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Institut für Experimentelle Kernphysik

The Use of AVF-Cyclotrons for Nuclear Physics

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The Use of AVF-Cyclotrons for Nuclear Physics +)

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+) Invited paper given at the European Conference on AVF - cyclotrons, Eindhoven, April 1965.

Since I have the privilege to give the first paper of this conference I should like to start with a few general remarks. Before I talk about the use of AVF-cyclotrons in nuclear physics I want to discuss for a few minutes the question why one should do low energy nuclear physics at all. The question is being asked and will be asked with even more emphasis not only by physicists but also by politicians. The reason is that more Van-de-Graaffs and more cyclotrons are built and the cost increase is considerable. I might mention that in the next years about 100 Mio DM will have to be spent in the federal republic of Germany for installing new low energy accelerators (the natural boundary between low and high energy accelerators is given by the meson's threshold at about 150 MeV). Because of the large sums involved the politicians will ask us what the whole activity is good for and certainly they suspect, that all we want, are new and shinier toys.

Science gets its justification from two sides :

1. It may lead to technical applications and thus eventually change our style of life. No doubt solid state physics has to be justified on this basis since most of the principal questions are solved in that field (with the exception of phenomena like super-conductivity and super-fluidity, of course).

2. Science has an ethymological value in itself giving us insight into the world surrounding us. The knowledge gained in this way may have no immediate practical consequence but it influences our thinking and acting deeply. Obviously high energy and elementary particle physics are justified by such arguments.

Now what about low energy nuclear physics ? The very important application of nuclear physics for the energy production in nuclear reactors is well known. However, I have the impression that most of the necessary nuclear physics data are known and the problem is now in the hands of engineers. Thus the possibility of applications is not a very convincing argument for the construction of new accelerators.

Even the other aspect, the gaining of new fundamental knowledge does not look too promising at a first glance. Going from the dimension of atoms (10^{-8}cm) to the dimension of nuclei (10^{-12}cm) one might have expected that a drastic change of the physical laws might occur in a similar way as atomic and quantum physics are fundamentally different from classical physics. However, nothing of that sort has been detected thus far. It seems that one has to go one step further, to elementary particles, in order to find qualitatively new phenomena. Of course the detection of parity violation is an exception but this is a problem connected to the so-called weak interactions which I shall not discuss here today.

After this somewhat pessimistic view let me take now a positive attitude. The central problem of nuclear physics is the investigation of the strong interactions. These forces are one of the four interactions known in nature (gravitation, electromagnetic force, weak interaction leading to ß decay, strong interactions) and to establish their features is one of the fundamental tasks of physics. What we would like to have is a theory for nuclear forces corresponding to Maxwell's equation in electricity or to Einstein's theory of gravitation. It seems that we are still far away from this goal and hence much work has yet to be done in low and high energy nuclear physics.

Since we are here at a conference for particle accelerators let me now turn to the problems that can be attacked by investigating nuclear reactions. One of the tasks is to determine the interaction potential between two nucleons. This can be achieved in the most direct way by p-p and n-p scattering. Since the potential does not only depend on the distance between the two particles but on their relative spin orientation such experiments must be performed with polarized particles and / or polarized targets. These investigations are difficult and require high beam intensities and the AVF-cyclotrons will certainly be very useful.

Besides the spin dependence their may exist also a charge dependence of nuclear forces. This implies that the forces between p-p, n-p and n-n are different even if the Coulomb effects are corrected for. Recent experiments indicate that indeed a small charge dependence exists which may be related to the mass difference of charged and uncharged pions. Precise experiments are necessary to answer this question definitely. The same is true for a test whether the nuclear forces are strictly invariant against space reflections, charge conjugation and time reversal. Small violations might exist.

A very important question that cannot be answered simply by nucleon-nucleon scattering is the existence of many body forces. It could well be that the forces between two nucleons are changed by the presence of other nucleons because of meson exchange effects. Very little is known about this type of force.

Even if all the features of the nuclear forces would be known we are still confronted with the problem of <u>nuclear structure.</u> I want to remind you that the investigation of the atomic shell was a difficult but rewarding task although the forces that tie the electrons to the nucleus had been known very well. You know that some ingenious models have been invented (the shell model, collective model, optical model etc.) in order to describe the behaviour of nuclei. One difficulty with those models is that thus far it turned out to be very difficult to find a unified model that would combine the models developed for particular purposes. Besides this also not much success has been gained as yet with respect to correlating the models to fundamental principles, say to the properties of nuclear matter. Because of these difficulties some nuclear physicists claim that nuclear spectroscopy is of no use at all whereas others think that it is of paramount importance. As always the truth lies somewhere inbetween. Of course an unsystematic investigation of arbitrary nuclei does not promote our knowledge appreciably. But a well directed search may reveal very interesting general features of the nuclear behaviour. Let me mention only a few examples.

Originally it was thought that the concept of isotopic spin would be applicable only to light nuclei where Coulomb effects are small. Surprisingly Anderson, Wong and McClure [1] (Livermore) inferred from an investigation of (pn) reactions that in heavy nuclei there are so-called isobaric analogue states with definite isospin quantum numbers. These experiments have recently been extended to nuclei as heavy as Ag and U at Harwell with 90 MeV protons. The explanation of these analogue states is based on the fact that in heavy nuclei $N \gg Z$ and hence the neutron shells are filled to a much higher level than the proton shells. This implies that the conversion of a proton into a neutron requires much energy and is unfavoured. It would be interesting to study medium heavy nuclei more in detail where the Coulomb effect is large enough to destroy the isospin purity but the neutron access is still small.

Another problem that is finding much attention is the existence of particle clusters in nuclei. In most cluster theories the clusters must not be visualized with a definite position in space since the Pauli principle forbids such a localisation inside the nucleus. The situation is different, however, for the nuclear surface. There the density of nuclear matter is reduced and not all states are occupied. Hence real clusters can be formed. Some experimental results seem to indicate that indeed α clusters exist in the surface of heavy nuclei. The probability of their formation and the momentum distribution of the clusters for example can be investigated by knock-out reactions like $(\alpha,2\alpha)$, $(p,p\alpha)$ or pick-up reactions e.g. (d, Li^6). In all cases energies well above 20 MeV are required and therefore AVF-cyclotrons are very useful tools for such investigations.

Also with respect to nuclear excitation interesting features have been detected. Surprisingly it was found that the reaction cross sections show large fluctuations even at high excitation energies whereas previously it had been expected that the levels would overlap resulting in a smooth variation of the cross section. An investigation of these fluctuations requires a good energy resolution, of course.

