AE-354
UDC 621.384.653(0471.1)
539.171.4

AE-354

NEUTRON PHYSICS LABORATORY
Annual Progress Report
October 1, 1967-September 30, 1968

T. Wiedling

AKTIEBOLAGET ATOMENERGI

STOCKHOLM, SWEDEN 1969

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ABSTRACT

The present progress report gives some short descriptions of experiments going on in the neutron physics branch at the Studsvik laboratories. The main program concerns fast neutron physics at the Van de Graaff laboratory with a strong emphasis on neutron scattering cross section data of elements of interest for reactor calculations.

Since the Van de Graaff accelerator is still the one in Sweden giving the highest potential, it has been quite natural to use the machine also for some nuclear physics experiments with charged particles, though in some cases related to the neutron physics program.

In connection with the use of the reactors at Studsvik for physics experiments, research programs have been in progress for several years concerning the use of reactor neutrons for production of isotopes for a systematic study of short lived nuclear isomeric states as well as for the study of the gamma emission in the fission process.

Printed and distributed in April 1969.

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1. INTRODUCTION

The present progress report gives some short descriptions of experiments going on in the neutron physics branch at the Studsvik laboratories. The main program concerns fast neutron physics at the Van de Graaff laboratory with a strong emphasis on neutron scattering cross section data of elements of interest for reactor calculations. With regard to the neutron physics program initiated several years ago the accelerator was equipped at an early stage with a pulsed ion source. Recently the pulsing system has been much improved in the respect that a klystron buncher has been installed. This modification has appreciably extended our research abilities in the fast neutron physics field with respect to the improved energy resolution as well as the higher neutron peak intensity.

Since the Van de Graaff accelerator is still the one in Sweden giving the highest potential, it has been quite natural to use the machine also for some nuclear physics experiments with charged particles, though in some cases related to the neutron physics program.

In connection with the use of the reactors at Studsvik for physics experiments, research programs have been in progress for several years concerning the use of reactor neutrons for production of isotopes for a systematic study of short lived nuclear isomeric states as well as for the study of the gamma emission in the fission process.

2. VAN DE GRAAFF ACCELERATOR

P Tykesson

The Van de Graaff accelerator has been used with protons, deutrons and helium ions, both with DC beams and pulsed beams. The accelerator was run in alternately two and three shifts for 5 days per week and the calculated total time available for experiments was 2,728 hours, 2,633 hours of which were used by scientists and 95 hours were required for unforeseen maintenance.

The distribution of the available machine time for experiments with the accelerator performed by physicists from various institutes, is shown in Table I and that of different experimental branches in Table II.

Table I

AB Atomenergi	74.8 %
Research Institute of National Defence (FOA)	20.7 %
Chalmers University of Technology	4.5 %

Table II

Nuclear physics	39.2 %
Neutron physics	30.8 %
Solid state physics	29.2 %
Irradiations	0.8 %

The number of normal breaks for maintenance of the machine has been four during the year, each generally consisting of one week, except for a break for mounting and testing a klystron bunching system which required eight weeks.

The above-mentioned klystron bunching system has been designed and built by the personnel at the Van de Graaff laboratory. The test results of the system have been very good and beyond expectation. Fig. 2.1 shows the width of the bunched pulses plotted for different machine voltage settings at regular accelerator column length as well as with the column electrically shorted by grounding the lower half. The pulses were measured with a fast pick-up just after the analysing magnet, and the mean current during the tests was about 3 μA. The pulse width without bunching was 15 ns. Fig. 2.2 shows the measured peak amplitude gain corresponding to the measured bunched pulse widths in fig. 2.1.

To summarize, the accelerator is now able to deliver pulses with 1 ns width and 7-10 μA mean current at 1 MHz repetition frequency.

3. SCATTERING OF POLARIZED FAST NEUTRONS

O Aspelund

The research activities during the period under review were primarily devoted to the presentation of final reports on projects for which experimental data had been collected previously but not completely processed.

The final reports issued are concerned with the following items:

1) A comprehensive method for correction of experimental fast neutron polarization data for finite geometry and polarized multiple-scattering effects.

Combined with our previously reported Monte Carlo program for simulation of the fast neutron detection process in hydro-carbonous plastic scintillators, the Monte Carlo routine MULTPOL allows total correction accuracies of the order of 1 %, viz. accuracies comparable to those of the experimentally determined finite-geometry left-right ratios.

An important experience gained during the work on the development of appropriate methods for correction of experimental fast neutron polarization data is that the left-right ratio is not affected by unpolarized multiple-scattering effects but solely by polarized multiple-scattering effects. Consequently, the polarization dependence of the differential scattering cross section must be correctly included not only in the first scattering but also in the higher scattering orders, in the digital computer routine used for evaluation of multiple-scattering corrections. Due to this unobserved circumstance, practically all fast-neutron polarization data reported in the current literature have not been properly processed.

Our data reduction scheme will also be applicable when new polarization experiments are planned. If the polarization effects are expected to be small, large samples may be tolerated, for which reason the left-right ratio may be accurately determined without excessive running times.

This work on the processing of fast neutron polarization data is in some respects unique.

2) The energy and angular dependence of the polarization in fast-neutron scattering off ^{12}C.

Important results are:

a) For energies exceeding 1 MeV, the polarization effects are sufficiently large to render ^{12}C applicable as a fast neutron polarization analyser. This fact is of considerable practical interest, because for energies below approximately 2 MeV, ^{4}He cannot be used as an analyser of unknown polarizations.

b) The relation between corresponding angular distributions of the polarization and the differential scattering cross section is not of Rodberg's derivative type. Relevant arguments for this not being the case are presented.

c) Scattering phase shifts describing integrated scattering cross sections, differential scattering cross sections and polarizations yield detailed information on the n-^{12}C interaction at relevant energies.

3) Work on the development of fast time-to-pulse height technique for semi-automatic acquisition of fast-neutron polarization data.

