SMALL ANGLE SCATTERING OF HIGH ENERGY PHOTONS

ON HEAVY NUCLEI (DELBRÜCK SCATTERING, PHOTON

SPLITTING)

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INTRODUCTION

During 1970 - 1972 an experiment has been carried out
at the DESY electron synchrotron with the aim to
study Delbrück scattering which is the elastic scattering
of a photon in the Coulomb field of nuclei via virtual
electron positron pairs. One of the corresponding Feyn-
man diagrams is shown in fig. 1b. The incoming photon
converts into a virtual electron positron pair, which
is scattered twice in the static Coulomb field of the
nucleus and subsequently annihilates into an out-
going photon.

There are at least two photons exchanged with the
nucleus, since the so-called Furry theorem says
that diagrams containing a fermion loop with an
odd number of corners do not contribute to the
cross section. Therefore one photon exchange with
the nucleus gives no contribution to Delbrück
scattering. The diagram contains 6 vertices which
means that Delbrück scattering is of at least 6th
order in the electro-magnetic coupling. This is
fairly high compared to the more common processes
like bremsstrahlung and pair production, that are only
of 3rd order. The coupling of the two photons to the
Coulomb field gives a factor Z^2 in the Delbrück
amplitude. Thus the cross section becomes propor-
tioned to $Z^4 \alpha^6$.

As the diagram shows, Delbrück scattering is the
direct consequence of vacuum polarization (fig. 1a),
that is the part time existence of a photon as a
virtual electron positron pair. This virtual electron
positron pair may be scattered by external fields.
If this field is the nuclear Coulomb field the pro-
cess is called Delbrück scattering. Detection of
Delbrück scattering is thus the most direct proof of
the existence of vacuum polarization.

There are two more processes related to vacuum pola-
rization, that is the scattering of light by light
(fig.1c) and the splitting of a photon into two by
interaction with an external field (fig. 1d).
Especially the first one, scattering of light by
light has attracted the interest of physicists for
a long time as a basic process predicted by QED, but
not possible in linear electrodynamics. Up to now
the experimental detection of scattering of light by
light has not been possible because of the small
cross section and the difficulty of getting dense tar-
gets. Delbrück scattering is a first approximation

to the scattering of light by light in the sense that the second photon is replaced by a virtual photon from a static Coulomb field. It is much easier to measure, since one can use solid target with high Z material.

Another aspect of the Delbrück process is its being the shadow scattering of photons resulting from photon absorption by electromagnetic pair production. The imaginary part of its forward amplitude is related to the total pair production cross section by the optical theorem

$$\text{Im } A_D(k, \vartheta = 0) = \frac{k}{4\pi} \sigma_{tot}(k)$$

Early approximate calculations of the Delbrück cross section used this relation. Starting from the known pair production cross section Bethe 'and Rohrlich (ref.1) calculated in 1952 the imaginary part of the Delbrück amplitude from the optical theorem and the real part via dispersion relations. These calculations gave results for small momentum transfer ($\Delta \ll m_o$, m_o = electron mass) and high energies.

In spite of the fact that Delbrück predicted the process already 40 years ago (ref.2) it was only recently that a calculation of the cross section via conventional perturbation theory was published by Cheng and Wu (ref.3). Even this calculation is valid only for asymptotically high energies and not too small momentum transfer. This is a consequence of the high order of the process, which makes calculations extremely lenghty and complicated. On the other hand it is interesting to study very high order processes, since there is no compelling reason why perturbation theory need be correct to such high orders. Stimulated by Cheng and Wu's paper we proposed a new measurement of the Delbrück cross section at high energies (ref.4).

Earlier measurements had clearly shown the existence of the Delbrück process, but suffered from various

systematic errors. At energies of a few MeV, where
most of the experiments were done, it was the inter-
ference with not well known low energy scattering pro-
cesses that made quantitative interpretation difficult.
There is one measurement of Moffatt and Stringfellow
(ref. 5) at an energy of 100 MeV, which is clean in
this respect, but there the contribution of degraded
photons from showers developing in the target was not
clear. Moffat and Stringfellow gave their results in-
cluding shower background. They made estimates on this
shower background using two different methods and get-
ting two different values as the answer, leaving it to
the reader to choose between the two alternative values
for the background. Depending on what value for the
background you choose, you get two distinct data sets
for the experimental cross section. Cheng and Wu (ref.3)
picked out the set most favorable to their curve, where-
as if you take the other, which is just as good, you find
the experimental data are now in agreement with the Bethe Rohr-
lich prediction which is quite different from Cheng and
Wu (fig. 2). In this situation it was clear that the
data of Moffatt and Stringfellow could not be used to check
Cheng and Wu's calculation and it seemed worthwhile to
perform another measurement in the GeV region, where we
expected the competing processes to be well known
(however, see below).

In fig. 3 the differential cross section is plotted as a
function of the scattering angle and photon energy for
Delbrück scattering and for Compton scattering on atomic
electrons as the competing processes. The target material
is Uranium, which is most favorable for the Delbrück pro-
cess, because this is proportional to Z^4, whereas Compton
scattering is proportional to Z only. Other competing
elastic processes one might think of, for example
Compton scattering on nuclei, are negligible compared to
these ones. Delbrück scattering shows a strong forward
maximum and dominates at small scattering angles. For the

primary photon energies considered, that is between
1 and 7 GeV, it is above the Compton cross section only
within a few milliradians from the beam. That means one
has to measure scattered photons at very small angles,
close to the primary beam. The differential cross section
is large, but since the relevant solid angle is very small
counting rates become nevertheless critical.

EXPERIMENTAL METHOD

The experimental set up used is shown in fig. 4. The
sketch is not to scale, only to show the principle. A
well collimated bremsstrahlung beam from the synchrotron
hits the scatterer and passes without interaction through
a magnetic pair spectrometer and is finally buried in a
totally absorbing ionization chamber, that serves as the
monitor. There are several sweeping magnets and colli-
mators between target and spectrometer (not shown in
fig. 4), that clean the beam from charged particles.
The scattered photons are converted into electron posi-
tron pairs on a ring shaped aluminum converter and ana-
lyzed with a magnetic spectrometer.

To be able to measure scattered photons at 1 mr one has
to make sure that the photon density of the primary beam
drops by 8 to 9 orders of magnitude at a distance of 2 cm
from the beam, which has a diameter of .8 cm. This re-
duction of the beam halo was achieved by a special system
of 3 collimators and sweeping magnets. The condition on
the collimation channel and the position of the converter
ring was the following: The first collimator is the de-
fining one, all the following ones are just to strip off
the beam halo and must not touch the primary beam any
more. The second collimator must not see the machine target.
The third must not touch the secondary beam from the
edges of the first collimator. The scattering target is
just behind the third collimator. Scattered photons are
detected by the conversion in a ring which in turn

must not see the target nor any edges of collimators
except the last one. We found, that each collimator
carefully positioned in this way reduces the beam halo
by about three orders of magnitude. With this arrangement
empty target background in our measurements ranged from
5 to 30% and has been subtracted in the following.

Another dangerous source of background are secondary
processes within the scatterer. A photon produces a
pair, the pair electrons change direction via multiple
scattering and finally emit bremsstrahlung that mixes
   with the Delbrück scattered photons. This is an
especially serious background since it is Z^4-dependent as is
the Delbrück scattering. There are two ways to keep this
background small:

1. The production of secondary photons is a two step
process. Their contribution rises quadratically with the
target thickness and can be kept small by using thin
targets. Since this would mean small Delbrück rates too,
a trick was used to overcome this limitation. The target
was split into a number of sufficiently thin foils
(~0.02 r.l.) which were placed one behind the other inside
a sweeping magnet with equal distances in between. The
magnetic field between the foils has to sweep out the
electrons and positrons produced in a previous foil so
that the emitted secondary photons from the next foil are
well outside the solid angle of the converter ring. In
this way we could increase the effective target thickness
by a factor of ten without getting a quadratic rise in
the number of secondary photons.

2. The other way to keep the contribution of secondary
photons small is based on the fact that secondary photons
are degraded in energy, because they originate from an
inelastic process and any inelastic process would move them
downwards in energy, contrary to the elastically scattered
Delbrück photons. If one uses photons only from the edge of the
bremsstrahlung spectrum for the measurement, one can keep

the contribution of secondary photons small. We used only
photons within 3% from the edge of the bremsstrahlung
spectrum in the Delbrück measurement. The relative con-
tribution of secondary photons in this bin was typical
10% and could be corrected for with good precision as
will be shown below.

The scattered photons are detected with the pair spectro-
meter. They hit a ring made of 2 mm aluminum, through the
central hole of which the primary beam passes. This ring
converts a definite fraction of the scattered photons
into electron positron pairs, which are bent in the mag-
netic field and detected by scintillation counters and
Charpak chambers. The wire separation in the Charpak chambers
was 2 mm and the gas used was a mixture of argon with carbon
dioxide; two crossed planes were used in each position. The
setup contained a total of 1000 wires. The efficiency of
the chambers was better than 99.5 % at a time resolution of
120 ns. The system worked reliably and caused us no trouble.

The information from the Charpak chambers made possible a
complete reconstruction of the event as to the energy and
the conversion point of the photon. The photon energy was
measured to 1%, the coordinates of the conversion point to
$\pm$ 3 mm, which gave a geometrical angular resolution or
$\pm$ .15 mrad.

If one plots the reconstructed starting points of pairs in
the plane of the converter one gets a true picture of the
ring as shown in fig. 5. This is the image of a small ring
with 2 cm radius and .4 cm width. One clearly sees the ring,
the holder and a few pairs produced by the primary beam in
the rest gas of the spectrometer. We had to have rather good
vacuum of 10^{-5} torr within the spectrometer not to be flooded
by those beam units. The reconstruction of the conversion
points enabled us to cover in one run the total angular
acceptance from 1 to 3.5 mrad using one large ring at the
expense of giving up some angular resolution.