I should like to turn now to a few specific examples that will give me also the possibility to discuss some experimental aspects of the use of AVF-cyclotrons.

<u>Elastic and inelasic α-scattering.</u> As is wellknown elasic α-scattering produces a diffraction pattern from which the nuclear radii and other nuclear properties can be inferred. The successful operation of the Berkeley 88" cyclotron made it possible to study the inelastic scattering in much more detail than it was possible before. With an energy resolution of 75 keV at an α-energy of 65 MeV it became possible to resolve the scattering from many individual levels. Fig. 1 taken from a paper

by Harwey et al. [2] shows the scattering of α-particles from O^{16} as an example. One sees clearly the diffraction pattern of the elastic scattering (full line). The other curves correspond to inelastic scattering from levels with negative parity. According to Blair's phase rule the maxima and minima should coincide with those for the elastic scattering as is indeed the case. An interesting exception is the upper curve. Here a phase jump occurs at an angle of about 40° indicating that two reaction mechanisms are involved, one predominant at small, the other at large angles.

Reactions : From the many interesting investigations on nuclear reactions I can again pick out only one. As an example I want to show you results for the reaction $C^{12}(\alpha,d)N^{14}$ again obtained at Berkeley by Harwey at al. [3]. Fig. 2 shows the deuteron spectrum for an α-energy of 53 MeV. As can be seen sharp peaks appear indicating well separated levels even at excitation energies as high as 18 MeV.

For the majority of the scattering and reaction experiments a very good energy resolution is required in order to resolve individual levels. Since this topic will be discussed in more detail in the next talk I shall restrict myself to these few remarks.

Coincidence experiments : In many reactions two particles appear in the final state and in order to identify the reaction and to determine the kinematics one wants to analyse the two particles in coincidence. Examples for such reactions are $(\alpha,2\alpha)$ (knock-out), p(dn)2p, d(d2n)2p (final state interaction of 2 protons), (d,np) (break up) and other few nucleon reactions.

Since the number of random coincidences is determined by the instantaneous and not by the average current a duty cycle $D = \bar{I}/i_{Peak}$ as close to one as possible is of vital importance. In fact the useful maximum current is limited very often by the random coincidences. In this respect Van-de-Graaffs are of course superior to any other accelerators. The AVF-cyclotrons have at least the great advantage that their macroscopic duty cycle is one, whereas linear accelerators (and also conventional synchro-cyclotrons) are pulsed machines with typically $D \approx 5\%$ and coincidence experiments are hardly possible. However, the cyclotron beam has a rf fine structure which leads to a microscopic duty cycle. This is mainly determined by the phase acceptance of the accelerator. In this respect AVF-cyclotrons are very favourable at least in principle since their phase acceptance can be as high as 180° and an overall duty cycle close to 50% could be obtained. However, machine designers usually proceeded just in the opposite way up to now. They make the phase bunching small in order to achieve a good separation of the orbits at the outer radius and a good extraction rate. Therefore most cyclotrons have a micro duty cycle of a few percent. I think much more effort should be put into the improvement of the duty cycle since only then the cyclotron will be competitive with Van-de-Graaff accelerators. To achieve this goal several measures can be taken. To reduce the phase bunching at injection one can narrow the gap between the dee or use a puller to increase the initial energy gain. Also dc injections of ions can be used. If the condition of isochronism is precisely maintained there will be no phase selection during acceleration. Finally the extraction system can decrease the duty cycle since particles with some phase have a better chance than others to clear the septum. Thus the duty-factor of the Berkeley cyclotron is 23 % for the internal and 8 % for the external beam. It has also been suggested to increase the duty cycle by an extraction mechanism using methods related to the stochastic extraction or using negative ions. Then the duty factor could even be larger than 50 %.

I want also to remind you of the wellknown fact that instabilities of the cyclotron parameters or of the ion source reduce the effective duty cycle. Fig. 3 shows an example. If the ion source of the Karlsruhe cyclotron is operated at a beam current of about 0.25 μA (instead of the design value of about 100 μA) only every third rf pulse has the full intensity. I want to emphasize again that any progress in improving the duty factor would increase the usefullness of cyclotrons considerably.

Discussing the importance of the duty cycle one has to distinguish two extreme cases. The coincidence resolution 2τ may either be large compared to the accelerator pulse length T or small. For the two cases the number of accidental coincidences is given by

$$N_a = N_1 N_2 \, 2\tau/nT = N_1 N_2 \, 2\tau/D \qquad \text{for} \quad 2\tau \ll T$$
$$N_a = N_1 N_2/n \qquad \text{for} \quad 2\tau > T$$

where N_1, N_2 are single counting rates and n is the number of accelerator pulses per second.
In the case $2\tau > T$ the pulse length T does not affect the coincidence rate and the duty cycle is of no importance.

I should like to discuss now another very important application of AVF-cyclotrons, i.e. neutron time of flight measurements. Since neutrons can be produced with targets in the internal beam very high n fluxes can be obtained. For time of flight measurements the rf structure of the beam can be exploited and here a good phase bunching is of advantage in contrast to what I said previously in connection with coincidence experiments . As I shall show later a pulse length of less than 1 nsec can be achieved without any special provisions. A difficulty however arised from the spacing of individual rf pulses. This is usually of the order of 100 nsec and is too short to avoid overlapping of neutrons originating from different rf pulses. There are two ways to overcome this difficulty. Both methods had been developed at the Karlsruhe cyclotron and I should like to show you the experimental arrangements and the results obtained until now.

In the first method the time between individual pulses is increased by suppressing a large number of pulses say 99 out of 100. This results of course in a considerable reduction of intensity. In order to compensate partly for this loss the following scheme has been invented by Beckurts, Cierjacks et al. . Fig. 4 shows a schematic diagram of the cyclotron with its threefold symmetry. Usually three spikes of protons are accelerated at the same time. However, as a first step two spikes are suppressed by a deflector near the center of the machine. Secondly the ion source is pulsed (5µsec) in such a way that 20-50 turns of the third spike are filled with protons. This bunch of protons is accelerated until it arrives at the largest radius. There it passes through a pair of deflector plates which are pulsed and deflect the beam vertically. After making one more orbit the whole bunch of protons hits at the same time the target which is positioned above the medium plane of the beam (as shown in the lower part of fig. 4). This is repeated every 20 to 50 µsec . In this way a short n pulse with high intensity is produced. The deflecting systems have been tested and a neutron flight path 65 m long has been installed. With a time resolution of about 1.5 nsec it is hoped that an energy resolution of 0.3 % at 50 MeV and 0.13 %.at 100 keV can be obtained. The neutron flux will be

0.5 x 10^5 n/cm^2sec at 65 m from the target. This set-up will be used to measure total cross sections and neutron induced reactions.

