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Proposal for experiment at SC2:

An experimental study of binary fission induced by 600 MeV protons in U, Pb, Pr, Ag, Sr and Cu.

(revised version)

G. Andersson, M. Areskoug, H-Å. Gustafsson,
G. Hyltén and B. Schröder
Department of Physics, University of Lund, Lund, Sweden
and
E. Hagebö
Department of Chemistry, University of Oslo, Blindern,
Norway

Abstract

An experiment is proposed to study nuclear binary fission induced by 600 MeV protons in the targets: U, Pb, Pr, Ag, Sr and Cu. Different parameters describing the fission process will be investigated with semiconductor detectors in combination with time-of-flight techniques. A similar experimental program will be performed with bremsstrahlung at the 1.2 GeV electron syncrotron at the University of Lund. The equipment, such as scattering chamber and electronic components, will thus be thorougly tested before the proposed experiment at the synchrocyclotron at CERN.

In section 1, the physical problems will be stated and discussed. The experimental arrangements will be described in section 2, and estimates of beam-time will be given in section 3 in addition to a preliminary run schedule.

Some facts:

Experimental area: Particle Physics Area in UR2
Intensity: $5 \cdot 10^{11}$ protons$\cdot$sec^{-1}
Duty factor: as close to 1 as possible
Beam-time: $182 \cdot$(duty factor)$^{-1}$ hours
Suggested date: in the period 15/6 - 15/8 1975
Equipment not available: small computer (type PDP 9) with a magnetic tape unit

1. Physical background

The fission phenomena has been extensively studied since it's discovery in 1939. As a result of the developments in the fields of accelerators, detectors, electronic components and computers it has been possible to study this process with a large variation in the experimental parameters such as target element, projectile and bombarding energy. Due to the complexity of the process different experimental methods must be used to obtain a complete description of the fission phenomena even for a specific combination of experimental parameters.

One of the most extensively used projectiles is the proton, and at present much experimental information has been collected concerning fission from proton energies around threshold to multi-GeV protons. Proton induced fission at intermediate energies has mainly been studied at four proton energies and for a few target elements only. Limitations also exists in the experimental information obtained depending upon method used. Some relevant information for the energy region considered has been collected in table 1:1.

In fig. 1:1, a possible scheme describing the binary fission process, induced by intermediate energy protons, is given. The different magnitudes of interest are indicated at different stages of the decay process. A summary of the main experimental methods is presented in table 1:2 in addition to parameters which may be determined by the different methods.

Most of the methods used yield information about the secondary fission products, whereas the theoretical desciptions concern the primary fission fragments. Thus, uncertainties in the interpretation of experimental data are imposed due to uncertainties in the description of the nuclear evaporation leading from primary fragments to secondary products (see fig. 1:1). Below we will propose an experiment (on lead) where these uncertainties may be reduced.

