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RESEARCH WITH AVF CYCLOTRONS IN EUROPE

Invited Paper

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Although AVF cyclotrons have been in operation only for a relatively short period an impressive number of experiments have been performed and much work is also currently being done. The available time for this talk is too short, of course, to give an exhaustive survey of what has been achieved in Europe during the last year and I must select some typical experiments for presentation, apologizing to those authors, whose work I cannot mention.

I want to discuss four types of experiments:

1. Experiments with High Energy Resolution

When extracted beams became available it was found that the beam quality of most AVF cyclotrons is surprisingly good. Of course such properties depend on the tuning and the dee voltages. But in most cases energy spreads well below 100 keV were observed corresponding to relative energy resolutions of a few times 10^{-3}. After analysis the resolution can be better than 10 keV allowing the full exploitation of the capabilities of solid state detectors. Since many of these cyclotrons have variable energy and since they allow the acceleration of different particles they are as convenient and powerful as tandem accelerators but will permit the carrying out of precision work at energies much higher than 12 MeV.

As an example of what has been achieved with the Saclay AVC cyclotron I should like to show in Fig. 1 the energy distribution of protons with an initial energy of 18,6 MeV scattered from Fe^{54}. The energy spread of the beam was about 40 keV. Litium-drifted silicon detectors 2.5 mm thick were used giving an overall resolution of 120 keV. It should be remarked that polarized protons are used in this experiment and I think that AVF cyclotrons offer for the first time the possibility of using polarized particles with high energy resolutions at energies above 15 MeV.

A resolution of about 10^{-3} could be obtained at Saclay by using a magnetic spectrometer designed according to Cohen's compensation method. Here no slits exist close to the target and background is negligible. The particles are located by a spark chamber. Results for proton scattering from Pb^{208} will soon be available.

Very high energy resolution is required for a study of fluctuations of the excitation function, since the width of the fluctuations is about 50 keV in the mass region $A \approx 30$ and decreases to 5 keV for $A \approx 50$. Hence, the investigation of these Ericson fluctuations was a domain which in the past was reserved for tandem accelerators. However, Put et al. using the Philips 30 MeV prototype cyclotron were able to extend tandem measurements of the reaction $Al^{27}(p\alpha)\,Mg^{24}$ from energies of 12 MeV up to 20 MeV. The energy spread of the analysed beam was 10 to 15 keV and the excitation function was measured in steps of 25 keV. Since this experiment will be described in a contributed paper I shall not go into further details.

2. Optical Model Studies

Under this heading I should like to discuss briefly the investigation of angular distributions for elastic and inelastic scattering and for various nuclear reactions carried out with moderate energy resolutions.

As an example I should like to show the results of the scattering of deuterons from carbon, which were obtained by Brückmann and Haase at the Karlsruhe cyclotron (Fig. 2). The full curve is a theoretical fit to the elastic data. It is remarkable how well the experimental results are reproduced. This demonstrates that the optical model fits have been refined to such a degree that it becomes possible now to attack the really

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interesting problem i.e. the determination of spectroscopic factors, which contain the relevant nuclear information.

Using the particle identification methods that will be described in section 3 Brückmann and Haase obtained, in addition to the scattering data, results for the (d,p) and (d, ^{3}He) reactions. Fig. 3 shows the results for the (d,p) ground state reaction. For the theoretical fit the potentials as deduced from the elastic deuteron and proton scattering data have been used and therefore there are no free parameters. The curves reflect the general behaviour of the measurements quite well although some discrepancies still exist.

Intensive investigations on light nuclei are also carried out at the Birmingham cyclotron. I.B.A. England and collaborators are studying the large angle scattering of α particles in the 20-24 MeV region from ^{12}C, ^{14}N, ^{16}O, ^{19}F and ^{20}Ne. Analysis of these data is at present in progress. In addition England and Wilne are measuring the angular distribution of the (^{3}He, t) and (^{3}He, d) reactions from targets of ^{9}Be and ^{27}Al at an incident energy of 32 MeV. Results will soon be available.