The second method has been developed by Brückmann and Haase in our institute in order to determine n spectra from nuclear reactions. The precise energy of the neutrons is again determined by a time of flight measurement. However, all cyclotron pulses are used in order to take advantage of the full intensity. Since in this case one does not know by which pulse the neutrons have been produced there is an ambiguity of multiples of 30 nsec (Δt for consecutive rf pulses) in the measured time of flight. In order to remove this ambiguity a rough energy measurement of the recoil protons produced in a plastic scintillator is performed by means of a counter telescope. The arrangement is shown in fig. 5. The external deuteron beam hits the target (for example beryllium). The neutrons traverse a flight path several meters long and hit a counter telescope consisting of a thin plastic scintillator in which recoil protons are produced. Their energy is determined by a pulse hight measurement in the second thick scintillator. The overall time resolution is about 1 nsec. This is demonstrated in fig.6 which shows the time of flight distribution of γ rays. The resolution of the detecting system is 0.7 nsec which implies that the pulse length of the cyclotron is of the same order of magnitude which corresponds to a phase spread of about 8^o. In order to determine the neutron energy uniquely we use a two dimensional analyser as shown in fig.7 . The time of flight is displayed along the y axis, the recoil proton energy along the x axis and the number of counts in the z direction. For a certain time of flight one finds several proton energies. If these are combined one obtains several clearly separated ridges which belong to different rf pulses. The first ridge corresponds to the directly measured time of flight. The second ridge implies that 30 nsec have to be added etc. Thus the neutron spectrum over the whole energy range can be obtained. With a flight path of only 5 m a resolution of about 2% at an energy of 50 MeV can be obtained. As an example the neutron spectrum produced by the reactions $Be^9(dn)B^{10}$ and $Be^9(d,np)Be^9$ are shown on fig.8 . The broad distribution originates from the break up of the d into n and p. In addition two lines corresponding to two different direct processes appear which might be associated to analogue states.

As I mentioned already AVF-cyclotrons are very useful instruments for work with polarized particles, too. I do not have time to discuss this field in detail and must restrict myself to two remarks. Polarized protons can be produced by scattering α-particles from hydrogen. This is the inverse reaction of the wellknown ($p\alpha$) scattering which is the usual method to analyse the proton polarization. In the inverse reaction polarized recoil protons are produced with polarizations close to 100% if the proper recoil angle is chosen. At Berkeley with an internal beam of 10 μA about $4x10^7$ p/sec could be produced (Conzett et al.[4]) which is somewhat less than the number obtained from linear accelerators with polarized sources ($2x10^8$ p/sec) but the degree of polarization of the protons is ≈ 80 % in the first case and only 35 % in the second and hence the two methods are comparable.
As an example I want to show in fig.9 the asymmetry obtained by scattering 40 MeV polarized protons from deuterons([4] Berkeley). The protons were polarized by the αp reaction. There is a considerable discrepancy between the experimental results and theoretical predictions based on various forms of the impulse approximation. For comparison let me show you in fig.10 the results obtained by Craig et al. [5] (Birmingham) with the polarized proton source of the Harwell linear accelerator. Here the polarized protons are scattered from carbon and silicon.

A quite complicated angular dependence appears and it is obvious that for such experiments a good angular resolution combined with high intensities is required. I am sure that many experiments with polarized particles will be performed using AVF-cyclotrons. Both methods to produce polarized particles, i.e. the α,p reaction and injecting polarized particles, will be utilized and we shall hear more about the second method in this conference.

In conclusion let me summarize the features a cyclotron should have in order to appeal to the nuclear physicists.

1. Good energy resolution also for energies above 20MeV. If possible the resolution should be better than 100 keV. Experiments possible only with Van-de-Graaffs could then be extended to higher energies.

2. High intensity.
   This presents no problem for AVF-cyclotrons except perhaps for extracted beams as the septum does not stand too high intensities.

3. Duty cycle.
   It should be possible to vary the duty cycle from 50% for coincidence experiments to small values in order to obtain pulses below 1 nsec for time of flight work.

4. Flexibility with respect to the possibility of accelerating different particles and to change the energy.

5. Large pol gap for internal targets, deflectors etc. Also low background is important especially for γ-work.

I am sure that considerable improvements can and will be achieved within the next years and AVF-cyclotrons will become to an ever increasing degree very valuable tools for solving the many interesting problems of which I could mention only a few. Nevertheless it must be admitted (and now I return to the beginning of my talk) that the more fundamental problems lie in the high energy region.

What is it then that attracts so many excellent scientists to work in this low energy field. I think a human aspect is involved. A great part of the attraction of cyclotrons comes from the fact that their dimensions are still comparable to the human size in contrast to the gigantic high energy accelerators. This implies that the style of work with cyclotrons is still not too different from the style of physics in the old days in which success or failure of an experiment depended on one or at most a few individuals. Many people on the other hand do not like the hectic and rather anonymous activity around high energy accelerators. An other implication is that the education of students and young scientists working with low energy accelerators is much more versatile and much less specialized then in some other branches of nuclear physics.

Therefore I think for both , the physical interest and because of psychological reasons, AVF-cyclotrons will find many friends in the future and I think we are only at the beginning of a promising development.

References

[1]	J.D.Anderson, C.Wong, and J.W.McClure	Phys.Rev. 129, 2718 (1963)
[2]	B.G.Harvey, E.J.-M.Rivet, H.Springer, J.R.Meriwether, W.B.Jones, J.H.Elliott, and P.Darriulat	Nucl.Phys. 52, 465 (1964)
[3]	R.H.Pehl, E.Rivet, J.Cerny, and B.G.Harvey	Phys.Rev. 137, B 114 (1965)
[4]	H.E.Conzett, H.S.Goldberg, E.Shield, R.J.Slobodrian, and S.Yamabe	Phys.Lett. 11, 68 (1964)
[5]	R.M.Craig, J.C.Dore, G.W. Greenlees, J.S.Lilley, J. Lowe, D.L.Watson, and P.C. Rowe	Congrès International de Physique Nucléaire Paris 1964, Vol. II , p. 856

Figures

Fig. 1 Angular distributions for inelastic scattering of 65 MeV helium ions from negative parity levels of O^{16} at 6.134, 7.118 and 8.876 MeV. The elastic angular distribution is shown for comparison.
Elastic ——— , 6.134 MeV — o — ,
7.118 MeV — • — , 8.876 MeV — △ — .

