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RESULTS ON DEEP INELASTIC SCATTERING

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ABSTRACT

Recent measurements of deep inelastic processes involving charged leptons, primarily muons, are reviewed. Their relevance in testing the ability of Quantum Chromodynamics to describe strong interactions is outlined.

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INTRODUCTION

Processes which have been well described by the quark parton model are generally considered to be good candidates to provide critical tests of the theory of strong interactions, Quantum Chromodynamics (QCD). In this paper three such processes involving charged leptons are considered and recent results are reviewed^{*)}.

1. Deep Inelastic Scattering
 - Nucleon Structure Functions
2. Dimuon Production by Hadrons
 - The "Drell-Yan" process
3. Hadrons Produced in Deep Inelastic Muon Scattering

The greatest emphasis is given to Section 1.

1. NUCLEON STRUCTURE FUNCTION

Deep inelastic scattering of charged leptons on nucleons is described within the one photon exchange approximation (Fig. 1a) by the formula

$$\frac{d\sigma}{dQ^2 dv} = \frac{2\pi\alpha^4}{Q^4} \frac{F_2(x, Q^2)}{v} \left[(2EE' - \frac{Q^2}{2}) + \frac{Q^2 + v^2}{1 + R(x, Q^2)} \right]$$

The two a priori unknown, functions describing the nucleon are in this case taken to be $F_2(x, Q^2)$ and $R(x, Q^2)$ where the latter is the ratio of the absorption cross-sections for longitudinal and transverse polarized photons.

According to the quark parton model, the photon interacts with a quasi-free quark (Fig. 1b) and both F_2 and R are independent of Q^2 . If the quarks have spin 1/2, $R = 0$ thus giving the cross-section a very simple form. Within QCD this picture is modified by the presence of gluons (Fig. 1c) which lead to logarithmic Q^2 dependences for F_2 and a well-defined behaviour (non-zero) for R . This still simple picture is, however, manifestly incomplete since one starts with a nucleon and finishes with hadrons, none of which are free quark states. The complicated exchanges which lead to this quark binding are also expected to contribute to the cross-section with terms involving inverse powers of Q^2 , the "higher twist" terms.

While the early deep inelastic lepton scattering experiments used electron beams, the existence of muon beams at FNAL and CERN has allowed the use of heavy

^{*)} Where updated results appeared between the time of the Symposium and the XX Int. Conf. on High Energy Physics, Madison, especially referring to Section 1, these have been included.

nuclear targets without causing a prohibitive increase in radiative corrections ($X_0^u \gg X_0^e$). Table I provides a catalogue of recent experiments from which results have been presented.

Except for the measurements from the MSU-FNAL group, the results are not yet final and systematic errors of the order of $\pm 15\%$ are generally quoted. Within such bounds the agreement between different measurements is satisfactory. As an example, the data set from EMC (120, 250, 280) GeV is compared, in Fig. 2, with the mean of the three BCDMS measurements; there is a general trend of weak, but significant, decrease of F_2 with increasing Q^2 for $x > 0.25$.

From Fig. 2 it is apparent that deviations from scaling are not dramatic in this high Q^2 region; neither are the QCD predictions.

Before the data can be fed to a full QCD fit of F_2 there are several details which must be considered.

i) Data presentation

There is no universal convention for the presentation of F_2 . The data values may be adjusted to refer to particular x, Q^2 values or may be averages over bins in these variables which then depend on how the bin is sampled (different for muons and neutrinos, different from experiment to experiment). The strong x variation of F_2 can then generate differences. Similarly, differences appear between data which have been treated differently as far as the nucleon Fermi momentum is concerned. Some groups prefer to attempt a correction, others do not.

ii) Value of R

The determination of F_2 from $d\sigma/dQ^2 dv$ involves a knowledge of R which has its largest effect at high y (high Q^2 for fixed x), as shown in Fig. 3. This is avoided by making measurements with different beam energies although it should be emphasized that at high y for the highest energy R will always be unknown. The value and behaviour of R itself is also interesting, although it is more difficult to make a significant measurement of R than to render negligible the contribution to uncertainty in F_2 (at least if R is small). Finite measurements have been reported from two sources, SLAC¹⁾ and CHIO²⁾ and the quoted "average" values are

$$0.21 \pm 0.1 \quad \text{SLAC}$$

$$0.51 \pm 0.35 \quad \text{CHIO}$$

Despite the large errors, the behaviour as a function of Q^2 and x has been examined³⁾ although, as shown in Fig. 4, conclusions with respect to theory are hardly possible.