The reconstruction was also useful for the rejection of
spurious tracks. Good events had to satisfy the constraint,
that electron and positron must start from the same point
within reconstruction errors.

To check the overall performance of the apparatus, especially
the efficiency and acceptance of the spectrometer, we
measured the primary bremsstrahlung spectrum using a con-
version foil instead of the ring and compared the result
with the theoretical prediction. This is shown in fig. 6.
The line is the theoretical spectrum normalized with the
monitor reading. The experimental points are event rates
multiplied by the acceptance of the spectrometer.The agree-
ment is satisfactory and gives a measure of the abso-
lute precision of data obtained with this apparatus.

DISCUSSION

Fig. 7 shows a typical spectrum of scattered photons for
gold as scatterer and a ring shaped converter. All open
points are event rates after subtraction of empty target
background. The line is drawn by hand to guide the eye.
The form of the spectrum is very much different from a
normal bremsstrahlung spectrum which looks similar to
the compton contribution, shown here as the broken line.
There are many more soft photons than in a bremsstrahlung
spectrum.

The Delbrück contribution is obtained from the highest
3%-bin. The energy resolution is one third of the width of this
bin.   We proceed in the following way: The Compton con-
tribution is subtracted, calculated from the Klein-
Nishina formula, which in this case amounts to 16% of the
counting rate in the Delbrück-bin. Further we subtract
the contribution from secondary photons calculated by
Monte Carlo methods from the known cross sections of
pair production and bremsstrahlung. This amounts to 7%
of the counting rate in this bin.After doing these

subtractions the full points are obtained. Since our
acceptance covers   down to roughly 75% of maximum
energy the calculation of secondary photons is exten-
ded down to that point and it can be seen how fast the
number of secondary photons is rising towards lower
energies.

To check experimentally the ccrrect description of se-
condary photons by the Monte Carlo method the thickness
of the scatterer was varied. Fig. 8 shows the ratio be-
tween counting rates for double-thickness and single-
tickness gold foils versus photon energy. For elementary
processes this ratio would be 2. If secondary processes
are present it comes out larger than 2. The open points
are the ratio of counting rates without subtraction, the
full points after subtraction of calculated secondary
photons. As expected at the edge of the bremsstrahlung
spectrum at the Delbrück-bin, there are practically only
elementary processes. At lower energies there is an
appreciable contribution from secondary processes, but
after subtraction of the Monte Carlo simulated secondary
photons there are only elementary processes left within
the full energy range considered. That means the Monte Carlo
simulation of secondary photons is correct over the full
energy range.

Fig. 9 shows the spectrum as we have seen before (fig.7)
after subtraction of Compton and secondary photons has
been done. We know that only elementary processes contri-
bute to these counting rates and we would expect this to
be the Delbrück signal. Let us compare it to the original
prediction of Cheng and Wu given here as the broken line.
There are two things, one can say at once: The counting
rate in the Delbrück-bin is at least a factor of 3 smaller
than predicted by Cheng and Wu. In addition the form of
the spectrum is quite different from what one would expect
for Delbrück scattering.

At the end of the spectrum there are only elastic pro-
cesses contributing. We are able to measure the elastic
contribution in the other parts of the spectrum by
varying the maximum energy of the bremsstrahlung spectrum
experimentally. We find then the heavy line as the elastic
contribution, that is the Delbrück contribution in this
spectrum. We see that with growing distance from the edge
of the bremsstrahlung spectrum the counting rate is in-
creasing much faster than expected from the elastic con-
tribution alone. Thus we know that the extra photons giving
the rise in the soft part of the spectrum 1) originate from
elementary processes in the target, 2) are inelastically
scattered photons. To find out what process might produce
these photons we plotted the number of extra photons, that is
number of photons above the heavy line, versus the atomic
number E of the target as shown in fig. 10. The ordinate
shows the number of photons per target atom divided by Z^2,
the abscissa is Z. The experimental points are within the
errors independant of Z in this plot, which means that the
cross section for production of extra photons is propor-
tional to Z^2.

When visiting DESY some time ago professor von Dardel
mentioned that the photon splitting process might give
a contribution to our counting rate. Based on an estimate
found in the litterature we then believed this contribu-
tion to be small, until our experimental results raised
the question anew. The photon splitting process exactly
has the properties we are looking for to explain our
extra photons, that is the scattering is inelastic and
proportional to Z^2.

If one looks into the litterature about the photon split-
ting process, one finds the following (refs 6,7):
1) There exists no experimental data up to this time;
2) there are some complete calculations, which come out
with some 100 terms, but have neither been evaluated
numerically nor integrated; 3) there are a few rough

estimates on the total cross section which differs by a factor
of 10. There was one very relevant statement among the rough
estimates saying that the cross section $d\sigma/dk'$ is rising
linearly with k' for small k'. This looks somewhat strange
since one is used from radiative corrections that the
probability of soft photon emission is proportional to 1/k'.
The different behavior here is the interesting consequence
of the fact, that photon splitting is not a radiative correc-
tion to some elastic process, since this elastic process
is not allowed (the Furry theorem).

The statement of the linear rise of the cross section with k'
of the splitted photon spectrum allows a simple prediction as
to the form in our experiment, i.e. the number of extra photons
should rise quadratically with the distance from the edge
of the bremsstrahlung spectrum. This is because the contri-
bution of splitted photons originating from primary photons
in the highest energy bin of the Bremsstrahlung spectrum is
rising linearly with the distance from this bin. Further
the number of photons in the beam is rising linearly too, as
a first approximation, with the distance from the edge.
                          Let us compare this behavior of
splitted photons with our counting rates of extra photons
as shown in fig. 11, where the spectrum of extra photons
is fitted with a parabola. There is indeed the quadratic
rise present. Together with the Z^2 dependence we take this
behavior as evidence for the extra photons to be produced
by the photon splitting process. This is the first experi-
mental evidence for this process.

From the fitted parabola we get numbers for the photon
splitting cross section integrated over the angles of one
of the outgoing photons:

$$\frac{d\sigma}{dk'd\Omega_{k'}} = C(k, \Omega_{k'}) * (1 - \frac{k'}{k})$$

The results are shown in fig. 12. Here the slope C
divided by Z^2 is plotted as a function of the angle of
the detected photon with the primary photon energy as
parameter. There is a steep rise of the cross section
with decreasing angle of the detected photon and with
decreasing energy. At the moment there are no theore-
tical data available for these results to be compared
with.

To compare our data on photon splitting with estimates
of the total cross section existing in the litterature,
we integrated our results over the accepted solid angle.
The expected energy distribution of splitted photons
is shown in fig. 13. The photon splitting distribution
looks different from the energy distribution in pair
production, which is almost rectangular at high energies.
Now there is a linear rise from the edges, the slope of
which we have measured. Nobody knows what it looks like
in between, whether there is a dip or a maximum. The
region measured in our experiment, hatched in the diagram,
integrates up to 2.3 mb for gold,which has to be compared
to the total cross sections of .87 mb given by Bolsterli
(ref. 8) and 4.5 mb as given by Bukhwostov (ref. 9).
Considering the fact that the angular integration was not
complete in our experiment even the second value for the
total cross section seems to be low.

The contribution of photon splitting to the counting
rate in the Delbrück-bin, the 3% energy bite at the edge
of the bremsstrahlung spectrum, is typically less than 5%
and will be neglected in the following, since the statisti-
cal errors are larger than this contribution. Thus there
is almost no interference in our experiment between the

elastic Delbrück scattering and the inelastic photon
splitting processes, as long as one stays close to the
edge of the bremsstrahlung spectrum for the Delbrück
analysis as we do.

Spectra of scattered photons like the one of fig. 7 have
been measured for a variety of angles, energies and
scatterer materials.The first check on the consistency
of the data from the so-called Delbrück-bin is shown in
figs 14 and 15 for two momentum transfer intervals. The ex-
perimentally observed cross section is plotted versus
atomic number Z of the scatterer. Both scales are logarith-
mic. The straight line is the Z^4-dependence of the Cheng
and Wu cross section (ref. 3). The experimental points of
copper, silver, gold and uranium are consistently lower
than the Cheng and Wu prediction by a factor of about 3
and the Z-dependence is somewhat less steep than Z^4
especially at high Z.

We were able to discuss this experimental evidence with
Cheng and Wu who then spent some time at DESY. There was
the suspicion that higher order effects not taken into
account in Cheng and Wu's original paper might produce
these effects. The effective coupling constant of the
virtual electron or positron to the target nucleus is
$Z.\alpha.$ which for large Z is no longer small compared to one.
The Born approximation then breaks down, as is well known
from pair production and bremsstrahlung where the actual
cross section for uranium is about 20% less than the Born
approximation gives. This can be accounted for by the so
called Coulomb correction, which in the picture of Feynman
diagrams means that one has to take into account the ex-
change of an infinite number of virtual photons between
electron and nucleus. Learning about our results Cheng
and Wu introduced the Coulomb correction into their Delbrück
cross section and indeed got an impressive reduction (ref.10)
of their cross section up to a factor of 5 for several MeV/c
momentum transfers and high Z. The broken lines of figs 14
and 15 shows the new

theoretical prediction for the Z dependence of this cross section. It comes much closer to the experimental values.

Fig. 16 shows our complete experimental results on the Delbrück cross section for gold as the target, compared to the theory with and without Coulomb correction. The measured values are a factor 3 to 5 below the Born approximation, called CWI, but are essentially in agreement with the theory including the Coulomb correction CWII. To our knowledge this is the largest effect ever observed for this special kind of higher order corrections. Indeed the Coulomb correction in this case is no minor correction but a drastic modification of the cross section.