Deuteron scattering from heavier nuclei has been investigated by Schmidt-Rohr et al. at the Karlsruhe cyclotron. Some results are shown in Fig. 4. For these nuclei the diffraction pattern is rather striking. This group also carried out a theoretical analysis of the yttrium and gold data both with the strong absorption model and the optical model. The best fits together with the potential parameters are shown in Fig. 5.

Many of these experiments have been performed in the past with other accelerators. Nevertheless I believe that AVF cyclotrons offer considerable advantages even in this classical field. Because of their flexibility and above all because of the high beam intensities more and better data will become available. This will certainly help decisively to make the step from testing different optical models to a determination of the relevant nuclear parameters, such as spectroscopic factors.

3. Time-of-Flight Experiments

AVF cyclotrons can be operated in such a way that the width of the individual particle bursts becomes less than 1 nsec and hence they provide an excellent opportunity for time-of-flight measurements. However, in most applications the time-of-flight of some particles is longer than the time-spacing between individual particle pulses and from this an ambiguity arises. This difficulty can be overcome in two different ways:

One possibility is to suppress a large number of particle pulses and use only one pulse out of several hundred. This, of course, results in a considerable reduction of intensity. An elegant solution for the production of neutron pulses with a width of about 1 nsec has been found by Beckurts, Cierjacks et al. at Karlsruhe. Since in this case the incident energy of the deuterons which produce the neutrons does not matter, about 50 deuteron bunches lined up along one radius are deflected simultaneously on to an internal target with a repetition frequency of 20 kHz. In this way the beam intensity is reduced only by about factor 30 with a pulse spacing of 50 µsec. A neutron flight path of about 50 m has been used. The flux at the detector was approximately $5 \cdot 10^4$ neutrons/cm^{2}sec. The resolution obtained was 200 eV for a neutron energy of about 500 keV. This spectrometer and results are described in more detail in a contributed paper to this conference. Therefore I shall only show one illustrative example out of the large amount of data obtained thus far. Fig. 6 shows the total cross section for Ca as derived from a transmission measurement in the energy range 1.4 to 2.2 MeV.

Another way to determine the time of flight unambiguously without supressing beam pulses was pursued successfully by Brückmann and Haase at Karlsruhe. Here the neutrons produced on an external target are detected by a scintillation counter telescope consisting of two thick plastic scintillators spaced about 40 cm from each other. Neutrons impinging on the first scintillator produce recoil protons Those recoil protons that enter the second detector are registered in fast coincidence. An energy signal approximately equal to the neutron energy is obtained from the sum of the energy signals of the two scintillators. A two dimensional display is used showing this energy signal versus the time τ relative to the last preceeding rf pulse. Fig. 7 shows such a neutron spectrum from the ^{12}C (d,n) reaction. One has several branches corresponding to neutrons emitted from successive primary particle bursts. As the neutron energy is determined from the time of flight t , the energy resolution has only to be good enough to distinguish between the branches, and this results in a much higher telescope efficiency. The neutron spectrum can be inferred from the counting rate along the ridge. An example for the reaction ^{12}C (d,n) is shown in Fig. 8.

I want to mention that the pulse length at the target could be made as short as 0.25 nsec. Normally pulse widths of about 0.5 nsec were used (Fig. 9). This is quite remarkable. Since the target was 17 m away from the cyclotron this also implies a narrow energy of the beam. In our case of 52 MeV deuterons the energy spread of the machine was less than 100 keV.

This time-of-flight technique can also be used for the identification of charged particles. One makes a two dimensional measurement of the energy signal from a scintillator or a solid state detector versus the time difference between the time of arrival and the last preceeding rf pulse. The relation between velocity and energy determines different curves or different particles in a τ versus E plot. This is shown in Fig. 10. The particles originating from a bombardment of ^{12}C with 52 MeV deuterons have been analysed. The spectra for p, d, t and ^{3}He particles are well separated from each other. The example shown in Fig. 10 was obtained with a plastic scintillation counter. A combination of a thin and a thick solid state detector delivered much better resolution. The results presented in section 2 have been obtained with this particle identification method.

