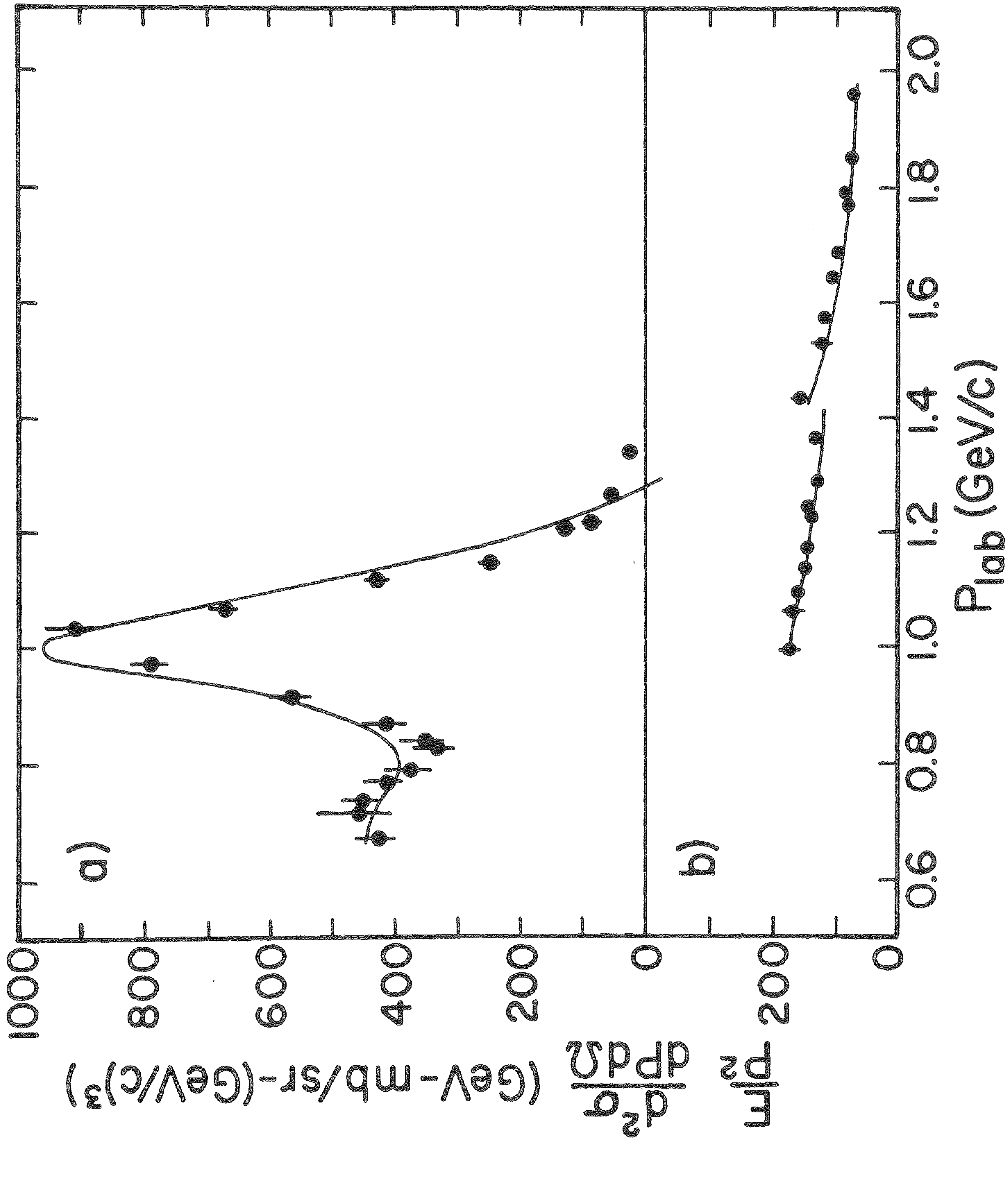
Fig. 1. Contours of constant proton decay energy T_p transformed into laboratory momentum P_{lab} at $\theta_{lab} = 14.2^o$ as a function of incident deuteron momentum P_d and E_{cm}. Hatched areas are momentum acceptances of the two spectrometer settings at each incident momentum. Dashed curve is the proton momentum for p+p elastic scattering at half the beam momentum.

Fig. 2. Invariant cross section for the reaction $d+{}^4He \to p+X$ at $\theta = 14.2^o$ showing least squares fit to the data at incident deuteron momentum of (a) 2.22 GeV/c and (b) 5.32 GeV/c.