As a result of our efforts in this field, the finite-geometry left-right ratio may be obtained to within an accuracy of 1 % during an accelerator time of less than 1 hour. The scattering samples used yield signal-to-background ratios of 1:1 and maximum total corrections of 5 %. One observes the need for a reliable scheme for application of these corrections. The scheme developed by us satisfies this requirement without excessive computer running times.

4. GAMMA-RAYS FROM INELASTIC NEUTRON SCATTERING IN NITROGEN

H Conde*, I Bergqvist* and G Nyström**

With the main purpose to meet data request for gamma-ray production cross sections in the incident neutron energy region from 4 to 8 MeV, an experiment has been set up at the Van de Graaff accelerator. The gamma-ray detector is a 17 ccm true coaxial lithium-drifted

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germanium detector which is run in a time-of-flight arrangement to reduce the neutron-induced background. The aim of the investigation is to measure the spectra as well as the angular distributions of the gamma radiation and to refer the cross sections to the (n, p)-scattering cross section by the use of a proton-recoil telescope.

Neutrons with energies of 4.5, 6 and 7 MeV were produced by the $D(d,n)^3He$ reaction in a gas target. The gas target had a thin Mo entrance window and the gas cell was 3 cm in length and 0.8 cm in diameter. The gas pressure was about 1.5 atm and the interior of the gas cell was covered with a thin gold layer to reduce the background. A plastic scintillator was used to monitor the output of neutrons from the source. The scintillator was set up in a time-of-flight arrangement to reduce the effect of background pulses in the scintillator caused by gamma rays and room-scattered neutrons. About 20 grams of ammonium azide, NH_4N_3, housed in a thin-walled cylindrical holder of plexiglass was used as scattering sample. The sample was mounted at a distance of about 10 cm from the neutron gas target. For background measurements an empty holder of the same type as described above was used.

As gamma-ray detector a 17 ccm true coaxial Ge(Li) detector was used. It was set up at 55^o to the incident neutron beam and at a distance of about 85 cm from the scattering sample. The angle 55^o was used because usually the gamma-ray angular distribution can be represented by an expansion of even-order Legendre polynomials and often the second order terms dominate the expansion. In these cases a good approximation of the integrated cross section is 4π times the 55^o differential cross section. The linear pulse spectrum from the Ge(Li) detector was recorded on a 4096 channel analyzer. The energy resolution was about 5 keV at 1 MeV of gamma-ray energy. To reduce the background caused by neutron interactions in the Ge(Li) detector it was run in a time-of-flight arrangement. Two typical time-of-flight spectra at 4.5 and 7 MeV are shown in fig. 4.1. The FWHM of the gamma-ray peaks was about 15 ns. The pulses from a single-channel analyzer adjusted to accept pulses in the gamma-ray peak (fig. 4.1) of the time-of-flight spectra was used to open a gate to the 4096 channel analyzer.

The incident neutron beam flux was measured with a proton recoil telescope. Four polyethylene radiators with different thicknesses (1.5 - 18 mg/cm^2) and a blank for background measurements could be used. The protons from the (n, p)-reactions in the radiator were counted with solid-state detectors. A typical spectrum at 7 MeV of incident neutron energy and with a 6.3 mg/cm^2 radiator is shown in fig. 4.2.

Several runs were made at each incident neutron energy both with the scattering sample and with the empty plexiglass cylinder. To get a counting statistic of better than 5 % of the pronounced gamma-ray lines the total running time at one neutron energy was about 10-15 hours. The detector efficiency was measured at several energies up to 1.8 MeV and 2.6 MeV with calibrated gamma-ray sources placed in the scattering sample position. At higher energies the efficiency was calculated from measurement of the gamma-rays from the 992 keV proton resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction and from the de-excitation scheme given by Azuma et al. In this way the efficiencies of photo as well as double-escape events were measured with an accuracy of about 5 % below about 3 MeV of gamma-ray energy and about 20 % above this energy. When the actual background of a certain gamma-ray energy spectrum had been subtracted, the number of counts in each peak was calculated. After applying the efficiency corrections for the Ge(Li) detector the number of gamma-rays was corrected for attenuation of gamma radiation in the ammonium azide sample. The attenuation of the gamma-rays in the sample was less than 10 % in the whole energy region of interest. The incident neutron flux calculated from the measurement with the proton-recoil detector was corrected for neutron attenuation and multiple-scattering effects using the Monte Carlo program MULTSCAT (Holmqvist et al.). The corrections were estimated to be about 5 %. The energies of the observed gamma-ray lines in the spectrum obtained with the Ge(Li) detector were estimated by using a linear interpolation between the 846.6 keV line from ^{56}Fe in the background and the 5104 keV line from ^{14}N as references together with the energy difference of 1022 keV between the photo and double-escape peaks.

A typical gamma-ray spectrum at 7 MeV of incident neutron energy is shown in fig. 4.3. The given energies of the different gamma-ray lines, where the half-lives of the excited states are of the order of the slowing-down times of nitrogen recoils, are in some cases affected by Doppler broadening and shift. From half-life values measured by Allen the gamma-ray shifts were estimated to be less than 5 keV in the present measurement.

Table I gives preliminary values of the differential gamma-production cross section in 55 ^{o} of the pronounced gamma-ray lines at 4.5, 6 and 7 MeV of incident neutron energies. The cross section for the $^{14}N(n,n'\gamma)^{14}N$ reaction including cascades at 7 MeV of neutron energy is 18.0 ± 2.5 mb/sr in good agreement with the value obtained by Hall and Bonner. Energies below 1 MeV are slightly decreased by an unsharp energy discriminator.

Table 1 Experimental differential (n,n'γ) cross sections of N^{14}, O^{16}, and $Si^{28,29}$ measured at an angle of 55 degrees.
The experimental errors are about 20 %.

E_n MeV / E_γ keV	4.5	6.0	7.0
	dσ/dΩ mb/sr		
	N^{14}		
722			0.47
1634	0.33	2.34	4.15
2313	1.21	3.31	6.23
5108		0.49	3.35
5839			1.05
	O^{16}		
5107[1]			2.10
	$Si^{28,29}$		
775			1.18
1780			18.2
2837			17.2

[1] Double escape peak of the 6129 keV line.