In Fig. 11 the proton spectrum from the bombardment of carbon with 52 MeV deuterons is shown as an example. Besides the sharp peaks corresponding to transitions to definite levels of the final nucleus a broad maximum at lower energies can be seen. This stems from the break-up process of the deuteron. This process has been studied for different target nuclei and the dependence of the cross section as a function of the atomic number of the target indicates that the break-up process at this energy must be predominantly caused by nuclear forces. An attempt to measure the proton and neutron in coincidence has unfortunately failed up to now, because the time structure of the cyclotron beam made coincidence experiments impossible.

4. Polarization Experiments

AVF cyclotrons have contributed considerably to the improvement of polarization experiments in two ways. First, because of the high intensity double- and triple-scattering or reaction experiments can be performed with much higher accuracy. Secondly, it has been demonstrated that particles from polarized ion sources can be injected successfully into such cyclotrons in various ways.

Since the injection and acceleration of polarized ions has been discussed in the paper by Powell I shall restrict myself to present two examples. In Fig. 12 results are shown that were obtained with the Birmingham polarized deuteron beam. Deuterons with energy around 10 MeV were scattered from carbon at forward angles. In the figure the left-right asymmetry is displayed as a function of the energy. No rapid fluctuations with energy were found and hence deuteron scattering on carbon might be a useful analyzing process.

In Fig. 13 the angular dependence of the asymmetry is shown, which was observed at the Saclay cyclotron in scattering polarized protons from different nuclei in the intermediate mass range. This figure clearly shows the high accuracy of polarization data that can be obtained from AVF cyclotrons. Their interpretation seems to provide some evidence for microscopic form factors.

In spite of these successes the polarized ion sources have not superseded double scattering experiments. Above all the production of polarized protons by scattering α particles from hydrogen (demonstrated for the first time by L. Rosen) offers many advantages.if performed with the higher intensities of AVF cyclotrons. Especially proton polarization with values larger than 80% have not been achieved so far by other methods.

Griffith and Roman (Phys.Lett. 19, 410, 1965) have set up a polarized proton beam utilizing the extracted 24 MeV α particles from the Birmingham cyclotron. They investigated the effect of the Coulomb barrier and the limitations of the optical model by scattering these protons from silver. Other interesting double scattering experiments are being carried out at Birmingham by Burcham and Harris. They are investigating the polarization produced in the elastic scattering of 32 MeV ^{3}He ions from ^{12}C and ^{27}Al. A maximum polarization of 38% was found for ^{12}C and 45% for ^{27}Al. Since no ^{3}He polarized ion sources exist so far this type of experiment is the only way to get this important information.

My survey dealt exclusively with nuclear reactions. However, AVF cyclotrons proved to be very usefull tools for the production of radioactive nuclei. Indeed the full currents of 100 µA or more, which can be delivered by these cyclotrons are mainly exploited for activation studies. However, I have no time to discuss the many interesting investigations in nuclear spectroscopy and radiochemistry, which were made possible by these facilities.

Several AVF cyclotrons in Europe, which came into operation only recently have not yet yielded physical results. I am sure, this will change in the near future and the abundance of information coming from AVF cyclotrons will result in a better and new understanding of the phenomena in the intermediate energy range.