A closer inspection of our data reveals that there might be some systematic deviations from the Cheng and Wu prediction, but our statistical errors do not allow a definite statement on this point. Besides, the Cheng and Wu calculation is for infinite primary energy. They neglect the real part of the amplitude altogether. What they calculate is the limiting value

$$\lim_{k \to \infty} \frac{1}{k} M_o^D$$

From the well-known forward scattering amplitude given by Rohrlich and Gluckstern (ref.13) we see that even at 1 GeV photon energy the real part still contributes 10% to the forward cross section. Thus it might be that our energy is not yet high enough to compare directly with Cheng and Wu, without having an estimate of the real part of the amplitude.

Fig. 17 shows results for uranium, together with some data from earlier experiments at low energy. The crosses are measurements of Bösch et al. (ref. 11) from Zürich in 1962 using 9 MeV photons, the rectangle is of Jackson et al. (ref. 12) at Argonne 1969 with 10 MeV photons. The open points are our data. There is about a factor of two between Cheng and Wu predictions and the low energy data. Our data are in rough overall agreement with Cheng and Wu, as it was with gold.

SUMMARY

From the results given above we conclude:

1) The Delbrück cross section at high energy, high Z and
   a few MeV/c momentum transfer is a factor of 3 to 5
   smaller than calculated in the lowest nonvanishing
   order of perturbation theory. This drastic reduction
   is due to a special kind of higher order corrections,
   called Coulomb correction, which fully accounts for
   the observed difference. Thus the result is that
   perturbation expansion gives correct results provided
   the calculation is extended to high enough orders.

2) There is strong evidence for the photon splitting pro-
   cess to be present in our data. The cross section
   deduced from these data is of the expected order of
   magnitude, but at present there are no precise theore-
   tical numbers to compare with. Experimentally the next
   step should be to do a coincidence experiment on the
   photon splitting process and from our experience such
   an experiment is feasable.

Finally one has to admit, that whereever one tries to check
QED once more it comes out as an astonishing good theory.

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Figure captions.

1. Feynman diagrams showing a) vacuum polarization b) Delbrück scattering c) scattering of light by light d) photon splitting.

2. Early results on the differential cross section of Delbrück scattering compared with predictions of a) Cheng and Wu (ref 3) b) Bethe and Rohrlich (ref 1).

3. Differential cross section for Delbrück scattering and Compton scattering on uranium.

4. Experimental arrangement (not to scale).

5. The converter ring as mapped by reconstructed events.

6. Measured Bremsstrahlung spectrum compared with the calculated spectrum normalized by the Quantameter reading.

7. Spectrum of photons scattered in gold and converted in a ring-shaped converter.

8. Ratio in counting rate of scattered photons in gold foils of thicknesses 2t and t versus photon energy $\mathbf{O}$ unsubtracted result $\bullet$ after the subtraction of secondary photons.

9. Spectrum of scattered photons from gold after the secondary and Compton photons have been subtracted compared to predictions of Cheng and Wu (refs 3, 10)

10. Excess photons (see fig 9) per target atom and divided by Z^2 as a function of Z.

11. Energy spectrum of excess photons fitted with a parabola.

12. Differential cross section for photon splitting integrated over one of the outgoing photons a) versus scattering angle θ b) versus primary photon energy k.

13. Energy distribution of splitted photons.

14. Differential cross section of Delbrück scattering as function of Z for the scatterer for a given momentum transfer $\Delta = 3.24$ MeV/c compared with predictions from Cheng and Wu I) without Coulomb corrections (ref 3) II) with Coulomb corrections (ref 10).

15. Same as fig 14 for $\Delta = 4.28$ MeV/c.

16. Differential cross section of Delbrück scattering in gold compared with Cheng and Wu predictions I) without Coulomb corrections II) with Coulomb corrections.