5. STUDIES OF NEUTRON CAPTURE

I Bergqvist*, B Lundberg*, L Nilsson and N Starfelt**

To explain the magnitude of MeV nucleon capture cross sections in medium-weight and heavy nuclei, one is forced to take into account the influence of semi-direct capture processes through the giant dipole resonance. The interaction between the incident nucleon and the target nucleus may excite the latter to its giant dipole resonance while the incident nucleon is captured into a low-lying single-particle orbit. The decay of the giant dipole excitation gives a high-energy gamma-ray transition from the capturing state to a low-lying single-particle state. In a few cases, it is possible to study gamma-ray decay to distinct single-particle states. In such cases the comparison with theoretical predictions becomes sufficiently simple to permit definite conclusions concerning the importance of semi-direct capture processes.

Gamma-ray spectra from neutron capture in the energy range 1 to 8.5 MeV were recorded for Si, P, S, Ni, ^{206}Pb and Bi using time-of-flight techniques. The gamma-ray detector is a NaI(Tl) scintillator, 20.8 cm long and 22.6 cm in diameter. The results for Ni and Bi are being published, and the data processing and analysis for the other elements are in progress.

For a few nuclei in the s-d shell photo-nuclear reactions have shown that the giant dipole resonance has a small satellite on its low-energy side. It is of interest to know whether this satellite is a "true" part of the dipole resonance or whether the peak in the photo-nuclear cross section curve is due to some direct process. The present experiment may clarify this point.

^{206}Pb(n, γ) is a suitable reaction to study the semi-direct capture process in the neutron energy range easily achievable by the D(d, n) reaction at the Studsvik Van de Graaff. The reasons are that the neutron binding energy of ^{207}Pb is 6.7 MeV and that the peak of the giant dipole resonance in ^{206}Pb is at 13.5 MeV. This means that

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it is possible to cover an excitation energy region extending up to about 2 MeV beyond the peak of the giant resonance. Preliminary analysis shows qualitative agreement with predictions based on the semi-direct capture theories.

6. STUDIES OF (d, pγ) REACTIONS

I Bergqvist*, B Lundberg*, L Nauclér** and L Nilsson

With the aim to achieve an understanding of the neutron capture mechanism in nuclei with mass numbers around 60, (d, pγ) reactions have been studied in ^{58,60}Ni and ^{63,65}Cu at 5.5 MeV deuteron energy. The gamma-rays were detected by a NaI(Tl) scintillator, 12.7 cm in diameter and 10.2 cm long, and the protons by a silicon surface-barrier detector of high resistivity. With the use of two-parameter multichannel analysis it was possible to measure simultaneously the gamma-ray spectra from several excitation energy regions populated by neutron transfer, in particular those below the neutron binding energies. The gamma-ray spectra from excitation energy regions not too far below the neutron separation energy show strong-intensity high-energy gamma rays. The shapes of the spectra are similar to those obtained in (n, γ) reactions and disagree with those expected from the theory of the compound-nucleus capture process. Similar experiments have been performed at Chalk River for nuclei with mass numbers around $A \simeq 200$ and $A \simeq 130$. Also for these nuclei there is a striking similarity between spectra from (n, γ) and (d, pγ) reactions. It is proposed that a semi-direct reaction process proceeding through 2 particle - 1 hole configurations is responsible for a considerable part of the cross section in nuclei around $A \simeq 200$. In the $A \simeq 60$ mass region, there is no possibility to determine whether a similar reaction mechanism plays a correspondingly prominent role, since the single-particle strengths are distributed over much larger energy regions than in the $A \simeq 200$ mass region. A report on the experiment is being published.

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7. TIME-OF-FLIGHT MEASUREMENTS OF NEUTRONS FROM (d, n) REACTIONS

I. Nuclear Spectroscopy in the 2s 1d and $1f_{7/2}$ Shells

B Erlandsson*, A T G Ferguson**, L Nilsson and N Starfelt***

Analysis and interpretation of the experimental data from (d, n) reactions in ^{31}P, ^{50}Cr and ^{54}Fe have been continued. A final report on the $^{31}P(d,n)^{32}S$ reaction study has been published.

The investigation of the $^{31}P(d,n)^{32}S$ reaction was initiated to study isobaric analogue states. These are identified by comparisons with positions, ℓ-values and spectroscopic factors obtained for levels in the analogue nucleus by the (d, p) reaction on the same target nucleus. Two s-wave isobaric analogue states and a few T = 0 states with various ℓ_p- values were identified. DWBA calculations were performed to give ℓ_p-values and relative spectroscopic factors. From the present work an isobaric spin energy splitting for s-wave states in ^{32}S of 7.5 MeV is derived. This value is larger than for other nuclei in this mass region, due to the configurational difference between the T = 0 and T = 1 s-wave states.

Experimental angular distributions of neutron groups to a number of levels in ^{51}Mn and ^{55}Co have been determined from neutron spectra from the $^{50}Cr(d,n)^{51}Mn$ and $^{54}Fe(d,n)^{55}Co$ reactions. Preliminary DWBA calculations showed that the calculated differential cross sections are very sensitive to the parameters of the deuteron optical potential. Therefore existing data from deuteron elastic scattering has been used to calculate a proper set of deuteron optical potential parameters by means of the computer code ABACUS II. The final DWBA calculations have been delayed due to an accident with the program magnetic tape, but are expected to be performed in the near future.