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

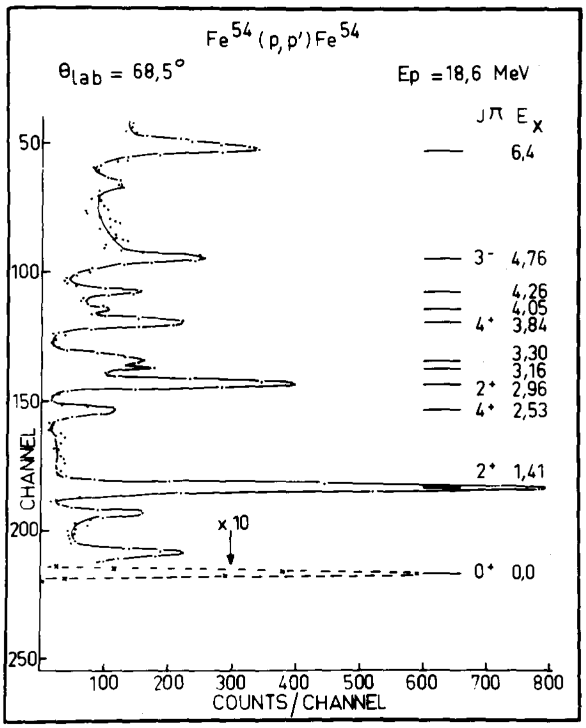

Fig. 1 The energy spectrum of protons scattered from ^{54}Fe as obtained with solid state detectors (Garin, Glashauser, Papineau, de Swiniarski and Thirion, to be published)

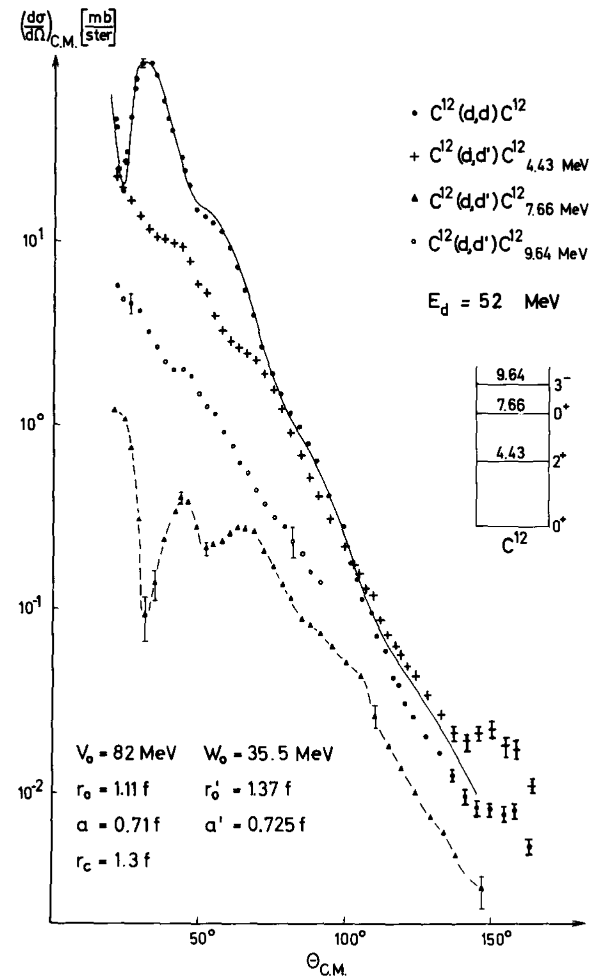

Fig. 2 The elastic and inelastic scattering of 52 MeV deuterons from carbon. The solid curve is an optical model fit (code TSALLY). The potential parameters are also given. (Brückmann and Haase, to be published)

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

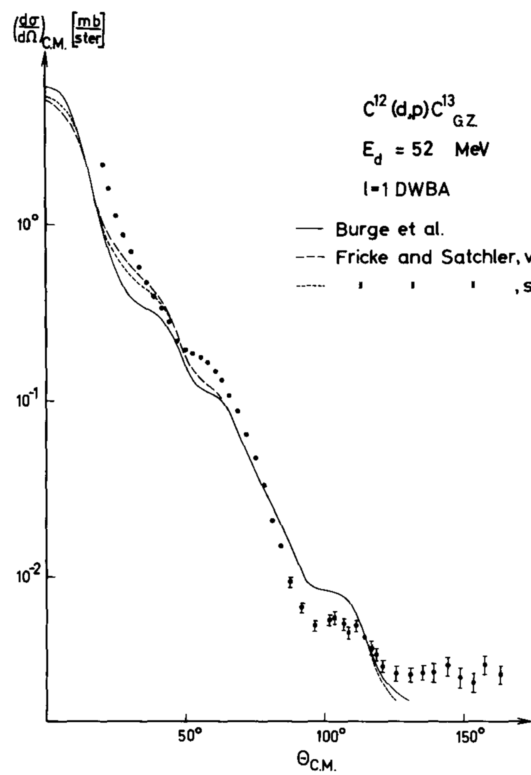

Fig. 3 The angular distribution of the ^{12}C (d,p)^{13}C ground state reaction induced by 52 MeV deuterons. Three DWBA fits with different proton potentials are also shown. (Brückmann and Haase, to be published)