Fig. 2 Deuteron energy spectrum from the $C^{12}(\alpha,d)N^{14}$ reaction at 30^{o} (lab).

Fig. 3 rf structure of the Karlsruhe cyclotron beam for different conditions of the ion source.

Fig. 4 Scheme of beam suppression and deflection

Fig. 5 Neutron experiments, schematic

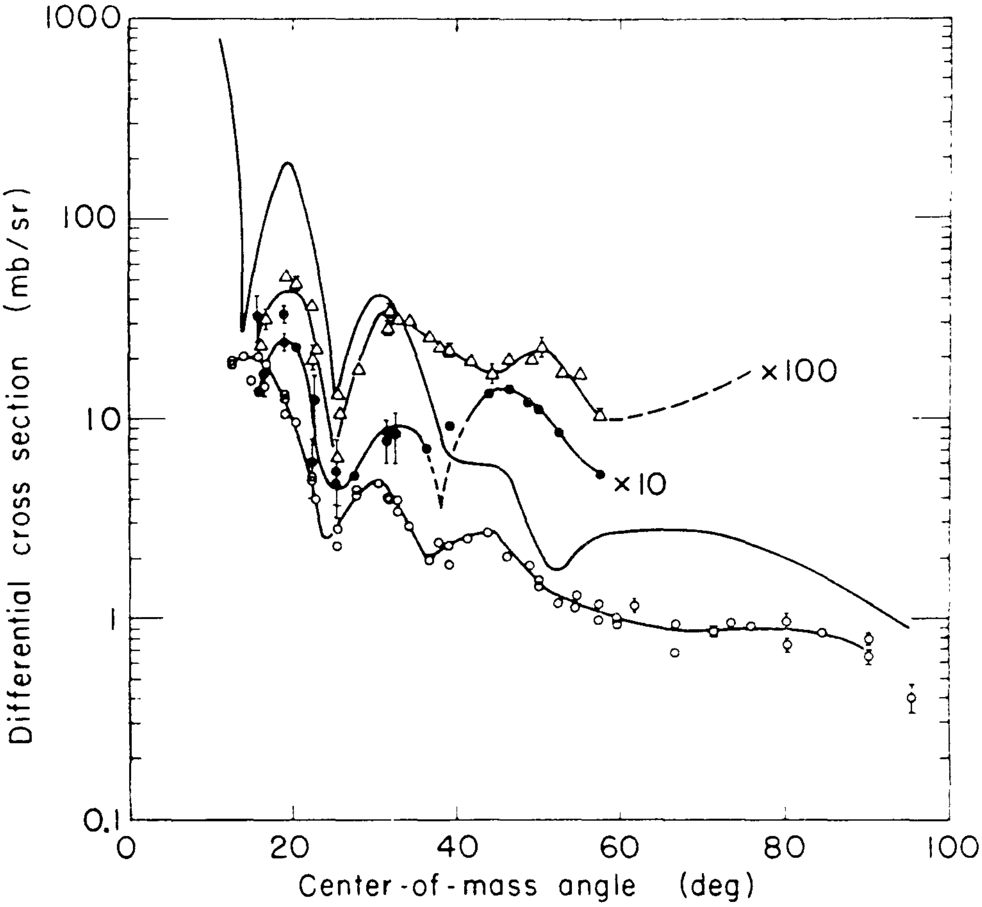
Fig. 6 Time of flight spectrum for γ and n; 52 MeV deuterons on a thick copper target with a flight path of 36 cm; shown are the number of events vs. time of flight on a linear scale; time of production of γ-rays and neutrons is 1.2 nsec to the left of the γ-peak. The electronic contributes 0.4 nsec to the observed resolution of 0.6 nsec.

Fig. 7 Isometric display (64 x 64 channels) of neutrons from 52 MeV deuterons on Be^{9}. Time scale 0.5 nsec/channel, energy scale 1 MeV/channel.

Fig. 8 Neutron spectrum from 52 MeV deuterons on Be^9. From fig. 7 the spectrum is obtained by summing over the ridge for each value of τ and given by the open circles. When the smoothed line through these circles is corrected for telescope efficiency and variable energy width of the channels the dotted neutron energy spectrum is obtained.

Fig. 9 Proton polarization, $P(\theta)$, in p-d elastic scattering at 40 MeV. The curves labeled CA, LA, and FA are results from impulse approximation calculations.

Fig. 10 Angular distributions of the polarization in the elastic and inelastic scattering of 30 and 50 MeV protons by C and Si.



1000
100
10
1
0.1
0
20
40
60
80
100
Differential cross section (mb/sr)
Center-of-mass angle (deg)
×100
×10