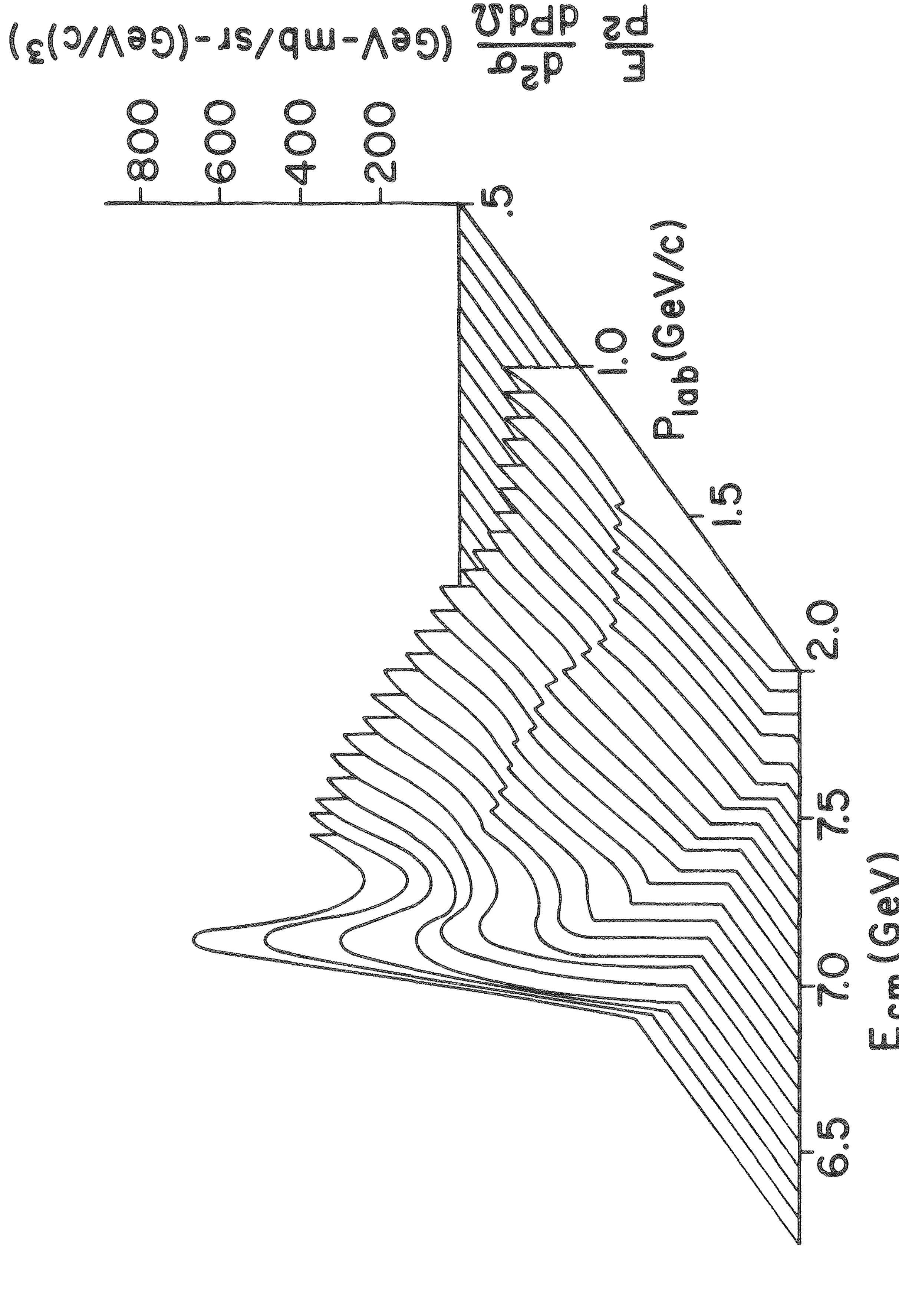
Fig. 3. Two dimensional least squares fit to the invariant cross section for the inclusive reaction $d+{}^4He \to p+X$.



E cm (GeV)
6.1
6.6
7.1
7.6
8.1
Tp=400 MeV
300
200
100
50
P lab (GeV/c)
2.0
1.5
1.0
.5
2.0
3.0
4.0
5.0
6.0
Pd (GeV/c)



a)
b)
P_{lab} (GeV/c)
$\frac{E}{p^2}\frac{d^2\sigma}{dp\,d\Omega}$ (GeV-mb/sr-(GeV/c)^3)
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
200
400
600
800
1000



E/p² d²σ/dpdΩ (GeV-mb/sr-(GeV/c)³)
800
600
400
200
.5
1.0
1.5
2.0
P_lab (GeV/c)
6.5
7.0
7.5
E_cm (GeV)