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II. The Cross Section of the $^{16}O(d,n)^{17}F$ Reaction

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The ^{17}F positon activity of the moderator has been proposed as an appropriate measure of the power of heavy water reactors. Deuterons are knocked out of D_2O molecules of the moderator by fast neutrons from the reactor core. If the energy of such a deuteron exceeds the threshold of the $^{16}O(d,n)$ reaction, there is a finite probability for the creation of a neutron. The residual nucleus, ^{17}F, is a positon emitter with a half-life of 66 sec. The ^{17}F activity of the moderator is thus a measure of the fast neutron flux in the moderator and consequently of the reactor power. This method necessitates that the $^{16}O(d,n)^{17}F$ reaction cross section be known. The time-of-flight facilities at the Van de Graaff accelerator at Studsvik are adequate for measuring the cross section of this reaction for deuteron energies between 3.0 and 5.5 MeV. The detection efficiency is determined by comparison with the efficiency of a polythene proton recoil counter. The experimental work has been finished and the final data analysis is being performed. Yield curves for the $^{16}O(d,n)^{17}F$ reaction to the ground state and to the first excited state at laboratory angles of 30° and 0°, respectively, are given in fig. 7.1.

8. FAST NEUTRON ELASTIC CROSS-SECTION MEASUREMENTS IN THE ENERGY RANGE 1.5 TO 8 MeV

B Holmqvist, S G Johansson, G Lodin and T Wiedling

It is important in connection with technological reactor calculations to have nuclear models available from which cross section data can be calculated at energies and for nuclei for which experimental information is lacking. Thus, the present measurements have been made in order to obtain neutron elastic cross sections for comparison with cross-sections calculated with the spherical optical model. In order to make a systematic study of the optical model a large and homogeneous experimental material has been collected. This material comprises neutron elastic scattering angular distributions measured at several energies in the interval 1.5 to 8 MeV from the elements Al, S, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, In, Ta and Bi.

The measurements have been performed by the fast neutron time-of-flight technique allowing the separation of elastically and inelastically scattered neutron groups. Monoenergetic fast neutrons were produced by using a pulsed 6 MV Van de Graaff accelerator together with the reactions $T(p,n)He^3$ and $D(d,n)He^3$. The scattering samples were in the form of hollow cylinders having lengths of 5.0 cm, 0.95 cm inner diameters, and 2.5 cm outer diameters. The scattered neutrons were detected with a scintillation detector consisting of a 5 cm long by 10 cm diameter fast plastic scintillator (NE102A) in optical contact with a fast photo-multiplier (RCA7264). The spectrometer time resolution was about 3 ns throughout the experiments. The primary neutron flux was monitored with a directional sensitive long counter. Elastic neutron cross sections were determined relative to the well-known (n, p)-scattering cross-sections (by observing scattering from a sample of the isotope under investigation and the hydrogen standard, each being exposed to a flux measured in relative units. A small scatterer of polythene was used for these comparison measurements.)

The experimental angular distributions have been corrected for the anisotropy of the neutron source, attenuation of the neutron flux in the scatterer, neutron multiple scattering and for the finite source-sample-detector geometry using a Monte Carlo computer program.

Theoretical angular distributions have been fitted to the experimental ones using a local central optical potential consisting of Saxon-Woods, derivative Saxon-Woods, and Thomas form factors describing the real, imaginary, and spin-orbit potentials, respectively. Optimum values of the real and imaginary potential depths, the corresponding nuclear radii, and the real potential diffuseness parameter were calculated independently for each element and energy with an automatic parameter search program. Very good agreements have been obtained between the experimental and theoretical angular distributions. The optical model parameters were found to be essentially independent of the neutron energy except for the even mass number elements, for which the real potential depth slowly decreases with the energy, and except for sulphur, the parameters of which show large fluctuations with the energy, probably caused by resonance effects. Examples of the optical model fits are shown for indium in fig. 8.1, where the circles represent the corrected experimental data and the solid lines are the best fits obtained from the optical model calculations. The corresponding parameter values, i.e. the real potential depth U, the imaginary potential depth W, the real and imaginary radii r_{oU} and r_{oW}, and the real diffuseness parameter a, have been plotted versus the neutron energy in fig. 8.2.[1)]

The mass number dependence of U and W also shows interesting features. Thus evidence has been obtained for a real isobaric spin potential as well as an indication of a corresponding imaginary potential.

There are indications that the real and imaginary radii do not follow the simple expression $R = r_o A^{1/3}$ assumed in the constant density nuclear model. The parameter r_o of the real and imaginary radii increases slowly with the mass number.

Information of pure physical interest has also been extracted from the present work. It has been shown that the root-mean-square radii calculated from the neutron data are in excellent agreement with the corresponding radii calculated by the use of proton elastic scattering data.

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1) Holmqvist B, Arkiv Fysik <u>38</u> (1968) 403

These results indicate that, within the experimental uncertainties, the same nuclear radius is measured in neutron and proton scattering in the present limited neutron and proton energy regions. Furthermore the extensions of the matter and charge distributions have been calculated for a number of nuclei from neutron and electron root-mean-square radii showing that the mass distribution extends beyond that of the nuclear charge distribution. This indicates that the surface of the investigated nuclei is neutron-rich.

9. GAMMA RADIATION FROM FISSION PRODUCTS

H Albinsson* and L Lindow

At the R2 reactor we have been studying gamma radiation emitted from fission fragments after slow neutron induced fission of ^{235}U. In particular the radiation has been studied as a function of fragment mass and different time intervals after fission.

A schematic diagram of the experimental arrangement is shown in fig. 9.1. The uranium, enriched to about 95 % ^{235}U, was electroplated on 100 $\mu g/cm^2$ nickel foils. The fissile deposit was in most runs less than 100 $\mu g/cm^2$ and one cm^2 in area. Two solid state detectors of the surface barrier type were placed in parallel and symmetrically around the fission foil to detect the energies of the fragments. The fission foil and the solid state detectors were enclosed in an evacuated fission chamber. A gamma detector, a NaI scintillator, was placed perpendicular to the plane containing the direction of the motion of the fragments and the direction of the neutron beam. The gamma quanta were detected in coincidence with fission events. The NaI scintillator was placed about 70 cm from the fission foil in order to get time discrimination between the fission gammas and the prompt neutrons released in the fission process. The gamma radiation emitted during different time intervals after the fission event was studied by a recoil distance technique, i.e. by changing the position of a collimator along the path of the fission fragments. In this way it was possible to get estimates of the life times of the gamma-emitting states.