Fig.1

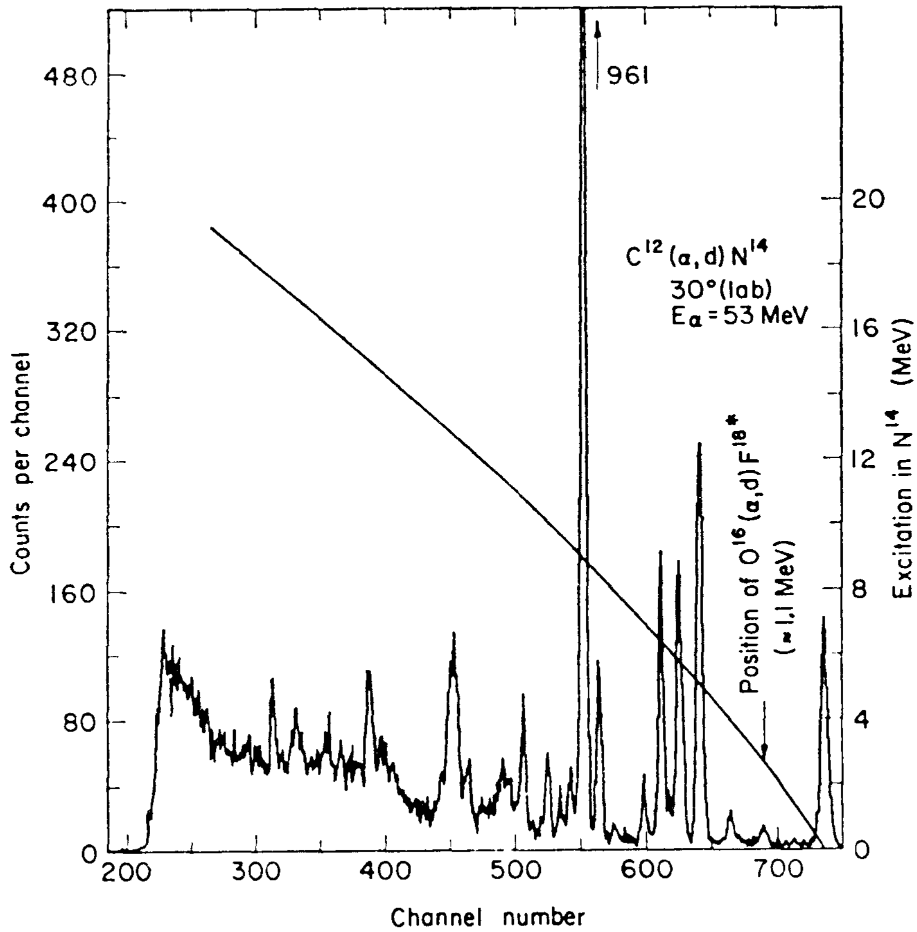

480
400
320
240
160
80
0
200
300
400
500
600
700
Channel number
Counts per channel
961
$C^{12}(\alpha,d)N^{14}$
30°(lab)
$E_\alpha = 53$ MeV
20
16
12
8
4
0
Excitation in N^{14} (MeV)
Position of $O^{16}(\alpha,d)F^{18*}$
($\approx$ 1.1 MeV)

Fig. 2

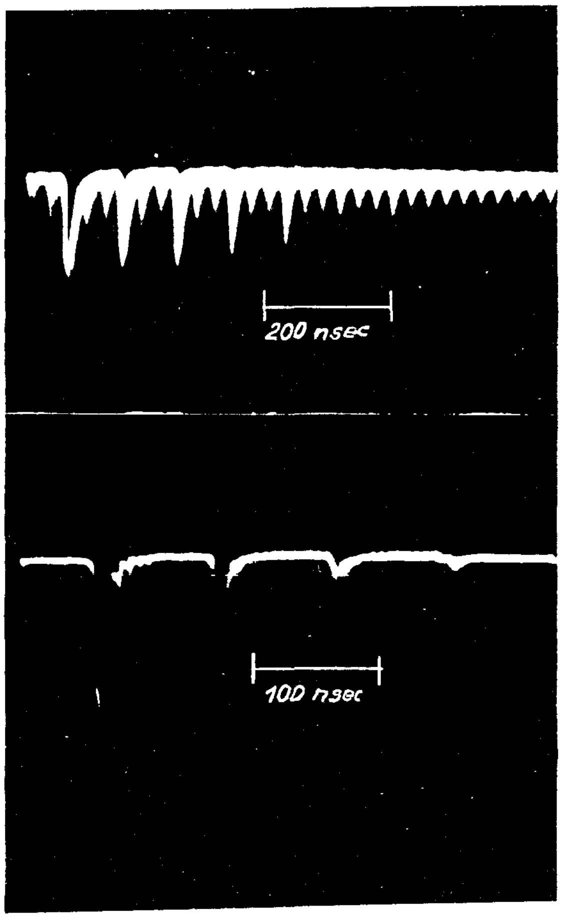
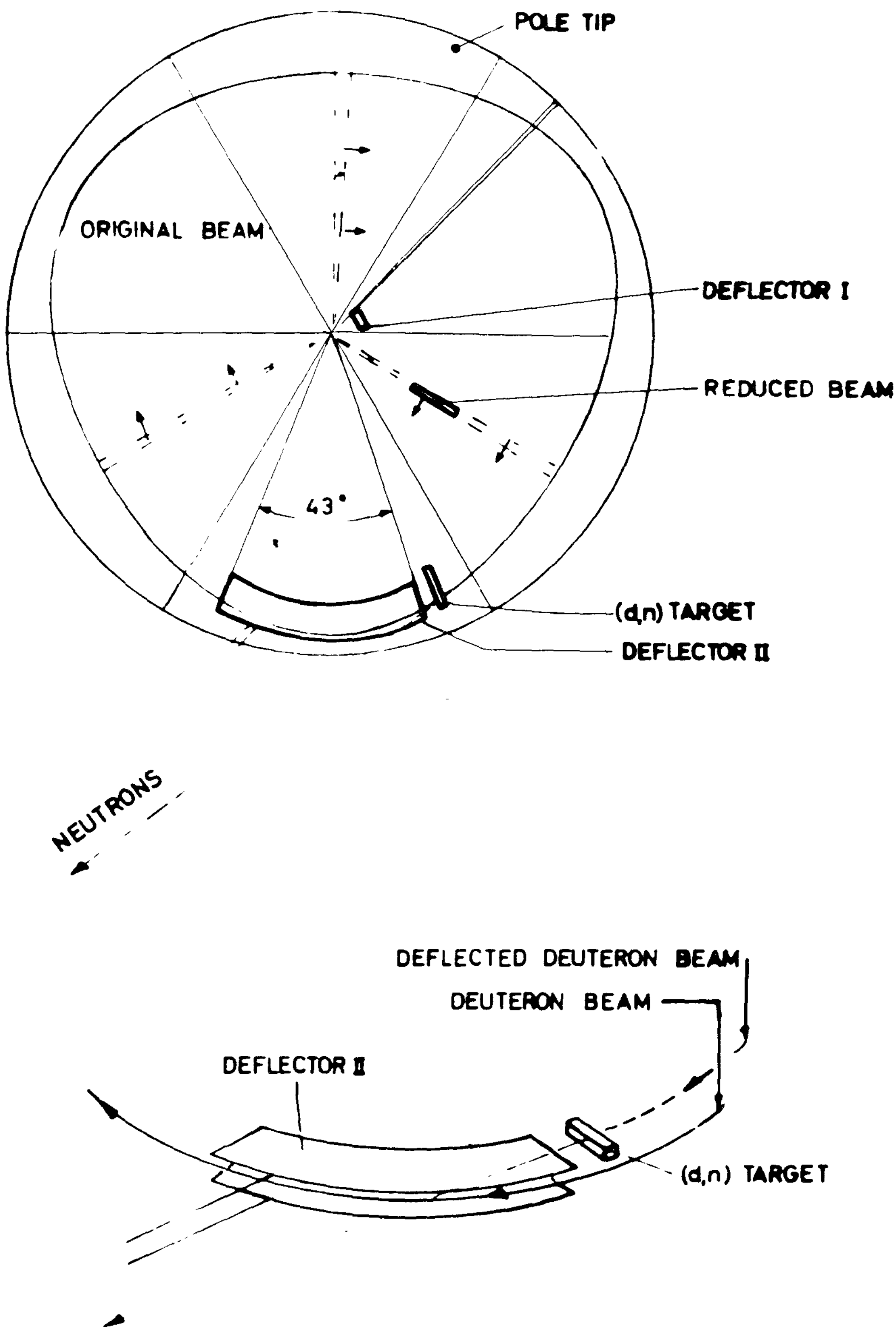