iii) Use of low Q^2 and low W^2 data

QCD most easily gives predictions which involve integrals of the structure functions, e.g., for moments

$$\int_0^1 dx x^n F_2(x, Q^2)$$

or in direct fits to the Altarelli-Parisi equations⁴⁾

$$\int_x^1 dx' F_2(x', Q_0^2)$$

In the first case, the lower limit of integration is zero, while the data are necessarily bounded at fixed Q^2 by the limit $x_{\min} = Q^2/2m_p E$ where E is the maximum available beam energy. At high x there is a contribution from resonances and elastic scattering which is significant, even at moderate Q^2 (Fig. 5). In principle, these contributions are to be included in the integrands⁵⁾; however, it seems evident that the resonances are coherent phenomena (higher twist) and cannot necessarily be expected to have a logarithmic dependence on Q^2 .

iv) Charmed sea contribution to F_2

The exchanged photon can couple to charm, anticharm quarks in the nucleon only above some threshold in ν . At fixed x such an onset of charm production would appear as a rise of F_2 with Q^2 . Information on the contribution of charm can be obtained by examining multi-muons produced by muons scattering on a heavy nuclear target. The energy deposited in the heavy target is measured using calorimetry and the signature for charm production is a missing energy (~ 20 GeV) corresponding to the energy carried by a neutrino from semileptonic charm decay

In Fig. 6, data from the EMC group⁶⁾ are shown in comparison with the predictions of a particular model, the photon-gluon fusion model, for the generation of the charm sea. Agreement between data and model is good and the model also fits well with similar measurements by the BFP group⁷⁾. The kinematics inherent in the model lead to a sharing of the photon energy between quark and antiquark and consequently, to a significant probability for both charmed particles to decay giving a muon within the spectrometer acceptance (mainly in the forward

direction). Such a trimuon signal with $\langle E_{\min} \rangle \sim 40$ GeV has been observed by EMC⁸⁾ above a calculated normal QED trident background. As shown in Fig. 7, the same photon-gluon fusion model reproduces well the magnitude and shape of the distributions. Given the success of the model it can be used to estimate the contribution to F_2 and to the observed scaling violations. While the conclusions are clearly model dependent, the result is that a significant part ($\sim 30\%$) of the observed rise of $F_2(x, Q^2)$ at small x can be attributed to charm production^{7), 8)}.

The regions affected by these considerations are shown schematically in Fig. 8. The trouble-free region remaining is somewhat limited and it is prudent to consider what each individual group concludes from its own data before a global fit is attempted.

CURRENT STATUS OF ANALYSES

MSU-FNAL

This group has presented final data⁹⁾ at 275 GeV which have been corrected for Fermi motion effects and refer to bin centres. R has been assumed to have the form $R = 1.2(1 - x)/Q^2$, although the effects of taking a constant $R = 0.25$ are also indicated. The data are shown in Fig. 9 compared with data on D_2 from the SLAC electron scattering experiment¹⁰⁾. The data were fit to the Altarelli-Parisi evolution equations using the program of Abbot et al.¹¹⁾. The value of Λ , the scale parameter of the QCD interaction, was determined to be $\Lambda = 0.1 \pm 0.05$ GeV ($\alpha_s(Q^2) = 12\pi/[(33 - 2n_f)\ln Q^2/\Lambda^2]$). This fit is shown as the dashed curve in Fig. 9. The solid line is a fit of the same form, but including the SLAC data with the result $\Lambda = 0.5 \pm 0.2$ GeV. The authors suggest that higher twist $(1/Q^2)^n$ contributions at low Q^2 could explain this. Such a conclusion is, however, sensitive to differences in relative normalization between the two data sets.