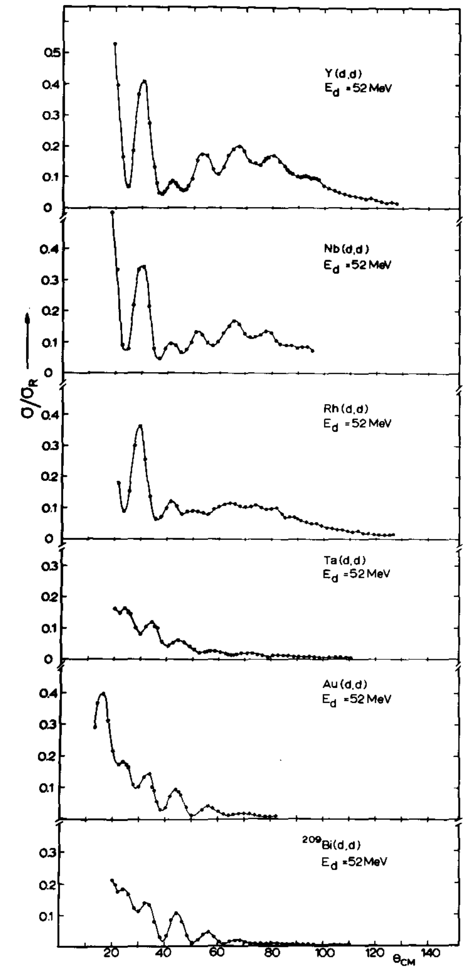

Fig. 4

Elastic scattering of 52 MeV deuterons from heavy nuclei. The ratio of the measured cross section and the Rutherford cross section is plotted (Duelli et al., to be published in Z. Naturforschg. 21 A (1966))

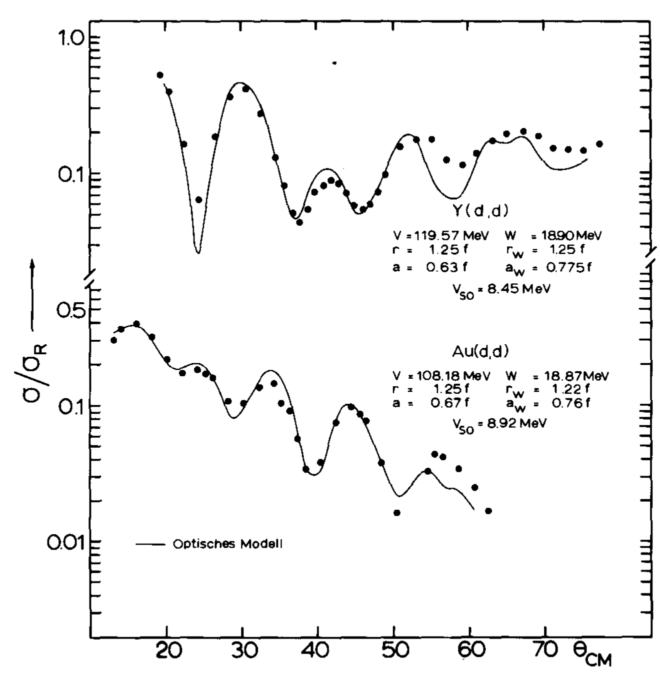

Fig. 5

Elastic scattering angular distributions of 52 MeV deuterons on Y and Au. The solid curves are the best optical model fits (Abacus). The potential parameters are also given.