17. Same as fig 16 for uranium.

Fig 1a
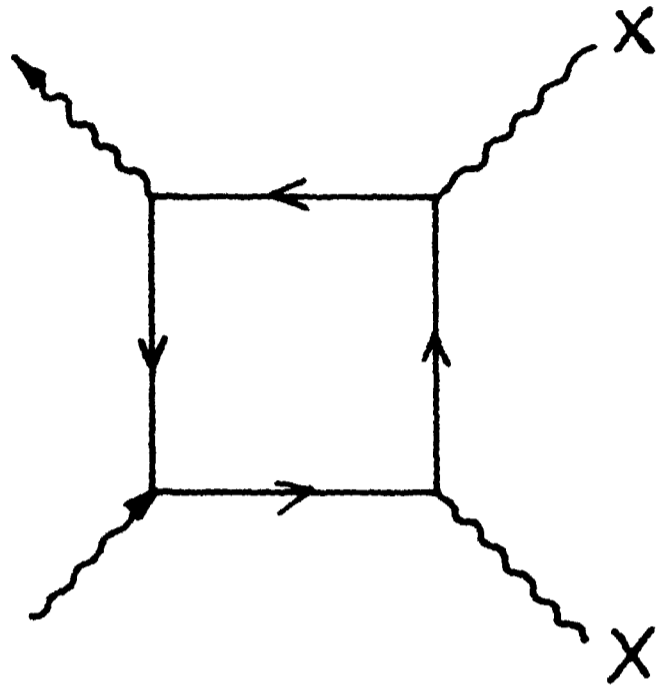
Fig 1b

Fig 1c

Fig 1d

Fig 2

Fig 3

REINIGUNGSMAGNET

SPEKTROMETERMAGNET
$(10^{-5}$ TORR$)$

P_3

P_7

S_3

S_1

P_1

P_5

VAKUUM

STREUTARGET

**KONVERSIONS-
TARGET** (RING)

QUANTAMETER

P_6

P_2