In one of the series of measurements we determined the relative number of photons of different energy portions as functions of mass. The yield curve for gammas of all energies (fig. 9.2) looks about the same as the yield curve for the number of prompt neutrons per fragment, the so-called saw-tooth curve. (In this figure the mass number is given on a logarithmic scale.) These curves reflect the internal energy conditions of the fragments just after scission. Frag-

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ments with high excitation emit more neutrons and evidently also more gammas than fragments with low excitation energies.

We can notice exceptions from the saw-tooth curve, namely dips at certain mass numbers and also a sharp decrease at mass numbers exceeding 148. In our measurement we have been studying the gamma radiation during a time interval of 5×10^{-11} - 6×10^{-10} sec. The decrease in the yield curve occurs at mass numbers around 82, 88 and 104 and above 148. The curve also seems to go through an inflexion point around mass number 140, i.e. in the transition region.

The deviations from the saw-tooth curve can best be understood from comparisons of fission gammas in ^{252}Cf fission. Johansson's results[1)] show a high yield of delayed radiations in the above-mentioned mass regions, except mass number 82 which is practically not seen in ^{252}Cf fission. The time interval investigated by him was 15 to 100 nsec. Also in the study of K X-rays and conversion electrons from ^{252}Cf fission[2,3)] a sharp decrease was found in the yield curve for mass numbers exceeding 148. However, if the measured time interval was made long enough (up to about 100 nsec) this effect became less pronounced. So we conclude that these fragments have a higher proportion of delayed gammas than have all other masses.

The time distribution of the gamma radiation has been studied by the recoil distance method. The smallest slit of the collimator used so far has been 0.25 mm and with this collimator it has been possible to obtain a decay curve from which we have determined the half-life of one major gamma component to be about 2×10^{-11} sec. After 7×10^{-11} sec another longer-lived component can be seen and, without having studied it in detail, we have obtained a half-life of about 10^{-10} sec. As regards the finer details, i.e. details in the component with the half-life of 2×10^{-11} sec, and also determinations of even shorter half-lives, investigations are going on and as yet we

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1. Johansson S A E, Nucl. Phys. 64 (1965) 147.
2. Kapoor S S, Bowman H R, and Thompson S G, Phys. Rev. 140 (1965) B1310.
3. Watson R L, Bowman H R, and Thompson S G, Phys. Rev. 162 (1967) 1169.

do not know how narrow collimator slits can be used without stopping the gamma radiation almost completely. Corrections for the collimator geometry may also give us problems in determining absolute values of, e.g., the yield of gamma quanta within a certain time interval after fission.

Gamma-energy spectra have been accumulated as functions of fragment mass and time after fission. The shapes of these spectra are various, reflecting the de-excitations of different types of nuclei: deformed, spherical and double-magic. In the magic mass number regions the spectra show a higher gamma yield around 1 MeV, while in regions of deformed nuclei the intensity maxima are at about 200 keV. This concerns at time interval after fission of about 10^{-10} - 5×10^{-10} sec. The gamma spectra as functions of earlier time intervals do not vary so much with mass, indicating a more general decay process during the first instants after fission.

During the period covered in this report we have installed for data recording a two-parameter system, the memory of which is a small computer, PDP-8/S. This computer is also used for data analysis.

10. BETA- AND GAMMA-RAY SPECTROSCOPY

S G Malmskog, M Höjeberg,* V Berg* and Å Höglund*

The experimental studies of decay properties of radioactive nuclei using beta spectrometers, Ge(Li) detectors and delayed coincidence technique for half-life measurements are continued.

Short reviews of performed experiments are given below together with the main results obtained.

W^{185m}

The gamma ray spectra have been measured. From these spectra and complementary measurements on the Ta^{185} decay 7 excited levels of W^{185} have been established, including the 1.6 min isomer at 197.5 keV. This level decays via an E3 transition to the $5/2^-$ 3/2 |512| Nilsson level, and is probably the $11/2^+$ |615| Nilsson level. Also members of the rotational bands built on the Nilsson levels $1/2^-$ |510| and $7/2^-$ |503| have been found. The level order is (energies in keV, spins given as IK^{π}): 0 ($3/2$ $3/2^-$), 23.4 ($1/2$ $1/2^-$), 65.9 ($5/2$ $3/2^-$), 173.9 ($7/2$ $3/2^-$), 188.1 ($5/2$ $1/2^-$), 197.5 ($11/2$ $11/2^+$), 243.5 ($7/2$ $7/2^-$) and 390.8 ($9/2$ $7/2^-$). The ($3/2$ $1/2^-$) level is not established.

As^{75}

The half-life of the 199 keV, 280 keV and 401 keV levels have been measured. The results are 0.87 ± 0.03 ns, 0.28 ± 0.02 ns and 1.67 ± 0.14 ns respectively. These results are in good agreement with resonance fluorescent and Coulomb excitation measurement.

Lu^{175}

The half-life of the 343 keV level has been measured. The preliminary result, 0.27 ± 0.02 ns, is in agreement with a resonance scattering measurement. The half-life of the 433 keV level is under investigation.

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Ir^{191} (in collaboration with A Bäcklin*)

Gamma ray and conversion electron energies and intensities for transitions in Ir^{191} have been measured. The following energies (in keV) and transition multipolarities were found: 41.92 ± 0.02 (E3), 47.05 ± 0.03 (E2), 82.46 ± 0.04 (56 % M1 + 44 % E2) and 129.52 ± 0.02 (88 % M1 + 12 % E2). The half-life of the 129.52 keV level was found to be (1.26 ± 0.11) x 10^{-10} sec.

Ir^{193} (in collaboration with A Bäcklin*)

Gamma rays have been measured and approx. 50 transitions have been found. For the strongest lines conversion electron spectra have been measured. The following energies and transition multipolarities were found from α_K and L sub-shell ratios: 73.10 (δ^2 = = 0.41 ± 0.03[1]), 96.90 (δ^2 = 0.024 ± 0.006), 107.10 (δ^2 = 0.023 ± 0.004), 138.97 (δ^2 = 0.120 ± 0.015), 142.26 (M1), 180.15 (δ^2 = = $0.73^{+0.30}_{-0.15}$), 181.89 (M1), 219.2 (E2), 251.7 (M1), 280.5 (M1), 289.0 (E2), 298.7 (E2), 321.6 (M1), 361.9 (M1), 377.6 (M1), 387.5 (M1), 420.1 (M1), 441.0 (M1), 460.6 (M1), 484.2 (M1), 557.4 (M1) and 559.2 (M1). The level structure is being investigated.