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Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

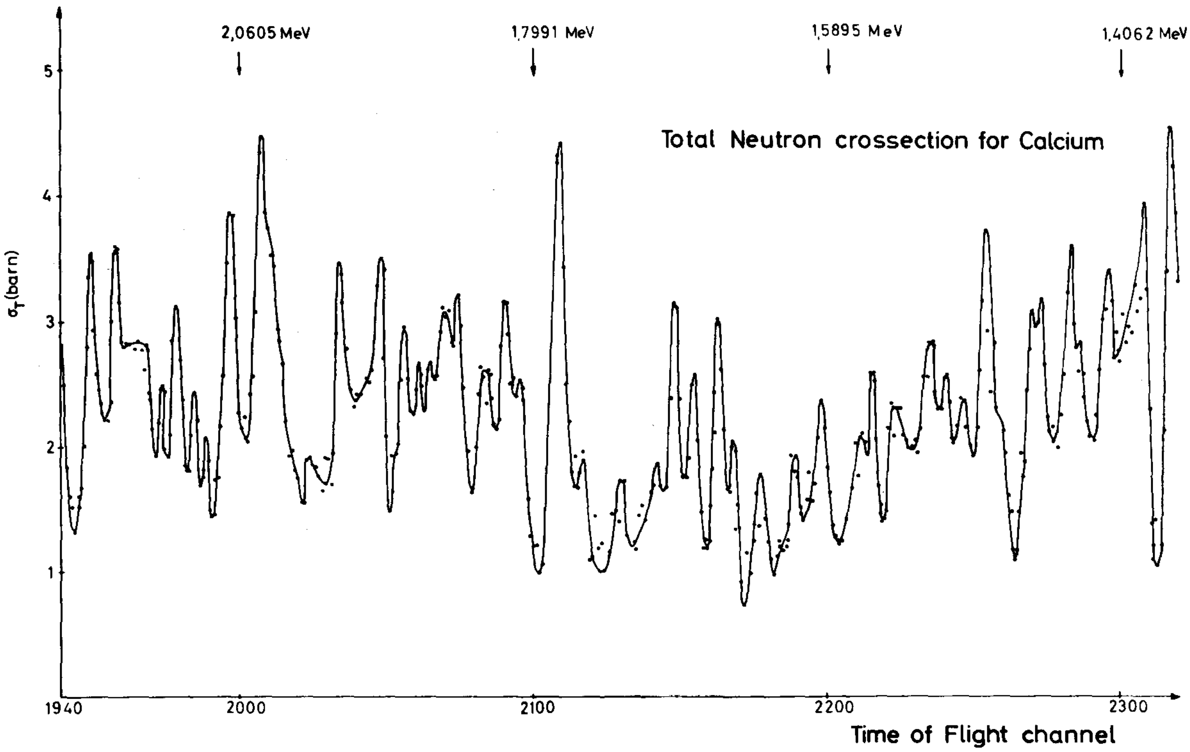

Fig. 6 Total neutron absorption cross section for Calcium from 1.4 to 2.2 MeV.

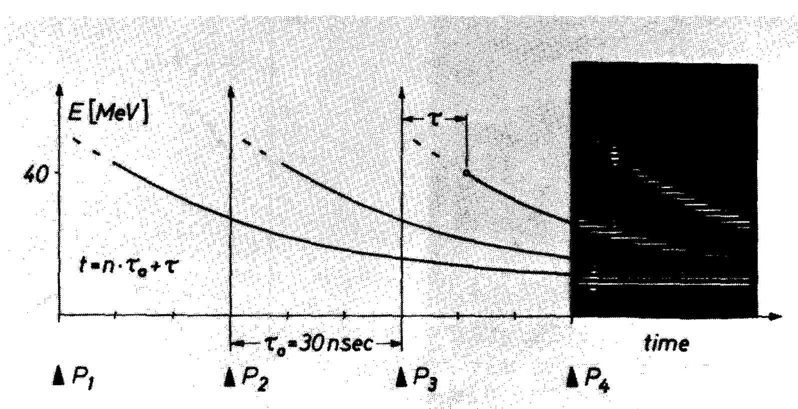

Fig. 7 Neutron time of flight versus neutron energy E for a flight path of 8.4 meters. The time of flight is longer than the spacing of the primary pulses P. The photograph is a two dimensional analyser spectrum of neutrons produced by 52 MeV deuterons on carbon.