BFP

Preliminary data from this experiment were presented in 1979¹²⁾ with partial statistics. The data were corrected for Fermi smearing and bin centred. Systematic uncertainties of $\pm 15\%$ are quoted. There are data from two beam energies, 90 GeV and 209 GeV, as shown in Fig. 10. In Fig. 11 the results of a fit to the form $\ln F_2 = a + b \ln \ln(Q^2/0.09)$ is shown. By comparison with the behaviour of the equivalent quantity in the QCD model of Buras and Gaemers¹³⁾, the very tentative conclusion that the data favour Λ values less than 0.5 is reached.

EMC

This group presented iron target data¹⁴⁾ at the Madison Conference from three energies, 280, 250 and 120 GeV, the results from the lowest energy being preliminary. The data were bin centred and corrected for Fermi motion. A constant value of $R = 0.2$ was assumed and systematic errors of $\pm 15\%$ were quoted. An apparent difference in normalization between 120 GeV and the higher energies was removed when combining the data by adjusting each data set by 5%. QCD fits, which are shown along with the data in Fig. 12, were then performed using two analysis prescriptions (see Refs 11) and 15)) both based on fitting directly the Altarelli-Parisi equations. The resultant value of $\Lambda = 0.1$ in leading order was obtained. While this value was also obtained when the problematical low x region was excluded from the fit, the residual systematic uncertainties prevent assignment of an error smaller than 100 MeV¹⁶⁾.

BCDMS

While very preliminary data were presented at FNAL¹⁷⁾, the most recent presentation from this group involves three energies, 120, 200 and 240 GeV¹⁸⁾. The data are bin centred, but not corrected for Fermi motion effects. For the first time a correction has been made for the expected contribution of the weak-electromagnetic interference term. The statistics are good to very high Q^2 (reflecting the high luminosity of the experiment) although only a fraction of the total data is so far included. Agreement is good between the three energies, as shown in Figs 13 and 14, and a fit shows small, but significant, scale breaking effects. The systematic uncertainties (indicated in the figures) are felt by the group to exclude, for the moment, a detailed QCD analysis.

Liquid target measurements

The measurements on liquid targets, hydrogen and deuterium, from the SLAC^{1),10)} and CHIO²⁾ groups, which until now have formed the basis of the most complete analyses of charged lepton data, have now been supplemented by high statistics data on a hydrogen target from EMC¹⁹⁾ at two energies, 120 and 280 GeV. Again, the lower energy results are preliminary. $R = 0.2$ has been assumed, the data refer to bin centres and, of course, there are no Fermi motion corrections to be made. Agreement between the two energies is excellent, as shown in Figs 15 and 16. The line is a fit using the same program as the iron data analysis¹⁴⁾. A value of $\Lambda = 0.1 \pm 0.1$ is obtained with these data as with the solid target data¹⁶⁾, although when the complete x range is fit there is an indication of a systematic failure at low x which may reflect the presence, mentioned earlier, of a significant charm contribution.

Complete analyses

The quality of the SLAC and CHIO data, mentioned in the previous section, is illustrated in Fig. 17; there is a good coverage in x for $Q^2 \leq 22.5 \text{ GeV}^2$. Moments analyses have been performed. As shown in Fig. 18, the moments depend rather smoothly on Q^2 . The values of Λ extracted from such analyses²⁰⁾ show (see Fig. 19) a dependence in leading order on the order of the moment n . This is expected by QCD and the variation virtually disappears (Fig. 20) when the analysis is carried to next-to-leading order. Such analyses indicated rather strongly, the anticipated perturbative QCD behaviour, although with a rather large value of Λ .

Similar results were obtained by Barnett et al.¹¹⁾ although here the suggestion was made that some, at least, of the behaviour observed could be interpreted as due to higher twist ($1/Q^2$) effects. This attitude has been pushed to the extreme in a paper²¹⁾ which suggests that all the observed Q^2 dependence in the data is due to higher twist and that perturbative effects have as yet not been seen. To the experimenter this is galling, since the data are rather complete and not at all in question, but still do not appear to be definitive in terms of theoretical interpretation.