1) δ^2 = E2/M1 ratio

Dy^{161}

Five new transitions have been found in the gamma ray spectrum. The preliminary energies are 315, 341, 348, 427 and 507 keV. They can be fitted to the level scheme already established. The half-life of the 131.77 keV level was found to be (1.45 ± 0.15) x 10^{-10} sec.

U^{235}

In order to be able to measure the delay of conversion electrons following alpha decay one lens of the spectrometer was replaced by a surface barrier detector, which was connected to our usual electronic set-up. The time resolution (FWHM) of this equipment was about 1.5 ns (65 % less than with electron-electron coincidences).

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* The Swedish Research Councils' Laboratory

With this experimental equipment we have measured the half-life of the 51.7 keV and 13.1 keV levels of U^{235} populated in the alpha decay of Pu^{239}. Preliminary results are: $T_{1/2}$ (51.7 keV) = 0.4 ± 0.1 ns and $T_{1/2}$ (13.1 keV) ~ 0.5 ns (certainly < 0.8 ns). We know of no previous results. The measured transition probabilities will be compared with the predictions of the collective model for the $1/2^+$ rotational band with members at 0.08 keV ($1/2^+$), 13.1 keV ($3/2^+$) and 51.7 keV ($5/2^+$) in U^{235} and current systematics in the region of deformed nuclei.

11. STAFF

T Wiedling	(in charge)
S Lindgren (Mrs)	(secretary)
J-O Andersson	(until December 31, 1967)
H Albinsson	(attached from Chalmers University of Technology)
O Aspelund	
V Berg	(attached from the University of Stockholm)
L Eriksson	
S Hellström	(until December 31, 1967)
J Higbie	(until May 31, 1968)
B Holmqvist	
Å Höglund	(attached from the University of Stockholm)
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S Johansson	
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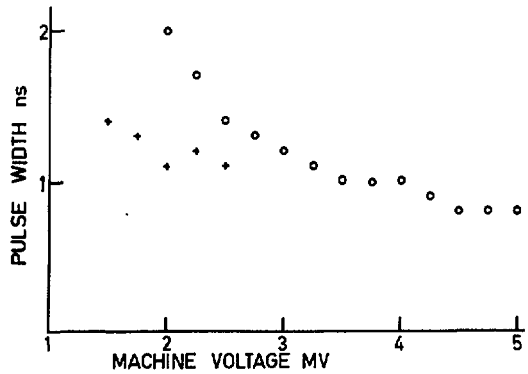

Fig. 2.1. The width of the bunched pulses for different machine voltage settings at regular accelerator column length (open circles) as well as with the column electrically shorted by grounding the lower half (crosses).

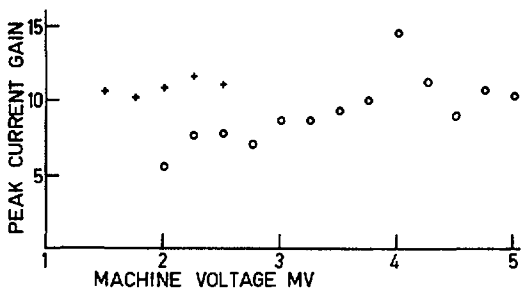

Fig. 2.2. The peak current gains for different machine voltage settings at regular accelerator column length (open circles) as well as with the column electrically shorted by grounding the lower half (crosses).

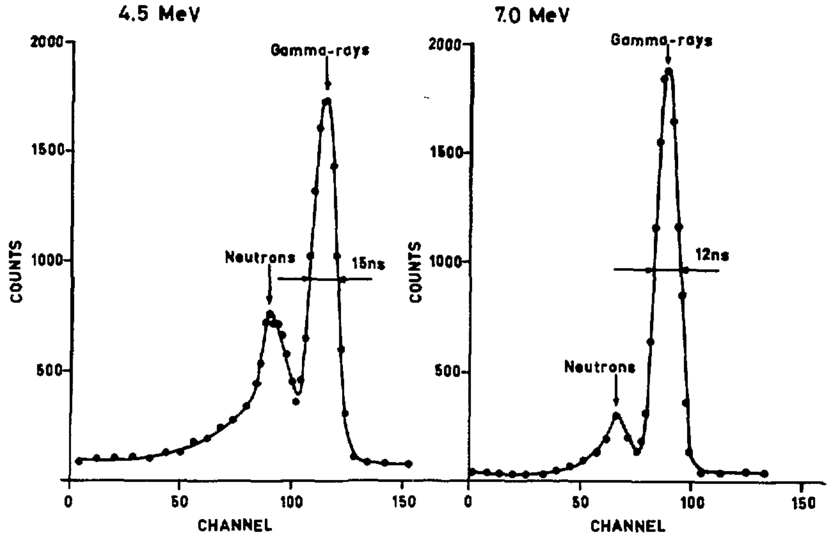

Fig. 4.1. Time-of-flight spectra of iron at the 4.5 and 7.0 MeV neutron energies.