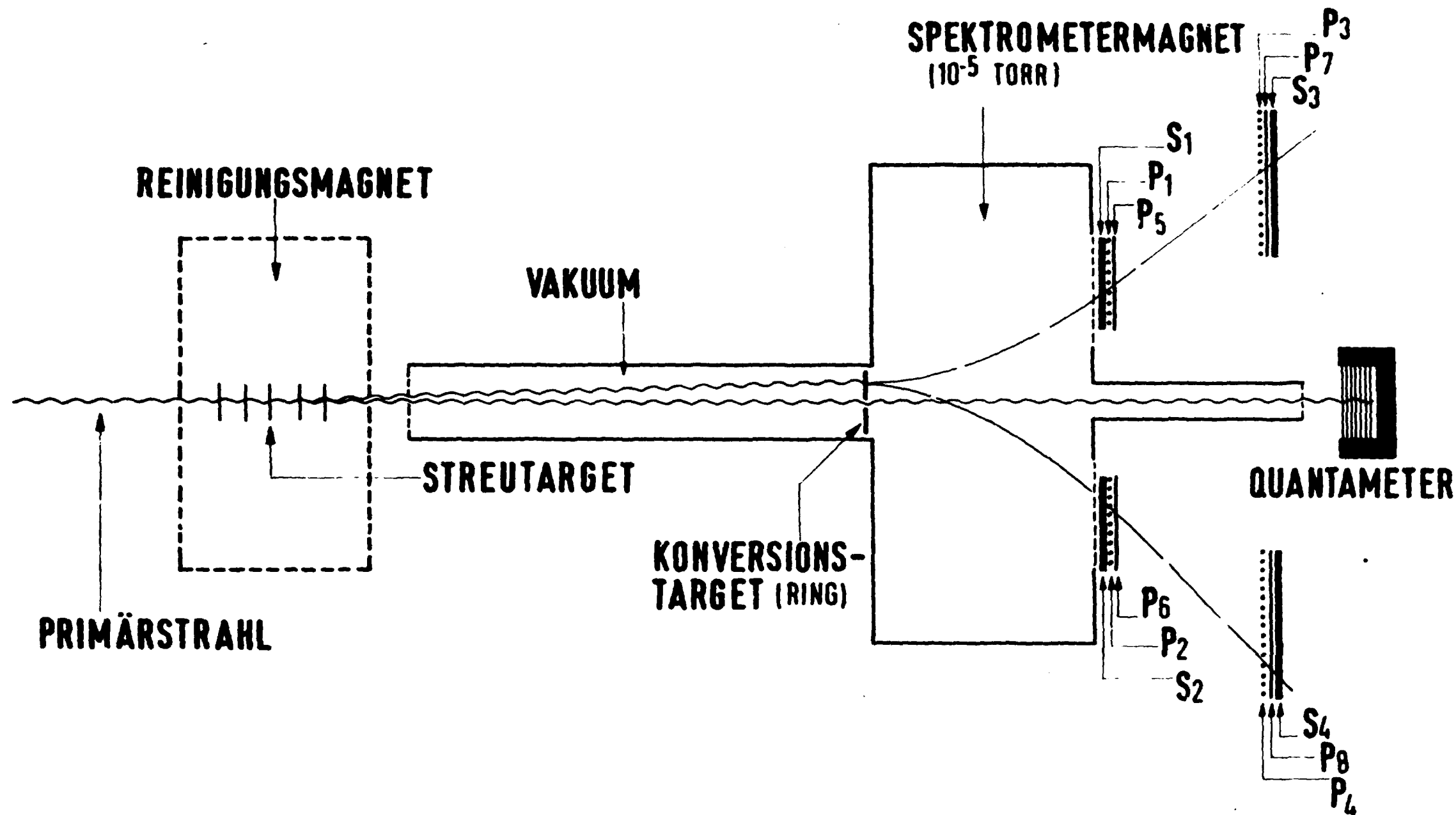S_2

S_4

P_8

P_4

PRIMÄRSTRAHL
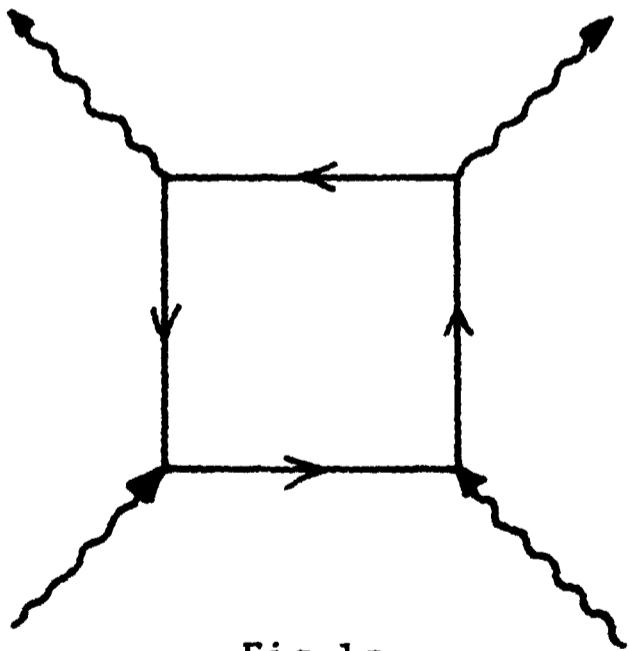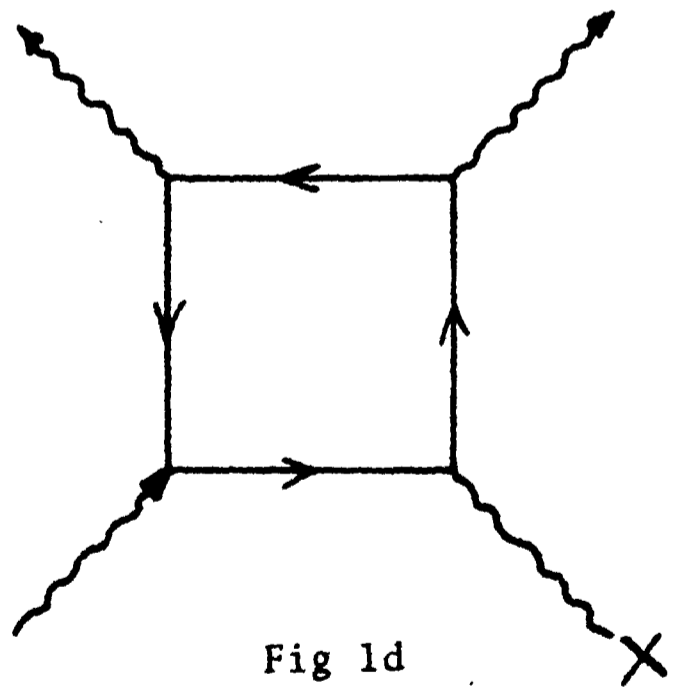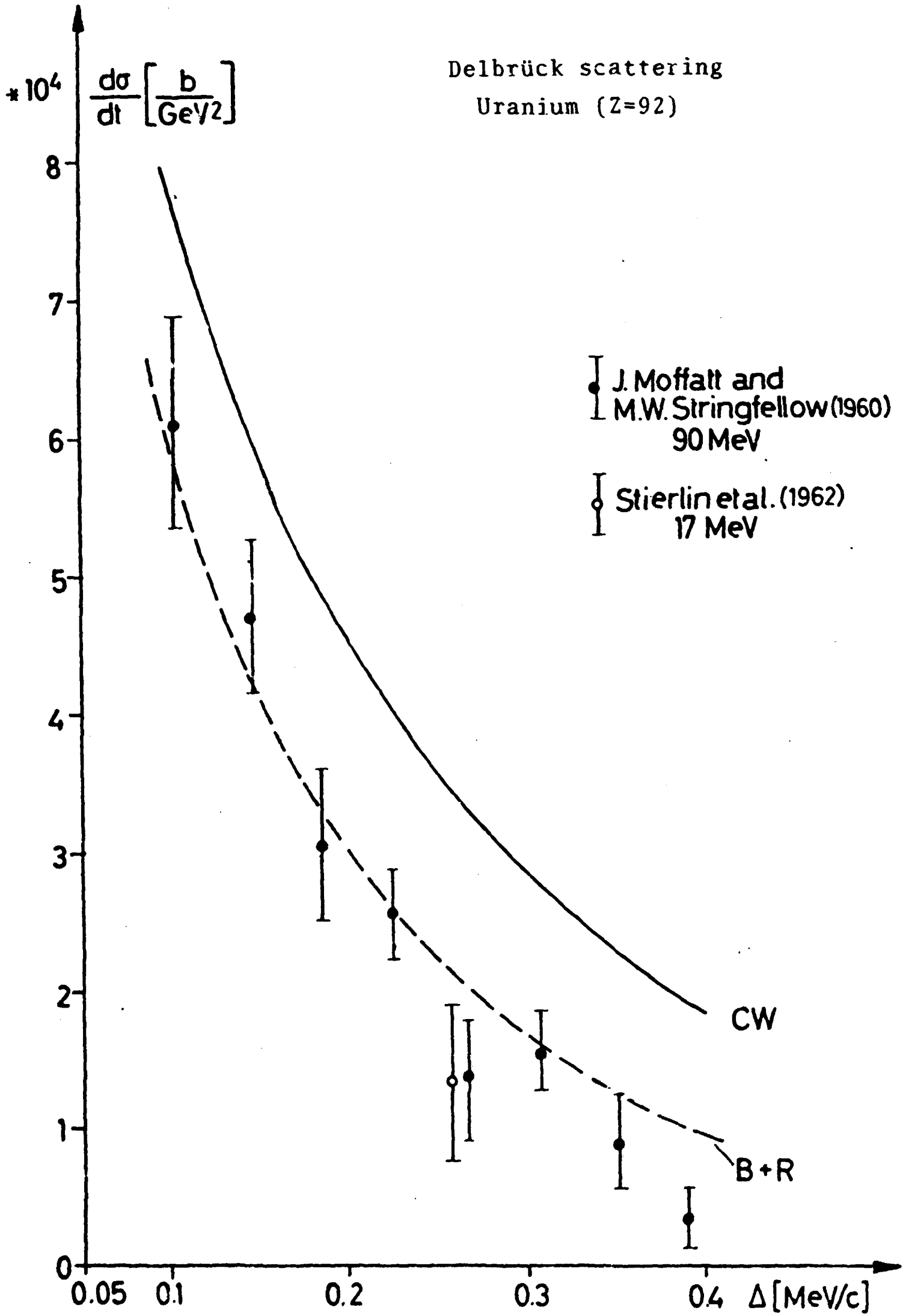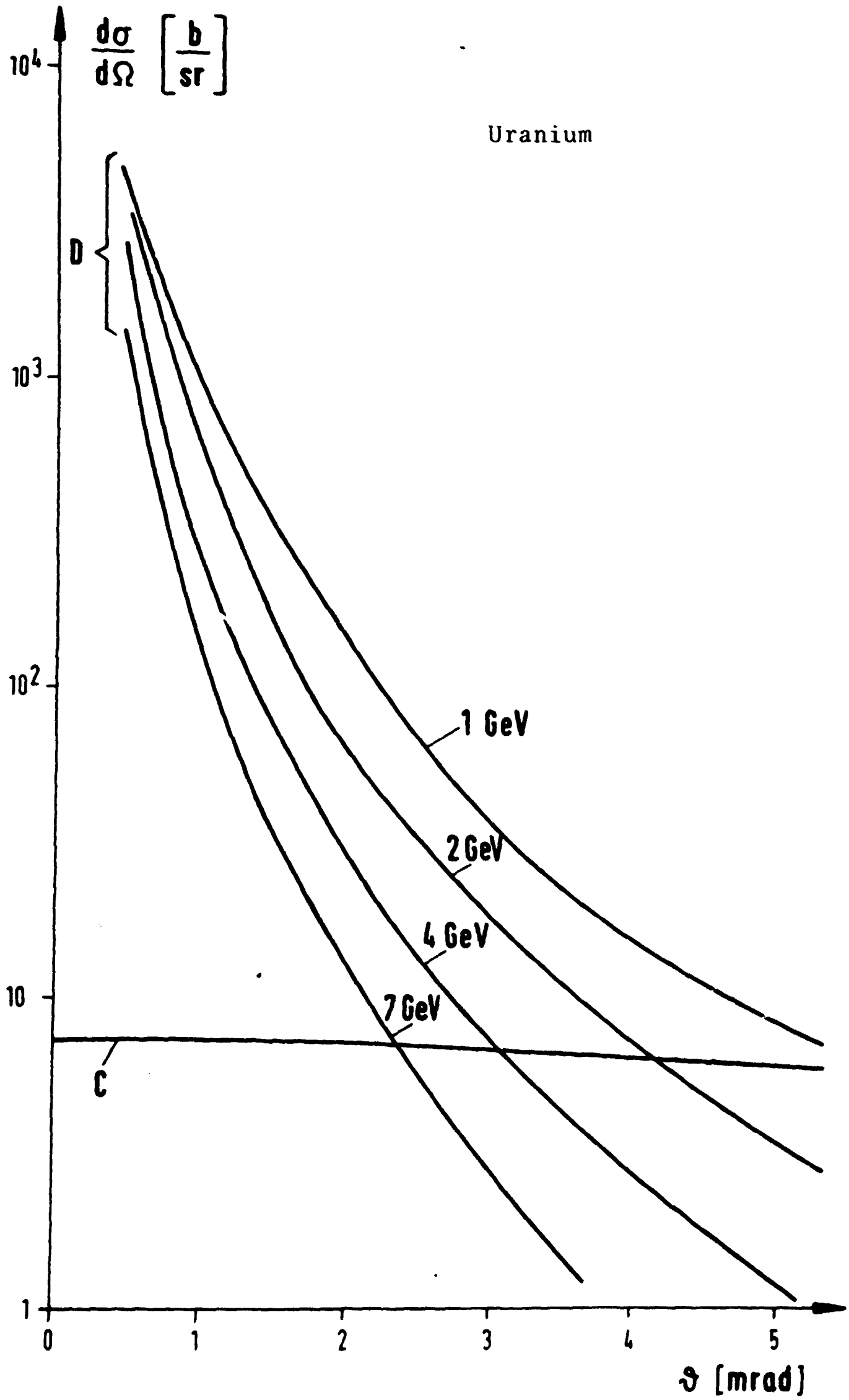
PRINZIP DER APPARATUR
(NICHT MASSTABSGETREU)