Conclusions on structure functions

- 1) There is substantial agreement among the high energy measurements of F_2 from nuclear targets, and a general consensus of a weak Q^2 dependence represented, by a Λ value of ~ 0.1 , is emerging. Within the next year "complete" analyses of these data can be seriously attempted.
- 2) The rather comprehensive low Q^2 H_2 and D_2 data have not provided a definitive interpretation. It is not excluded that the numerous modified scaling variables suggested during 1970-74 were on the right lines.
- 3) The new high energy hydrogen data from EMC have the required quality and, it is to be hoped, also the range in Q^2 to clarify the rather uncertain theoretical situation.

2. DIMUON PRODUCTION BY HADRONS: THE DRELL-YAN PROCESS

The production of high mass muon pairs by hadrons is postulated to proceed via quark-antiquark annihilation as shown in Fig. 21. The cross-section may then be written as:

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The formulae on page 7 should read:

$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{3s} \frac{1}{3} \frac{Q_1^2}{\sum x_1^2 x_2^2} \left(f_1^{h_1}(x_1) f_1^{h_2}(x_2) + f_1^{h_1}(x_1) f_1^{h_2}(x_2) \right)$$

$$\frac{d\sigma}{dM dx_F} = \frac{8\pi\alpha^2}{3M^3} \frac{1}{3} \frac{Q_1^2}{\sum (x_1+x_2)} \left(f_1^{h_1}(x_1) f_1^{h_2}(x_2) + f_1^{h_1}(x_1) f_1^{h_2}(x_2) \right)$$

$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{s} \frac{1}{3} \sum \frac{Q_i^2}{x_1 x_2} \left(f_i^{h_1}(x) f_i^{h_2}(x_2) + f_i^{h_1}(x_1) f_i^{h_2}(x_2) \right)$$

or

$$\frac{d\sigma}{dM dx} = \frac{8\pi\alpha^2}{M^2} \frac{1}{3} \sum \frac{Q_i^2}{(x_1 + x_2)} \left(\right)$$

$$x_1 x_2 = \frac{M^2}{s} = \tau$$

$$x_1 - x_2 = x_F$$

where Q_i is quark charge, $\alpha \equiv$ fine structure constant, and $f_i^h(x)$ are quark density distributions. A discussion of this process is facilitated by working through a list of quark-parton model predictions which follow from this picture of the process. This line will be followed below, starting with those predictions with which the data show no disagreement and proceeding to those which need to be modified and which, presumably, should have some QCD interpretation.

Quark-parton model characteristics not needing modification

i) A dependence

Since the cross-section is an incoherent sum of quark-antiquark annihilations, there should be no A dependence, i.e., that cross-section per nucleon should be independent of A. Although individual measurements have, in the past, found a different A dependence, the present consensus is clearly in favour of the incoherent interpretation²²⁾.

ii) Charge asymmetry

There is a clear prediction for the ratio of positive and negative pion cross-sections

$$\frac{\sigma(\pi^+ N)}{\sigma(\pi^- N)} \equiv \frac{d\bar{d}}{u\bar{u}} \Rightarrow \begin{cases} \frac{1}{4} & \text{for isoscalar target} \\ \frac{1}{8} & \text{for hydrogen target} \end{cases}$$

Such behaviour is illustrated in Fig. 22 by data from the CCOPS Collaboration at CERN²³⁾.

iii) Scaling

Provided that the Q^2 dependence of the quark distribution functions is ignored, the cross-section form implies

$$M^3 \frac{d\sigma}{dM} = f\left(\frac{M}{\sqrt{s}}\right)$$

This is illustrated in Fig. 23 taken from Ref. 22), in which are included data from FNAL and the ISR covering a range of $> 2000 \text{ GeV}^2$ in s . Similar conclusions are obtained by the CCOPS group using $\pi^- N$ data.