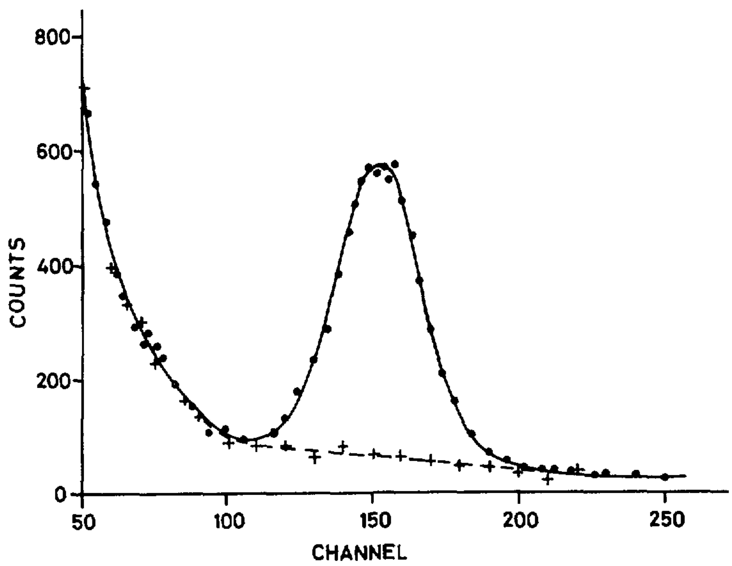

Fig. 4.2. Proton-recoil detector spectrum obtained at 7.0 MeV neutron energy with a 6.3 mg/cm^2 polyethylene radiator.

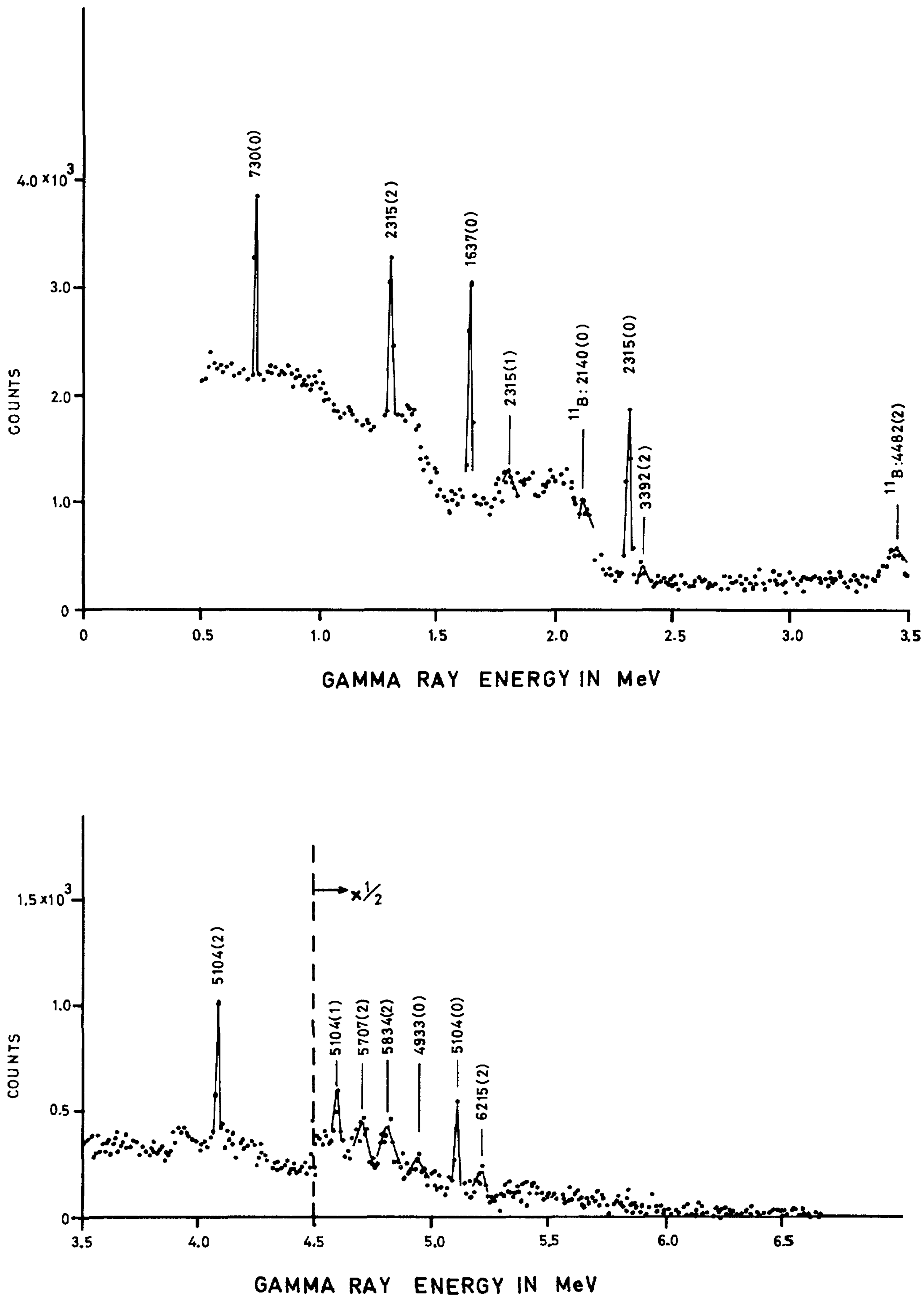

Fig. 4.3. Gamma spectrum from nitrogen obtained at 7 MeV neutron energy.

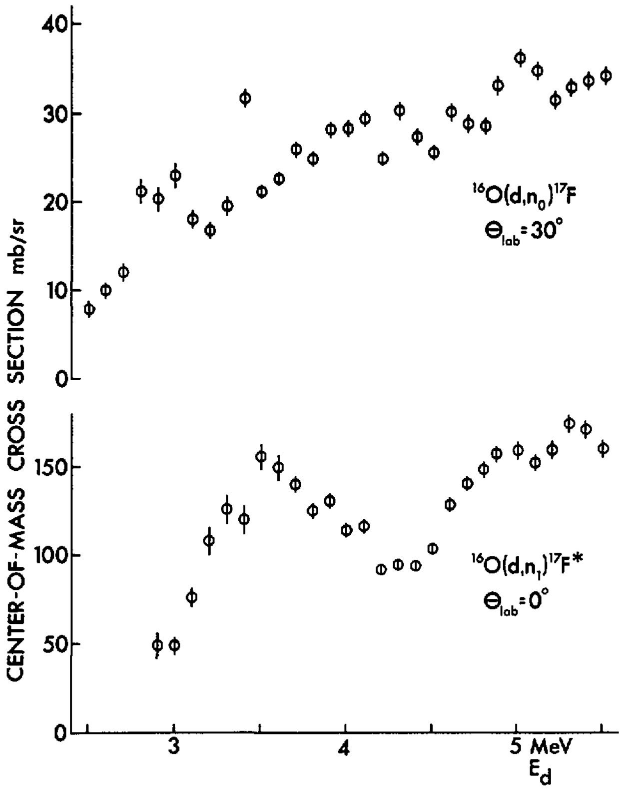

Fig. 7.1. Centre-of-mass cross sections versus deuteron energy for the $^{16}O(d,n)^{17}F$ reaction to the ground state and to the first excited state at laboratory angles of 30° and 0°, respectively. Relative errors are given as vertical bars.