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

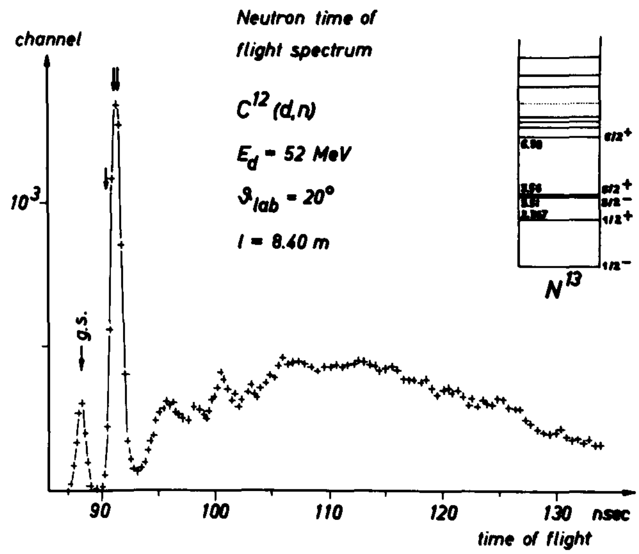

Fig. 8 The time-of-flight spectrum of neutrons from 52 MeV deuterons on carbon (Brückmann and Haase).

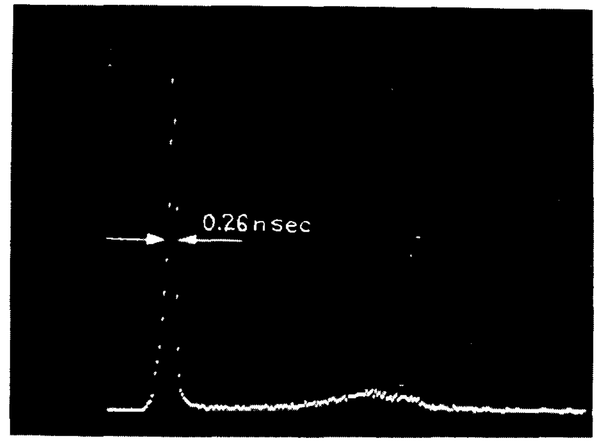

Fig. 9 Time-of-flight spectrum showing gamma rays and neutrons from the bombardment of a thick copper target with 52 MeV deuterons. The flight path was 30 cm. The width of the γ-peak is mainly caused by the time and the energy width of the machine pulses.

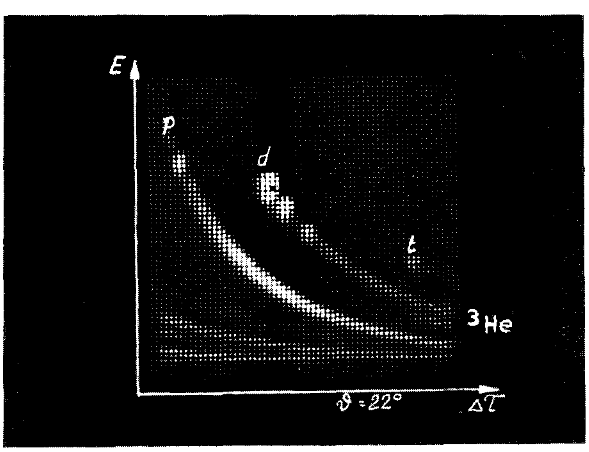

Fig. 10 Energy versus time-of-flight spectrum of various reaction products from 52 MeV deuterons on carbon.