Quark-parton model characteristics needing modification

i) Cross-section magnitude

With the definition

$$d\sigma_M = K * d\sigma_0$$

where $d\sigma_0$ is the standard Drell-Yan formula given earlier and $d\sigma_M$ is as measured, K provides a measure of the ratio between the two. The data²³⁾ show $K \neq 1$. The details of the deduction of K for different processes vary somewhat. For instance, a measurement using protons incident on a nucleon target involves a knowledge of the antiquark distributions. Two particularly clean measurements are provided by $\bar{p}N$ data (Fig. 24a) since valence distributions dominate, and by $\pi^- p$ (Fig. 24b) since no knowledge of A dependence is required. The complete set of K values measured by the CCOPS group²³⁾ is shown in Table II. The values are all consistent and it should be noted that the error is the same in each case and is entirely systematic. A calculation of the leading order QCD corrections to the parton model graph yields a value of order 2²⁴⁾.

ii) Angular dependence

In the quark-parton model the angular dependence is given by the 1^- character of the photon as

$$\frac{d\sigma}{d(\cos\theta)} \sim 1 + \lambda \cos^2\theta$$

with $\lambda = +1$. Averaged over x the data are consistent with this behaviour, however, for large x and/or large p_T λ is significantly altered, becoming negative at high p_T and high x . This general behaviour is well predicted by including higher twist effects²⁵⁾.

iii) p_T dependence

The pure quark-parton model diagram would lead to a zero p_T^2 for the muon pair, while the data shown in Fig. 25 have half the events with $p_T > 1$ GeV. Perturbative QCD calculations predict an s dependence and some dependence on energy is certainly seen in Fig. 26. A linear fit to the s dependence²⁶⁾ implies, however, a large residual $p_T^2(s = 0) = 0.5 \text{ GeV}^2$. The interpretation of this invokes a quark Fermi momentum within both the hadrons. Such an effect must surely be present, but the interest is to understand whether what is observed in this process is consistent both with what is measured elsewhere (see next section) and with the static properties of hadrons.

3. FINAL STATE HADRONS IN MUON SCATTERING

The basic quark-parton model for deep inelastic production of hadrons is described as in Fig. 1b. with reasonable assumptions about how the quark fragments into hadrons²⁷⁾ this picture has successfully described a large quantity of data. The underlying quark-parton model diagram, as for the Drell-Yan case, predicts no p_T with respect to the virtual photon.

The inclusion of gluon emission and gluon fusion graphs (Fig. 1c) leads to a prediction for the behaviour of the mean p_T^2

$$\langle p_T^2 \rangle \propto \alpha_s(Q^2) \cdot W^2$$

The W^2 factor comes from the phase space factors²⁸⁾. If the complication of the intrinsic motion ($\langle k_T^2 \rangle$) of the quarks in the nucleon and the $\langle p_T^2 \rangle^{\text{frag}}$ associated with the fragmentation process are also considered, then one has the expression²⁹⁾

$$\langle p_T^2 \rangle_{\text{obs}} = \langle p_T^2 \rangle_{\text{QCD}} + \langle p_T^2 \rangle_{\text{frag}} + z^2 \langle k_T^2 \rangle$$

The EMC group has presented data³⁰⁾ which show clearly the z^2 and W^2 dependences expected from such an ansatz. This is shown in Fig. 27. There is good agreement with lower energy neutrino data³¹⁾ and the s dependence is well reproduced by a standard QCD calculation³²⁾. As shown in Fig. 28, however, the description of the data require a value for the intrinsic p_T , $\langle k_T^2 \rangle \approx 0.6 \text{ GeV}^2$. In this analysis, it may be considered as a mere parameter, but given the similar large effect observed in muon pair production, it is of considerable interest to understand its significance. It should be noted that an alternative technique to determine k_T with somewhat lower energy data also obtained a comparable value³³⁾.

CONCLUSIONS

For all the three types of processes considered here, there are some impressive sets of data available. While there is strong evidence for behaviour predicted by perturbative QCD calculations, it is clear that this is not the complete story. It is important that non-perturbative effects (k_T , higher twist, etc.) be understood from both the experimental and theoretical points of view so that the full potential of these measurements may be realized.