Fig. 3



Scheme of beam suppression and deflection

Fig.4

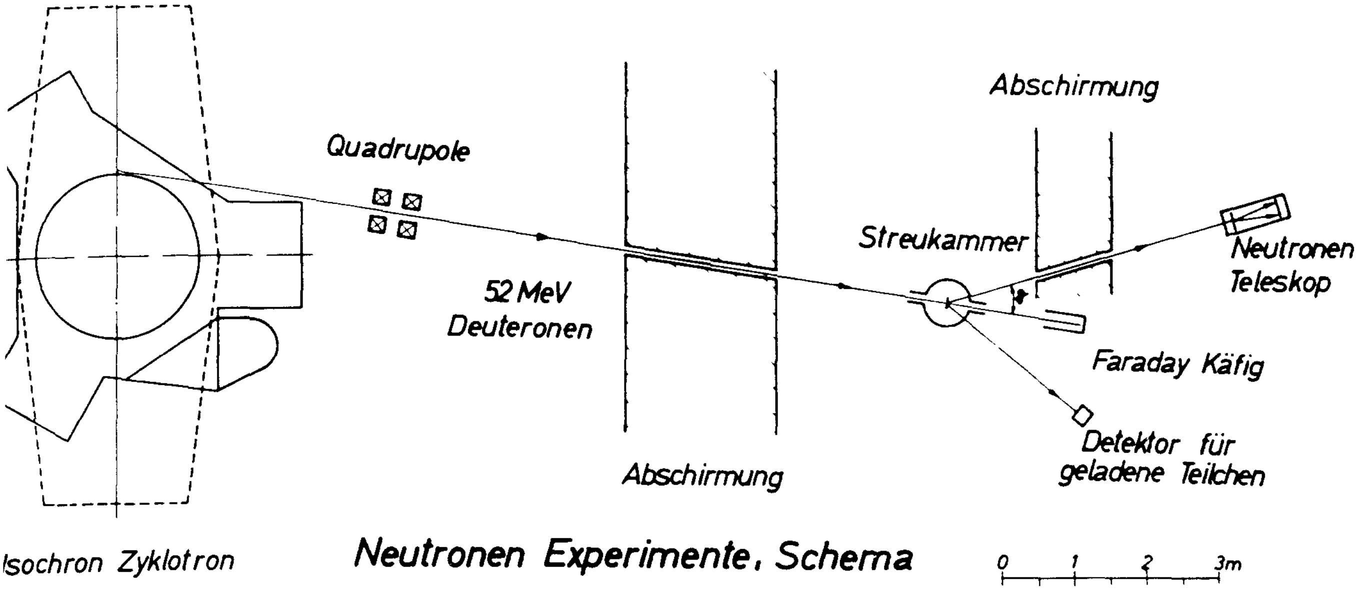

Quadrupole
Abschirmung
Streukammer
Neutronen
Teleskop
52 MeV
Deuteronen
Faraday Käfig
Detektor für
geladene Teilchen
Abschirmung
Isochron Zyklotron
Neutronen Experimente, Schema
0 1 2 3m