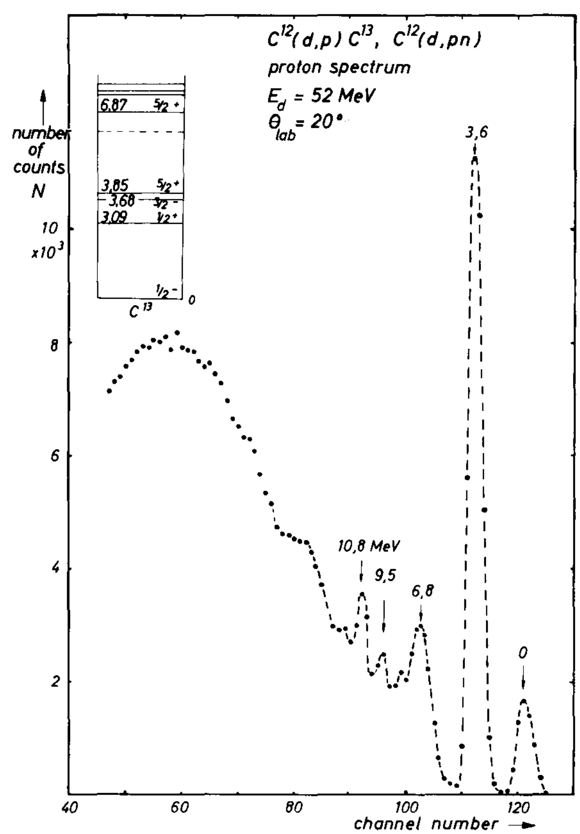

Fig. 11 Typical proton spectrum with a NaJ (Tl) detector.

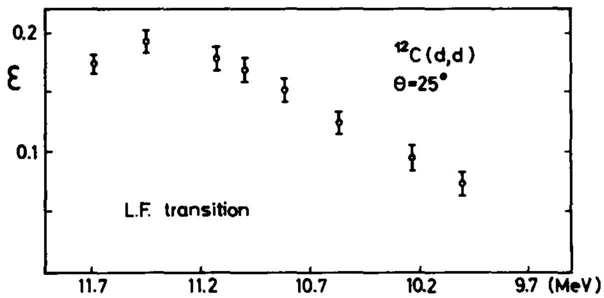

Fig. 12 Energy dependence of asymmetry in the elastic scattering of deuterons on carbon. (Dore et al., Proc. of the Int.Conf. on Polarization Phenomena, Karlsruhe (1965))

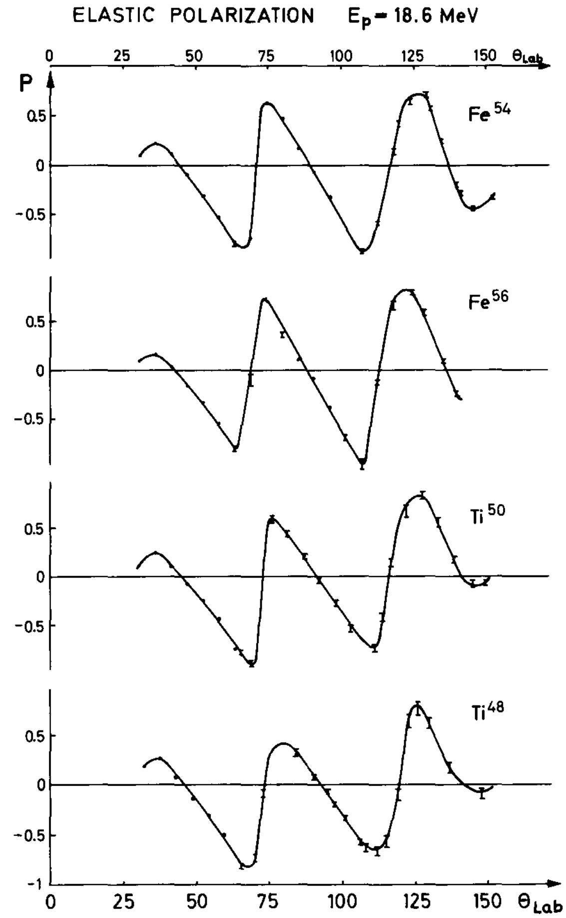

Fig. 13 The angular dependence of the asymmetry in the elastic proton scattering from various nuclei (Garin et al., to be published)