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Table I

Collaboration	Target	Beam Energy	Data taken
MSU-FNAL	Fe	275	1976
BFP	Fe	209	1978
		90	
EMC	Fe	280	1978
		250	1978
		120	1979
BCDMS	C	240	1979
		200	1979
		120	1979

Table II

Beam	Energy (GeV)	Target	K
π^-	150	Pt	2.25 ± 0.4
π^+	200	Pt	2.40 ± 0.4
$\pi^- - \pi^+$	200	Pt	2.20 ± 0.4
π^-		H ₂	2.4 ± 0.4
K ⁻	150	Pt	2.1 ± 0.4
$\bar{p}$	150	Pt	2.15 ± 0.4

Figure Captions

- Fig. 1 : a) Single photon exchange diagram for charged lepton scattering;
b) Parton model picture of deep inelastic scattering;
c) Leading order QCD diagrams involving gluon;
- Fig. 2 : Comparison between EMC and BCDMS F_2 measurements. Errors are statistical only.
- Fig. 3 : Effect on F_2 of different assumptions as to the value of R .
- Fig. 4 : Variation of R with x for different Q^2 ranges. Data from Ref. 1) 0, and Ref. 2) x ; the curves are predictions from Ref. 3).
- Fig. 5 : Integrands of moments indicating contribution from $W < 2$ GeV (arrow). Data from Ref. 1) and 2).
- Fig. 6 : Measurements of dimuon events from Ref. 6) compared with the predictions of the photon-gluon fusion model.
- Fig. 7 : Distributions of trimuon data from Ref. 8) compared with the photon-gluon fusion model.
- Fig. 8 : Schematic Q^2 vs x plane indicating the regions affected by various uncertainties.
- Fig. 9 : $F_2(\text{nucleon})$ from Ref. 9). Data from Ref. 9) solid symbols, and from SLAC¹⁰⁾, open symbols. Dashed line QCD fit with $\Lambda = 0.1$, solid line QCD fit with $\Lambda = 0.5$ (see text).
- Fig. 10 : $F_2(\text{nucleon})$ from Ref. 12): solid symbols - $E_{\text{inc}} = 90$ GeV; open symbols - $E_{\text{inc}} = 209$ GeV.
- Fig. 11 : $\partial \ln F_2 / \partial \ln \ln(Q^2/0.9)$ vs x from Ref. 12).
- Fig. 12 : $F_2(\text{nucleon})$ from Ref. 14). Line is QCD fit with $\Lambda = 0.1$ using program of Ref. 11).
- Fig. 13 : $F_2(\text{nucleon})$ from carbon, Ref. 18). Open symbols 120 GeV, solid symbols 200 GeV.
- Fig. 14 : $F_2(\text{nucleon})$ from carbon, Ref. 18). Open symbols 240 GeV, solid symbols 200 GeV.
- Fig. 15 : $F_2(\text{proton})$, Ref. 19). Open symbols 120 GeV, solid symbols 280 GeV. Line is QCD fit using program of Ref. 11), $x \leq 0.175$.
- Fig. 16 : As in Fig. 15, $x \geq 0.25$.
- Fig. 17 : Measurements from SLAC and CHIO of F_2^p .

- Fig. 18 : Moments of F_2^P and F_2^D as determined from SLAC and CHIO data.
- Fig. 19 : First order determination of Λ as a function of the order n of the moments used, Ref. 20).
- Fig. 20 : Second order determination of Λ as a function of the order n of the moments, Ref. 20).
- Fig. 21 : Quark model, Drell-Yan picture of high mass muon pair production by hadrons.
- Fig. 22 : Asymmetry in muon pair production using positive and negative pions²³⁾.
- Fig. 23 : Scaling of muon pair production by protons²²⁾.
- Fig. 24 : Determination of K factor:
 a) in $\bar{p}N$ interactions;
 b) in π^-p interactions in hydrogen.
- Fig. 25 : p_T dependence of muon pair production.
- Fig. 26 : s dependence of $\langle p_T \rangle$ of muon pair production from Ref. 22).
- Fig. 27 : Dependence of $\langle p_T^2 \rangle$ of hadrons produced in deep inelastic muon scattering as a function of s for different z ranges. Open symbols νNe data from Ref. 31), solid symbols μp data from Ref. 30).
- Fig. 28 : Dependence of $\langle p_T^2 \rangle$ on z^2 from Ref. 30). Curves I and II are contributions from fragmentation process and perturbative QCD, respectively.

Fig. 1

Fig. 2

Fig. 3

○ S.L.A.C. M.I.T.
* C.H.I.O.

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Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

a)

b)

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28