$S_1 - S_4$ **SZINTILLATIONSZÄHLER**
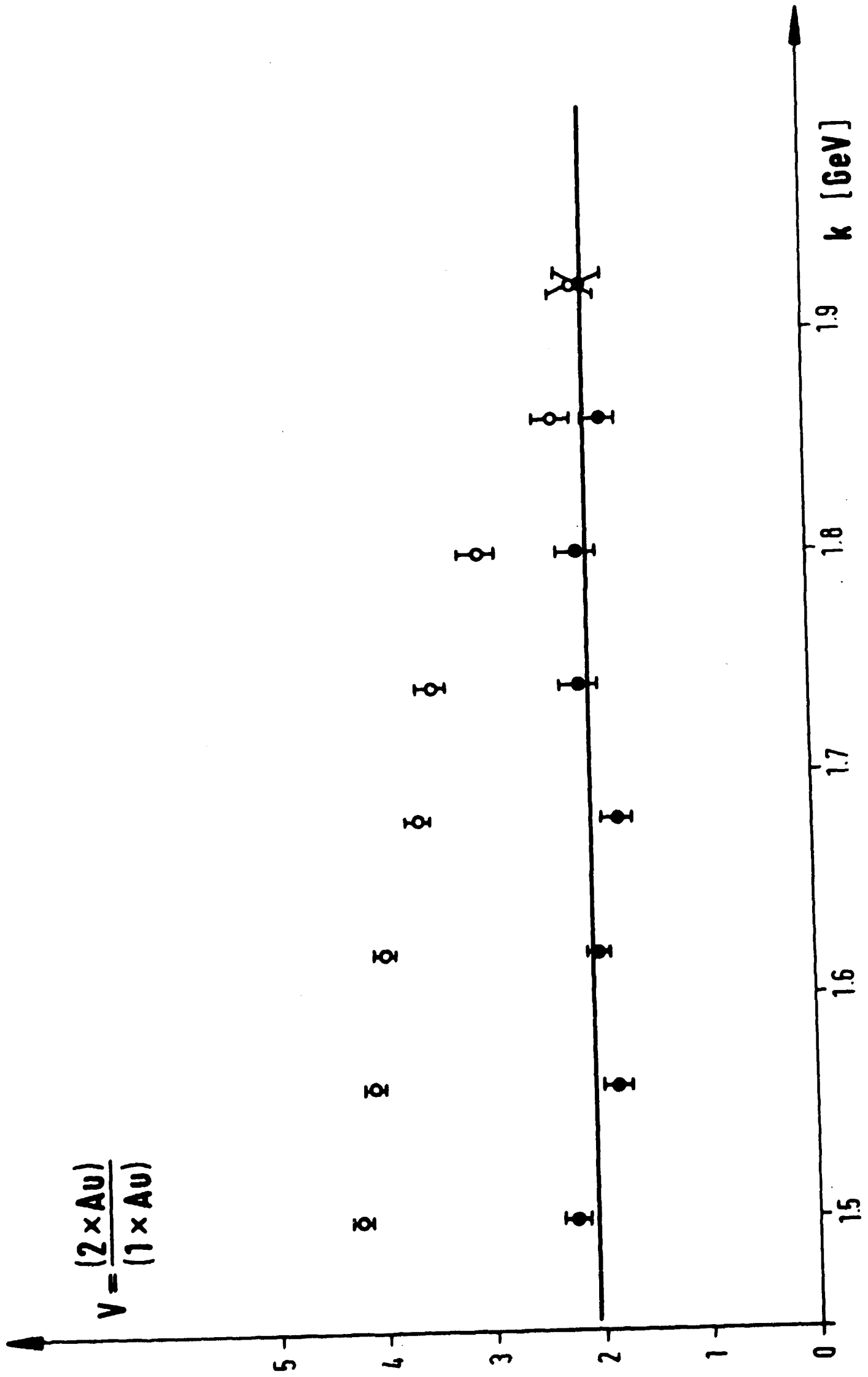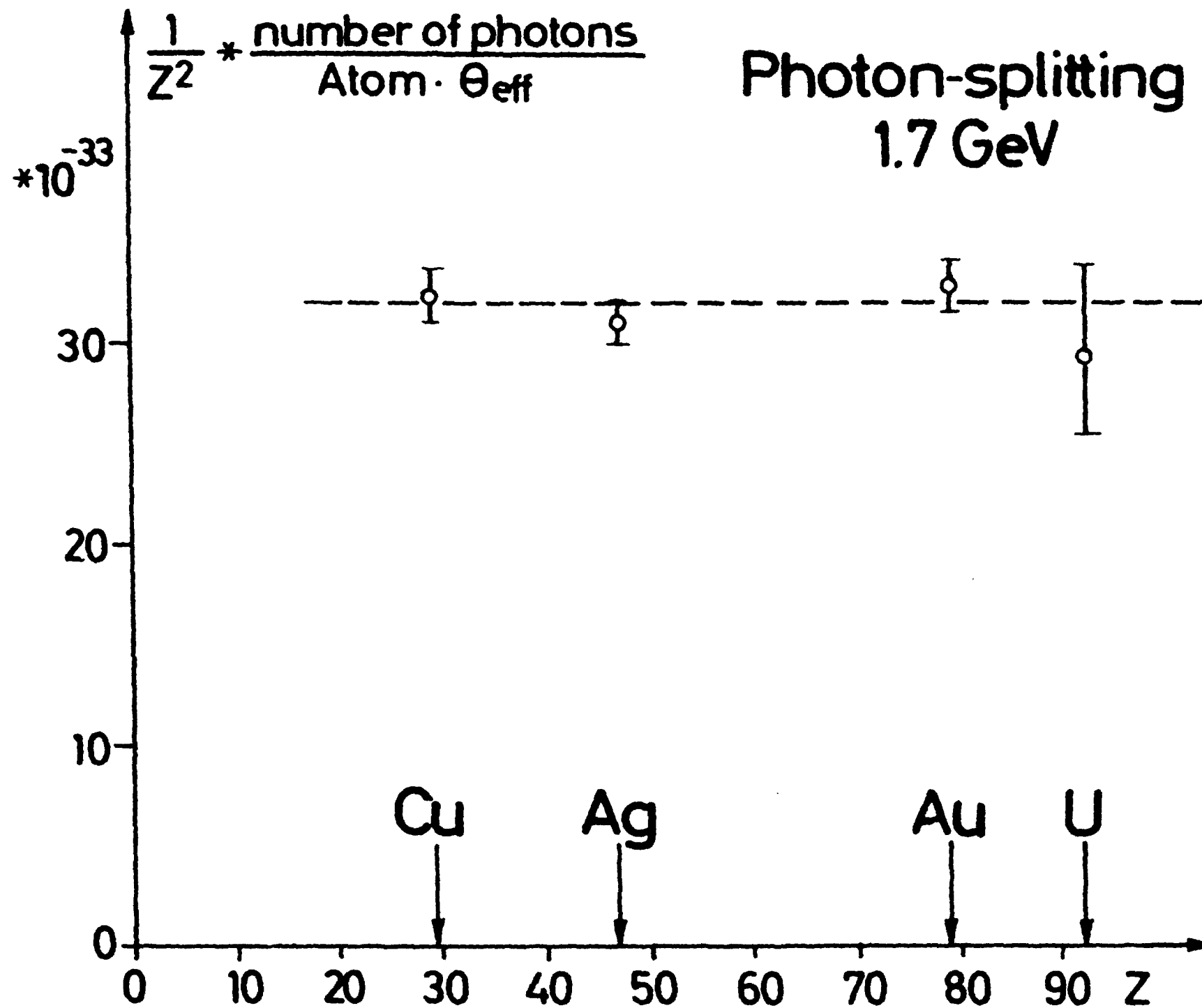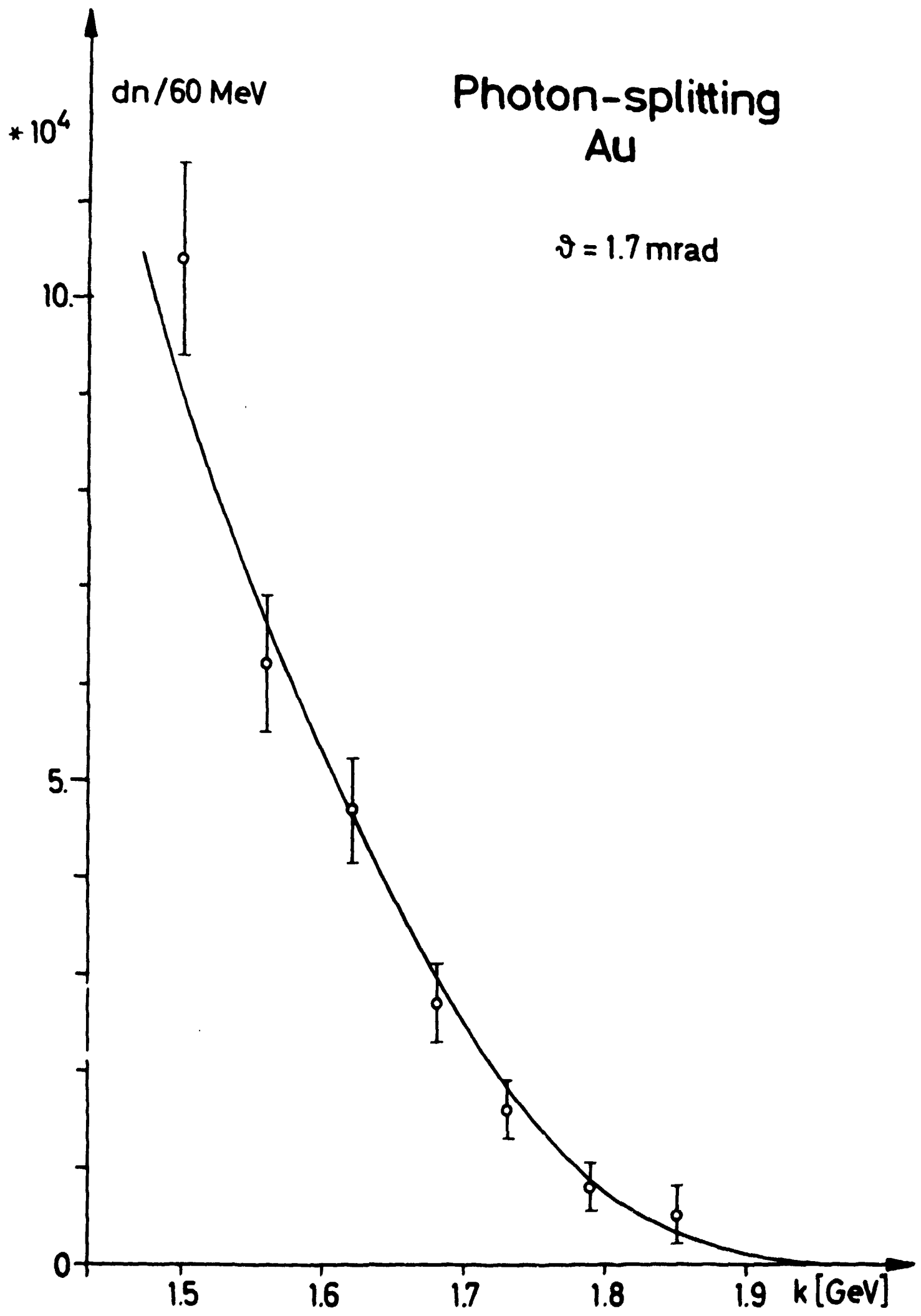