Fig. 5

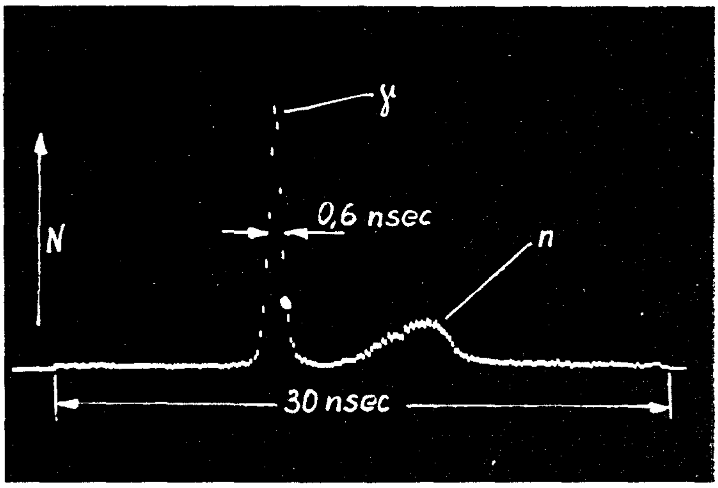

γ
N
0,6 nsec
n
30 nsec

Fig. 6

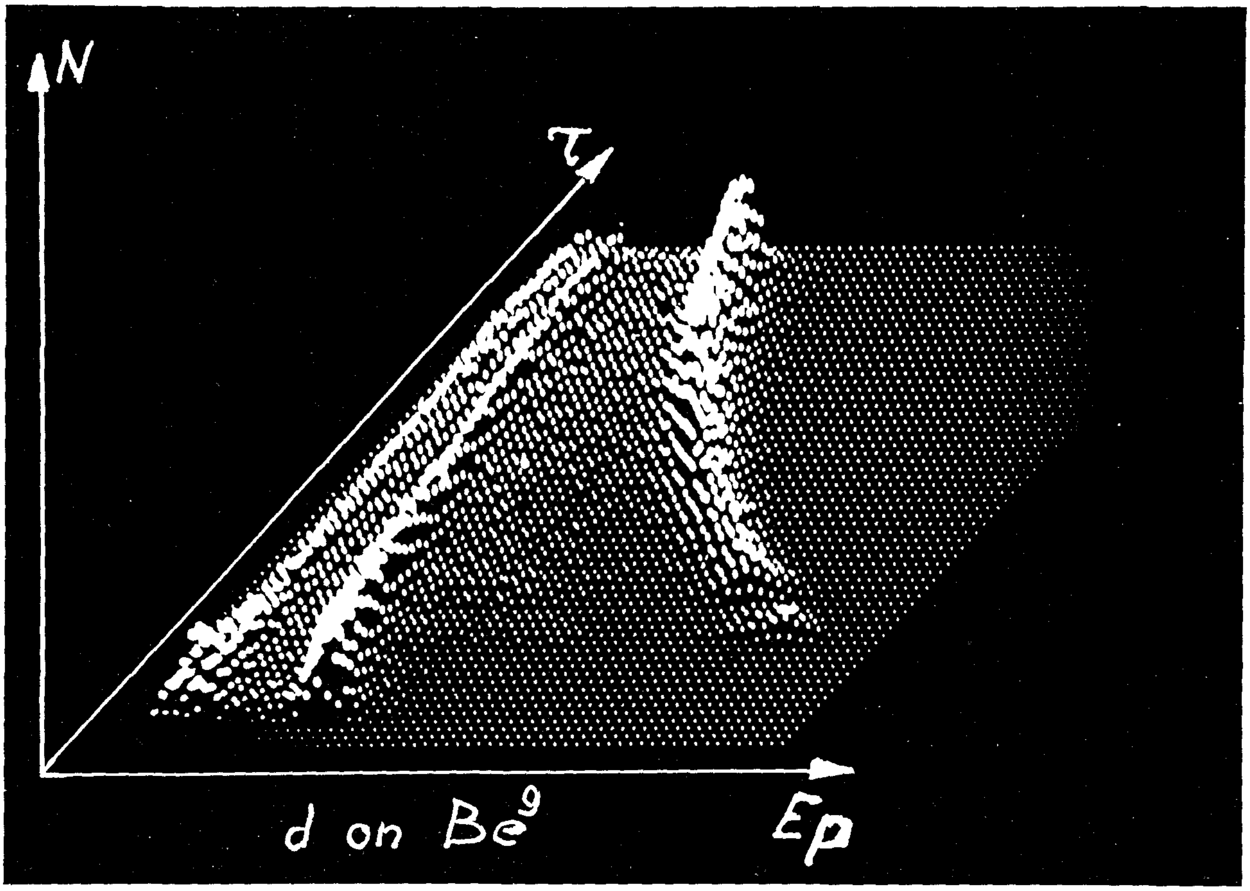
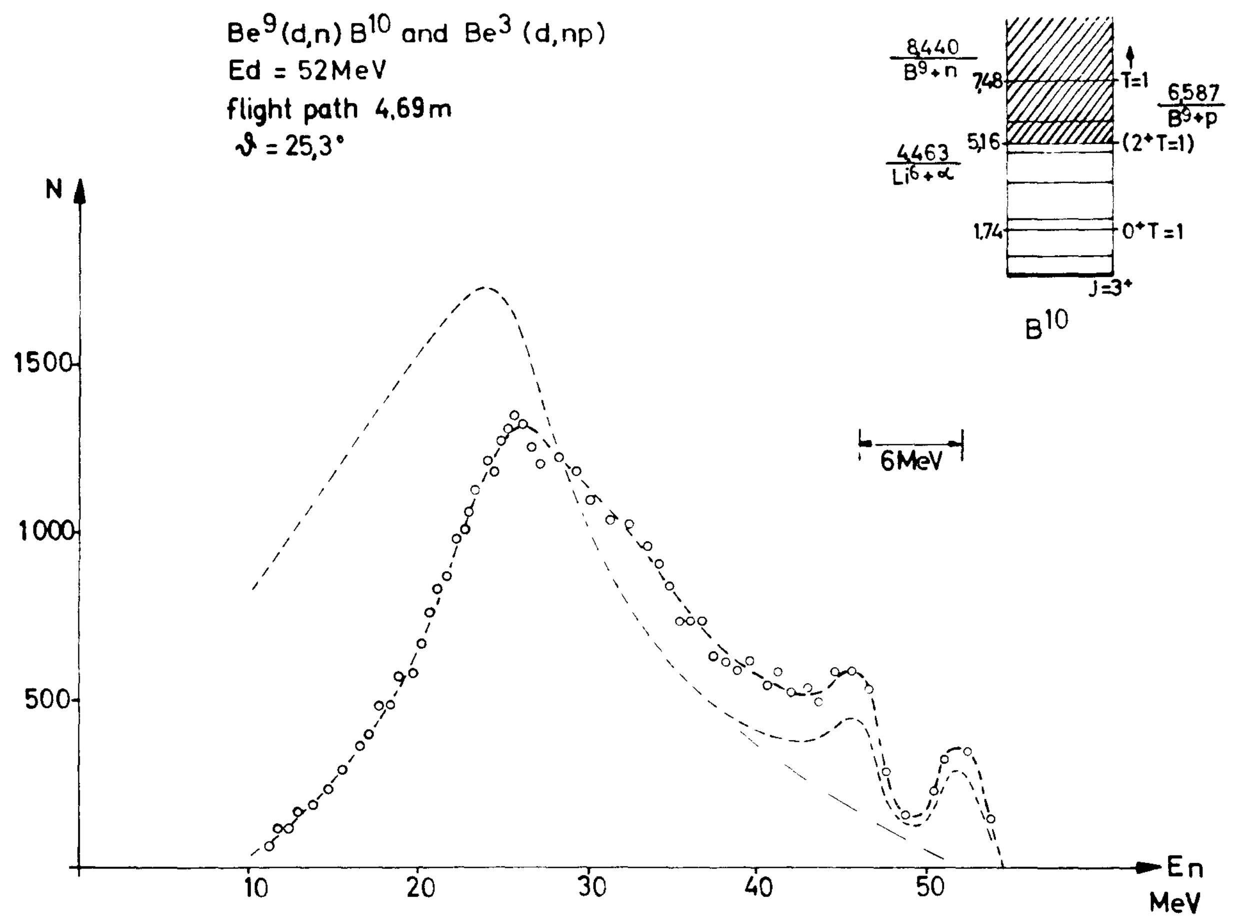


Fig.7



Be9 (d,n) B10 and Be3 (d,np)
Ed = 52MeV
flight path 4,69m
ϑ = 25,3°
N
1500
1000
500
10
20
30
40
50
En
MeV
6MeV
8440
B9+n
7,48
T=1
6587
B9+p
5,16
(2+T=1)
4463
Li6+α
1,74
0+T=1
J=3+
B10