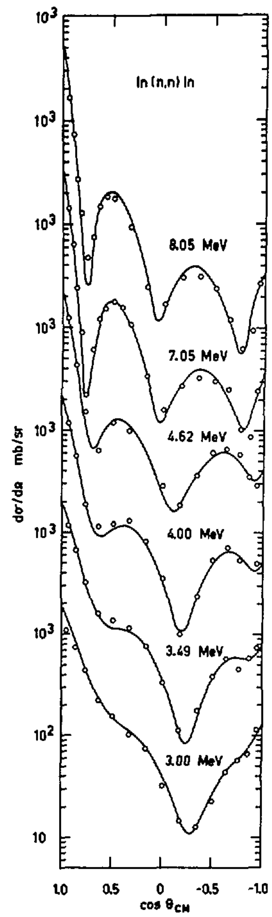

Fig. 8.1. The experimental (circles) and calculated (solid lines) angular distributions of neutrons elastically scattered by In.

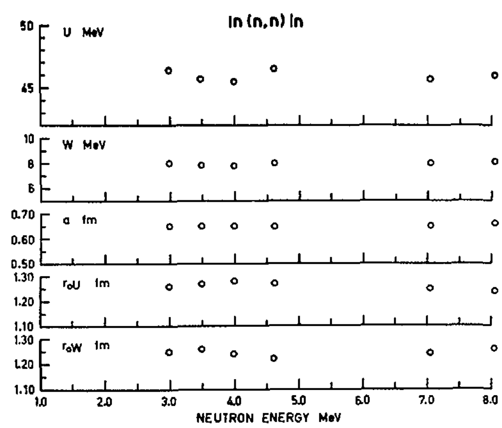

Fig. 8.2. The optical potential parameter values of In from the five parameter analyses plotted versus the neutron energy.

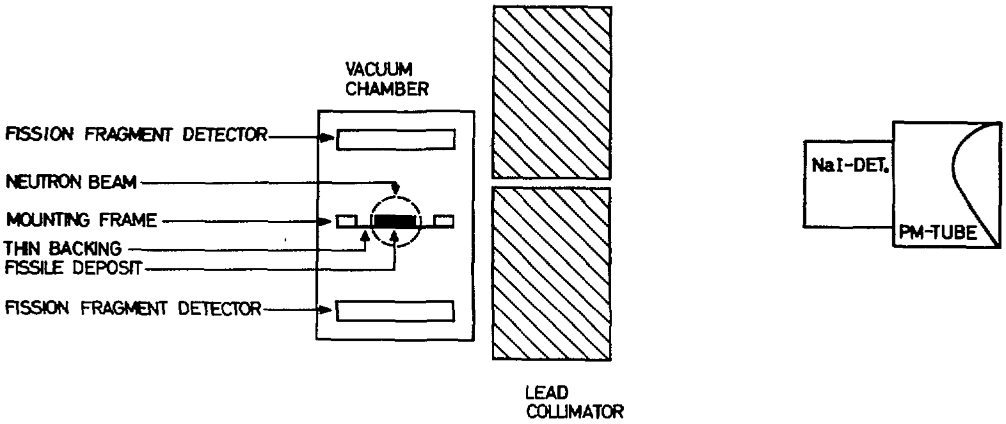

Fig. 9.1. Schematic diagram of the experimental arrangement.

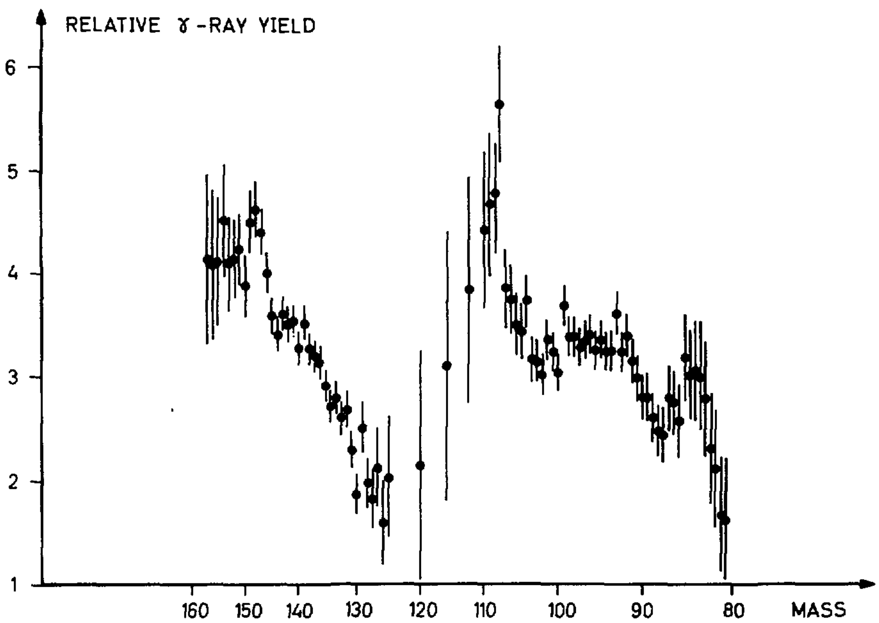

Fig. 9.2. Relative gamma-ray yield as a function of fragment mass.

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