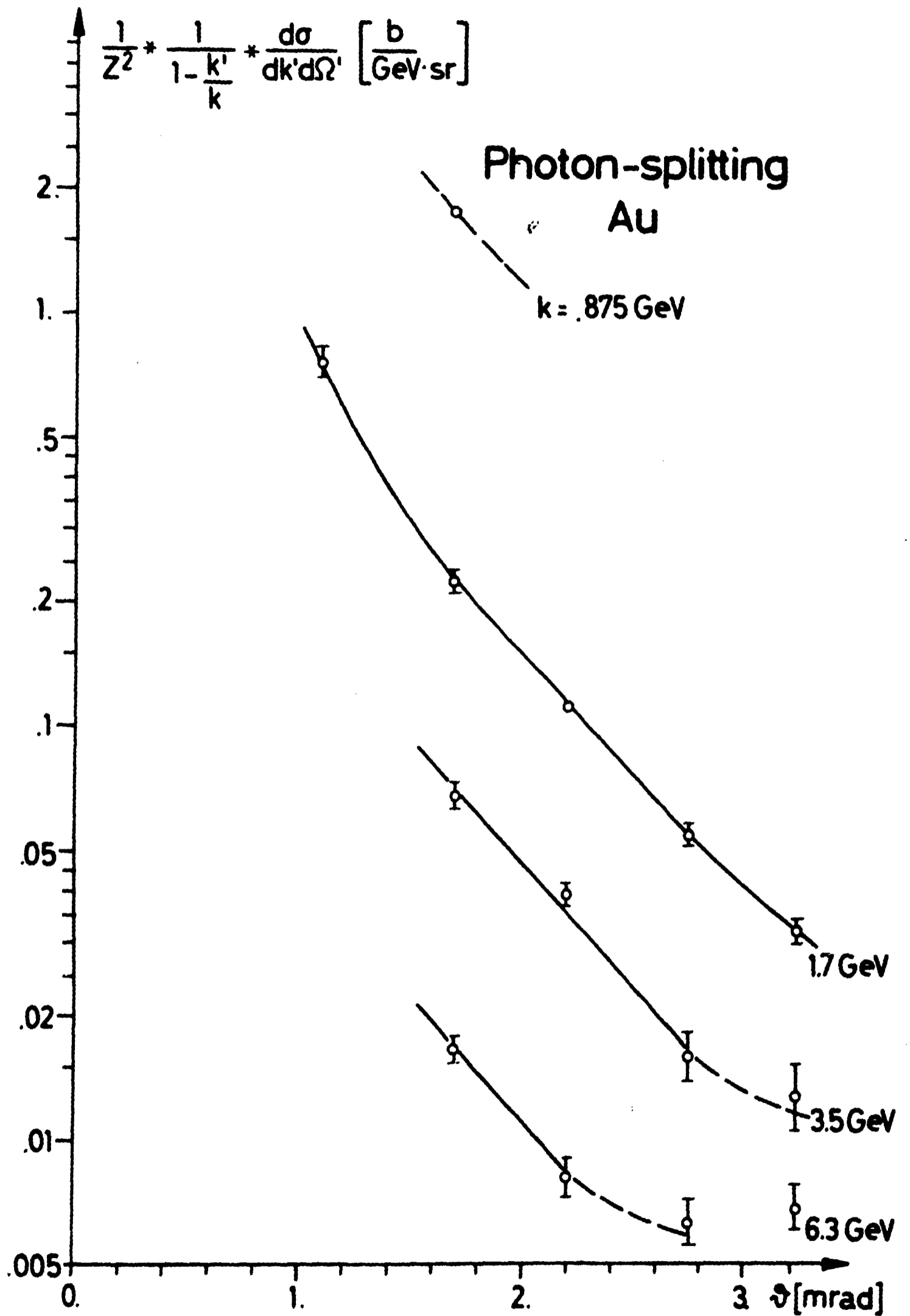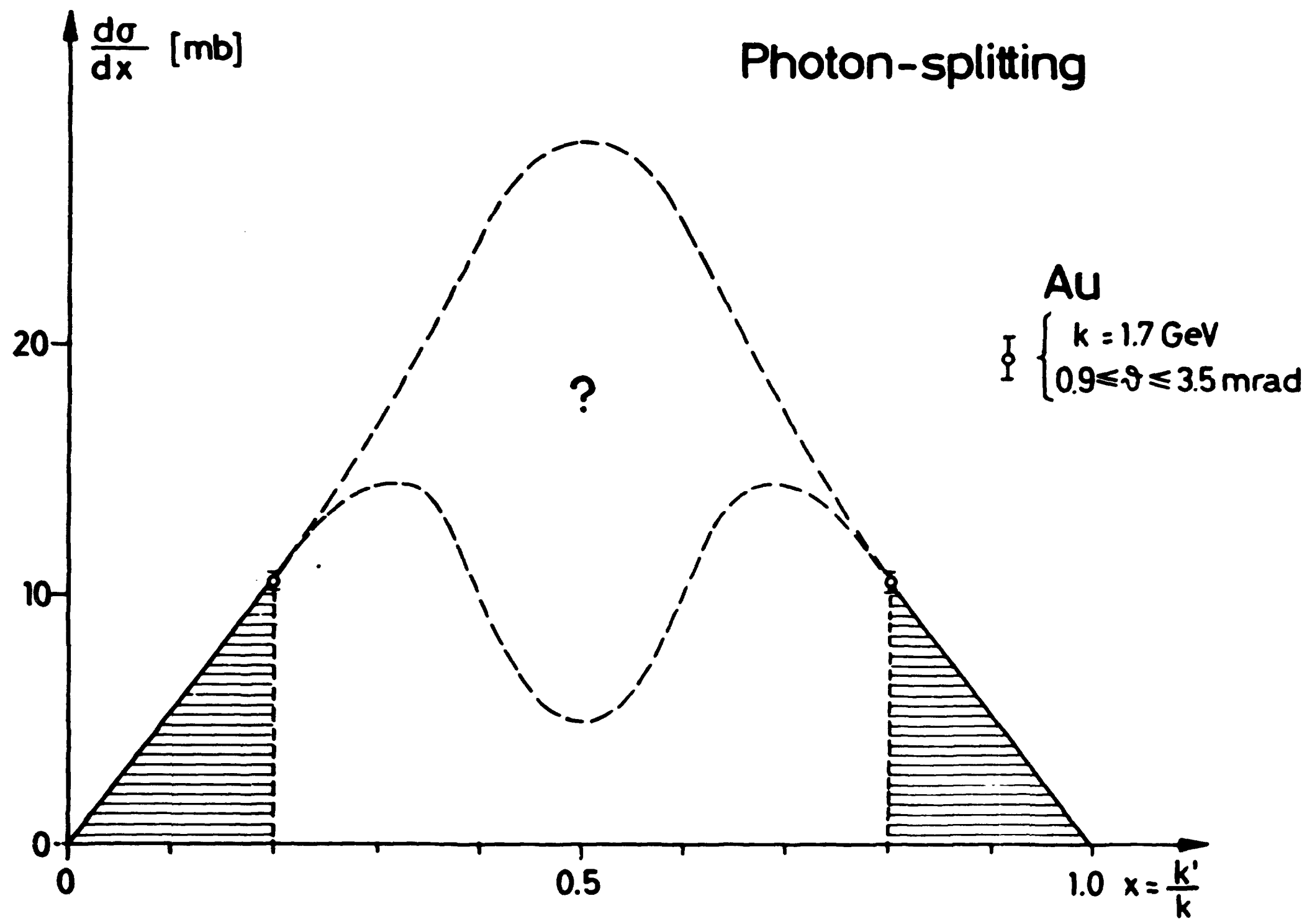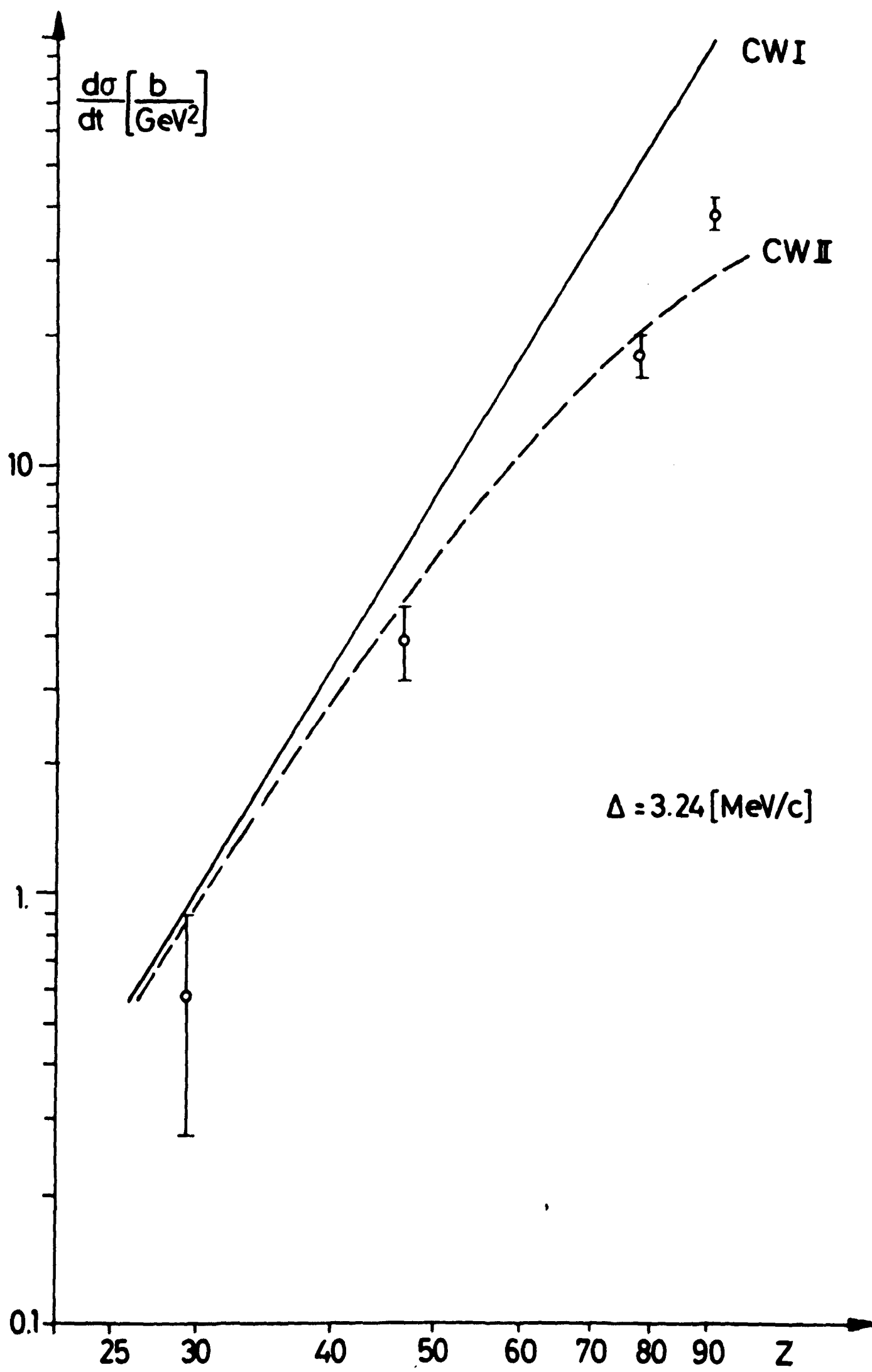
$P_1 - P_8$ **PROPORTIONALKAMMERN**