Fig.8

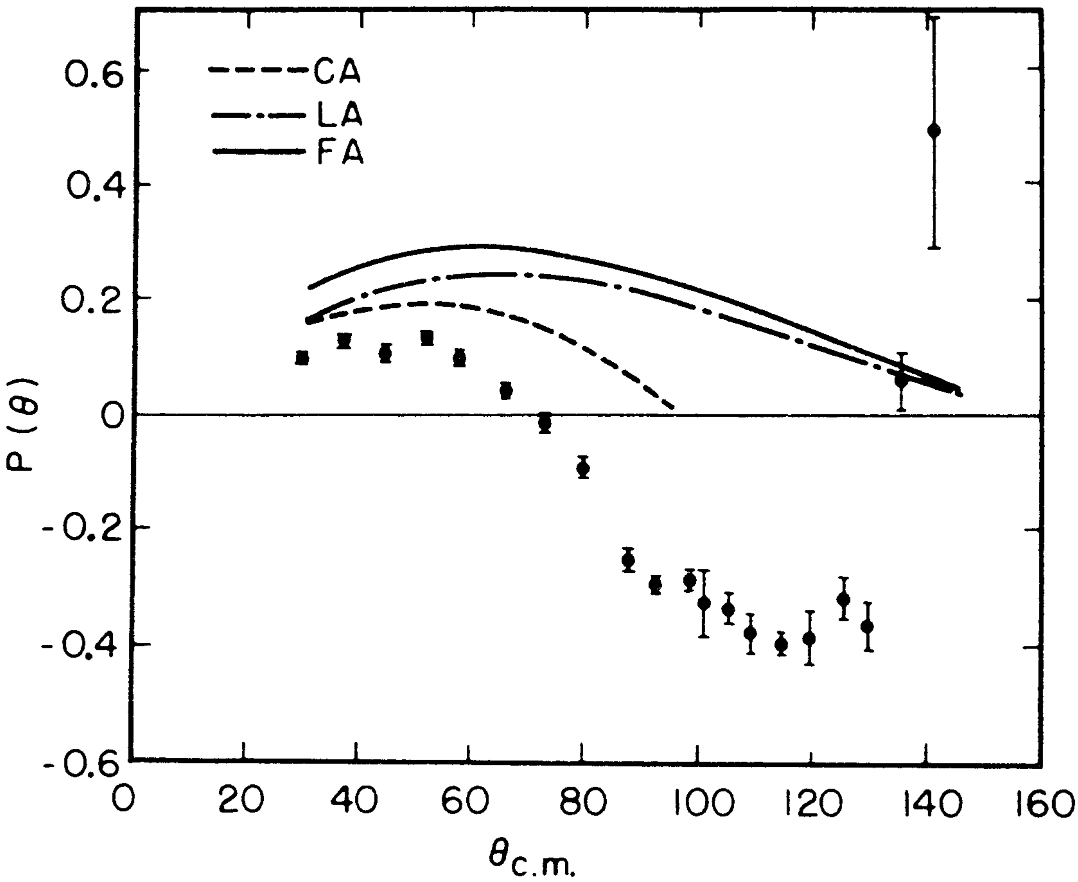
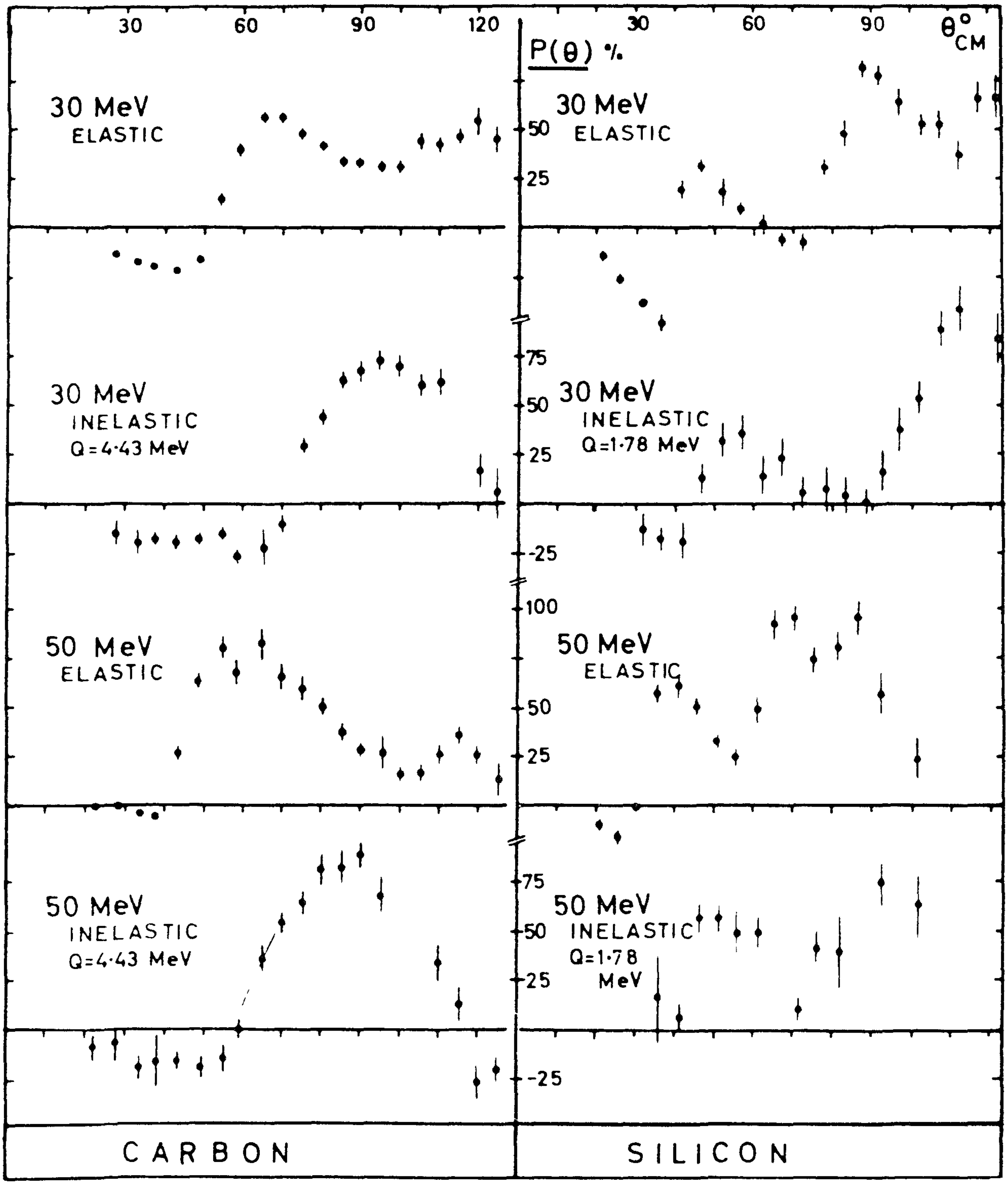


Fig. 9



30
60
90
120
P(θ) %
θ° CM
30 MeV
ELASTIC
50
25
30 MeV
INELASTIC
Q=4·43 MeV
75
Q=1·78 MeV
-25
100
50 MeV
Q=1·78
MeV
CARBON
SILICON

Fig.10