Fig 4

Fig 5

Fig 6

Fig 7

$V = \frac{(2 \times Au)}{(1 \times Au)}$

k [GeV]
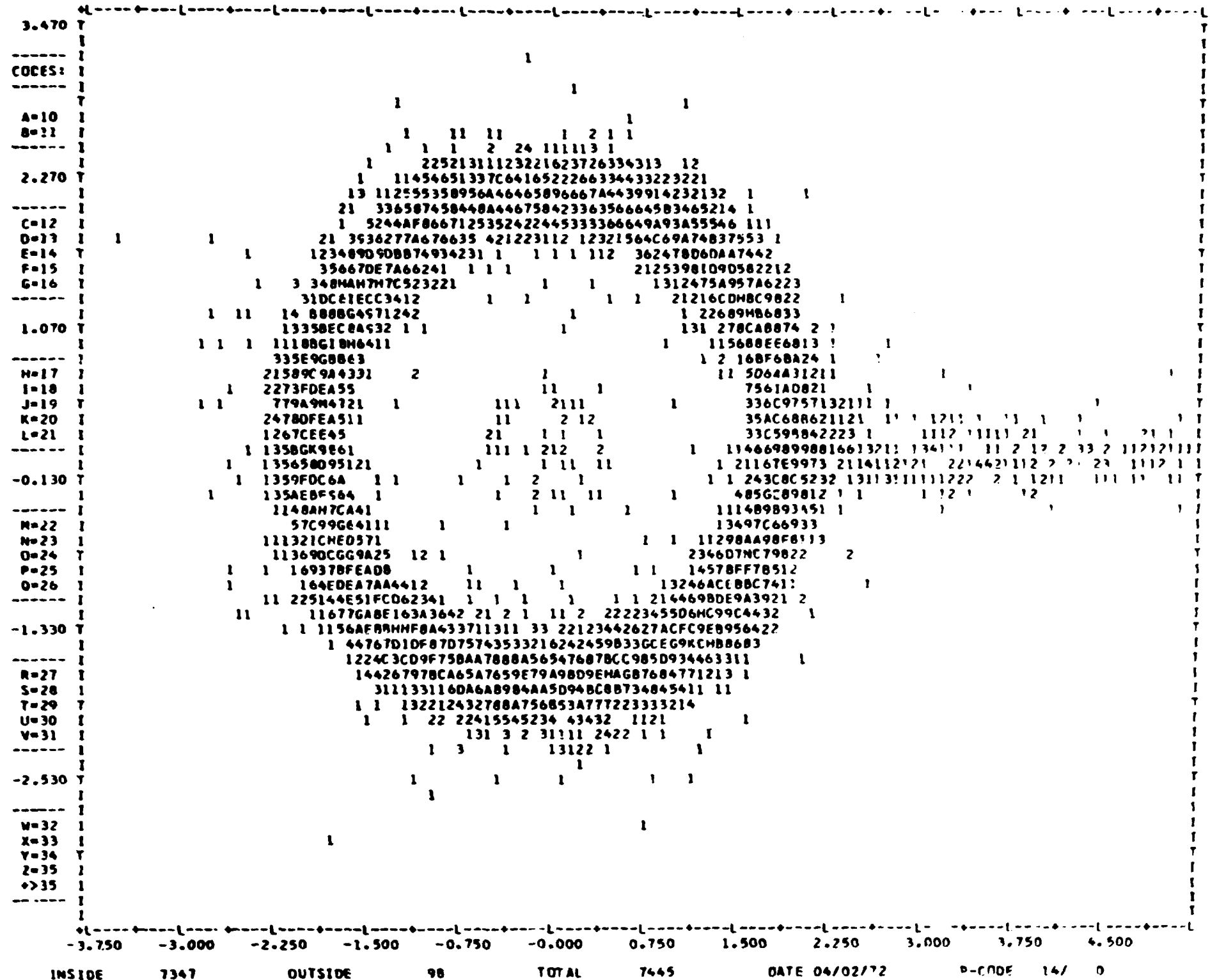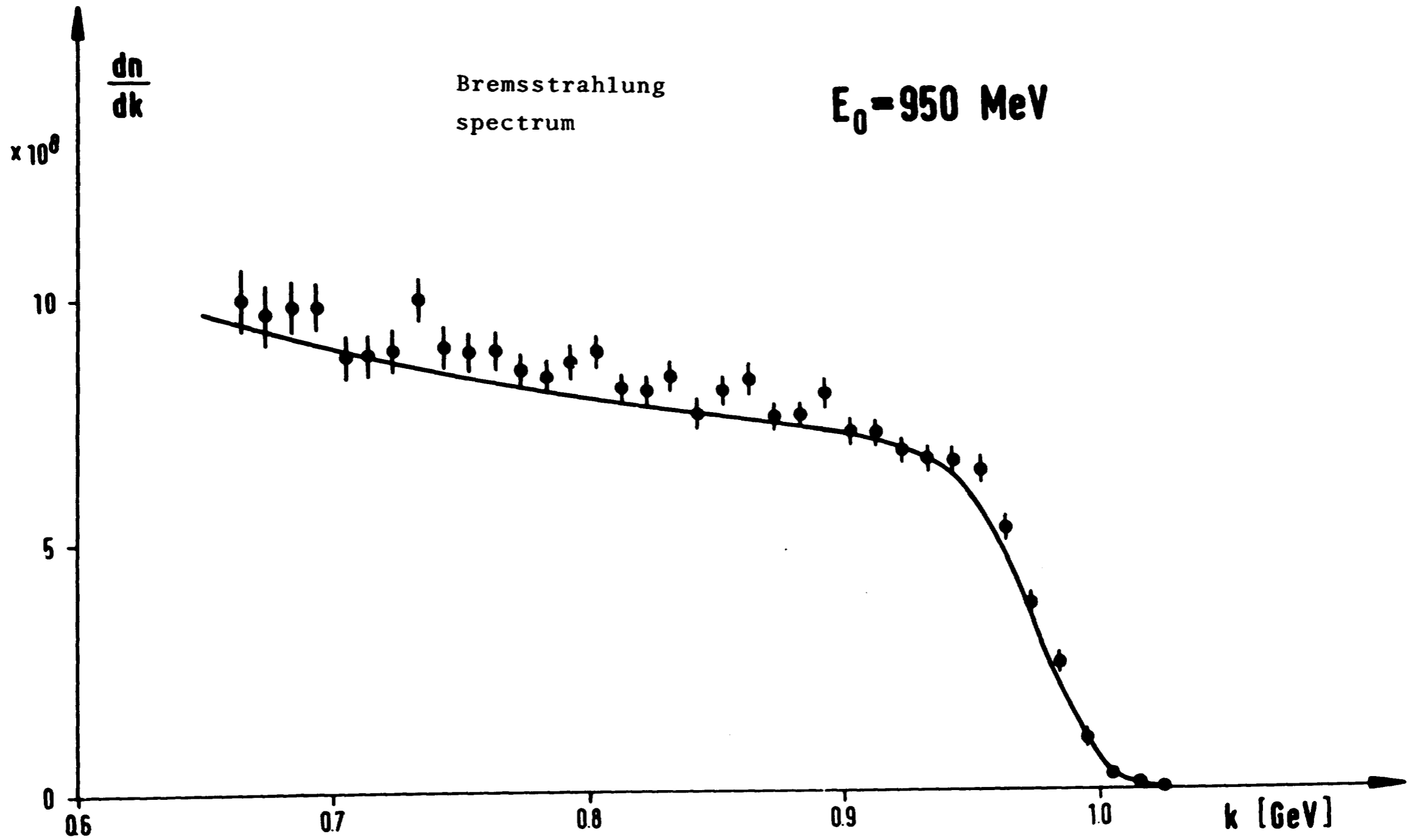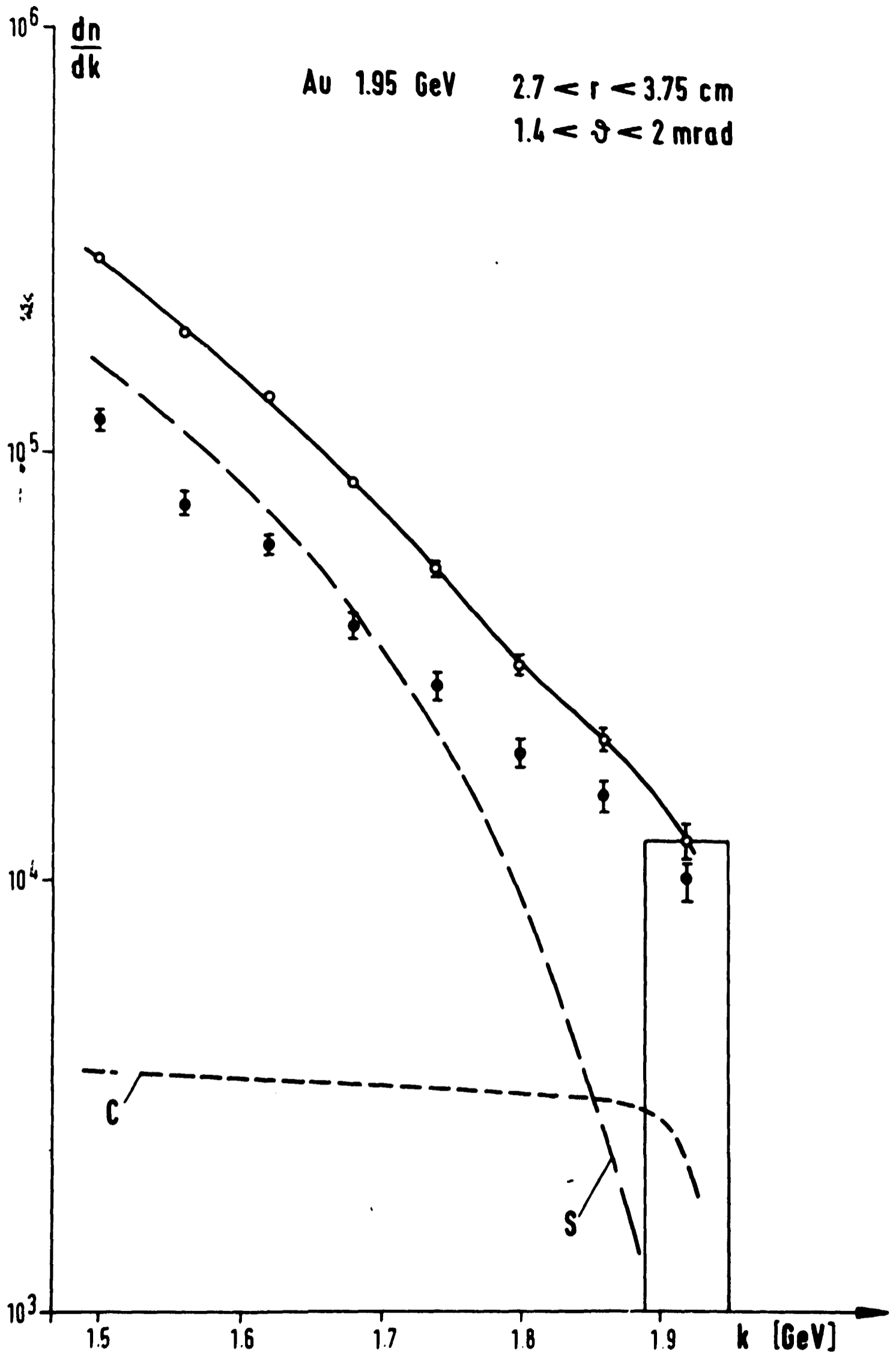
Fig 8
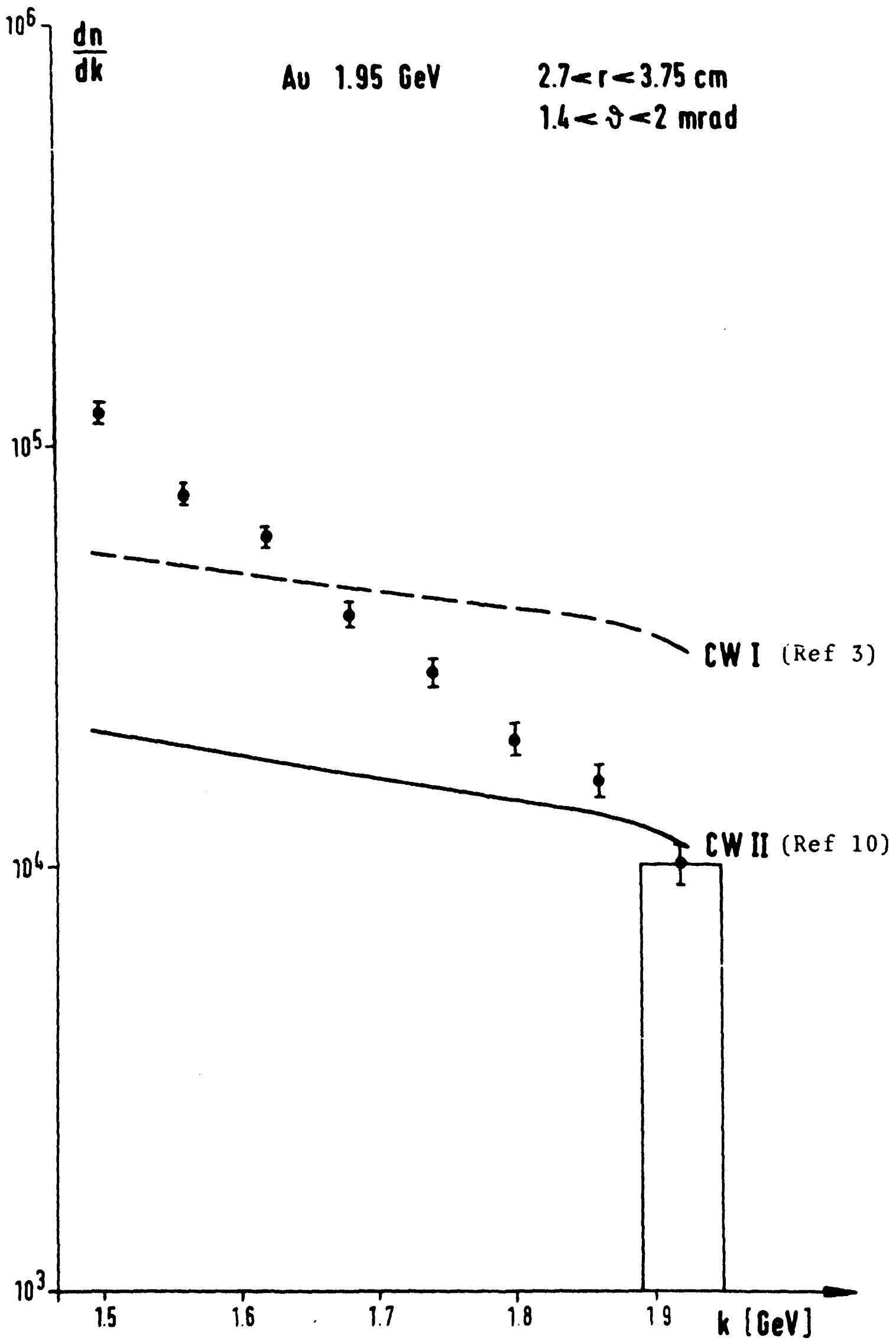
Fig 9

Fig 10

Fig 11

Fig 12

Fig 13

Fig 14

Fig 15

Delbrück scattering
Gold (Z=79)

Fig 16

Fig 17