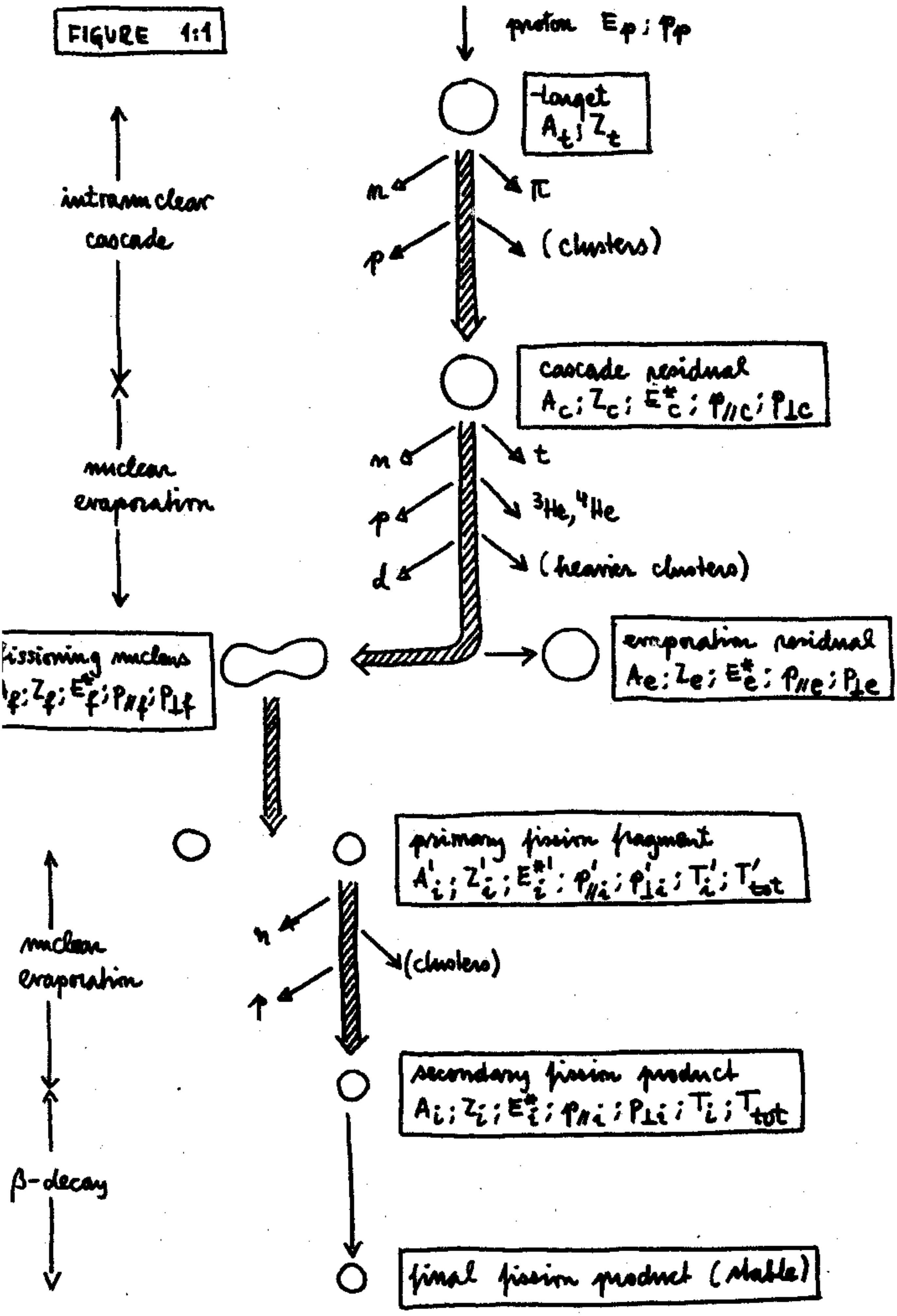
Table 1:1

Energy (MeV)	Target	Accelerator	Information obtained
85	≥U	McGill SC	Charge distributions, isomeric yield ratios
156	Au,Bi U	Orsay SC	Fragment kinetic energies, mass distributions, neutron emission in the fission process
170	U	Gustaf Werner SC	Charge- and mass distributions, deposition energies
450	Ta,Bi U	Chicago SC	Charge- and mass distributions, recoil parameters, fragment kinetic energies, deposition energies
600	Ag-U	CERN SC	Charge- and mass distributions, recoil parameters, fragment kinetic energies, deposition energies, fission cross sections

Table 1:2

Experimental method	Parameters determined
Solid state detectors(glass,mica)	Fission cross sections, projection angle between binary fragments. Estimates of fragment kinetic energies and masses
Radiochemical methods(mass-spectroscopy)	Detailed information on charge- and mass distributions of secondary fission products (A_i,Z_i in fig. 1:1)
Recoil methods	Detailed information on kinetic- and excitation energies of secondary fission products(T_i,$p_{\parallel i}$,$p_{\perp i}$ in fig. 1:1)
Semiconductor detectors	Detailed information on distributions of kinetic energies for complementary fission products,projection angles between pairs of fragments,energy-energy correlations
Semiconductor detectors and time-of-flight determination	In addition to above, the mass of one of the complementary fission products, mass-energy correlations, correlations for differing projection angles(i.e. different values of $p_{\parallel i}$,$p_{\perp i}$,E_f^* in fig. 1:1)

FIGURE 1:1


proton E_p ; p_p
target
A_t ; Z_t
intranuclear cascade
n
π
p
(clusters)
cascade residual
A_c ; Z_c ; E^*_c ; $p_{//c}$; $p_{\perp c}$
nuclear evaporation
n
t
p
^{3}He, ^{4}He
d
(heavier clusters)
fissioning nucleus
A_f ; Z_f ; E^*_f ; $p_{//f}$; $p_{\perp f}$
evaporation residual
A_e ; Z_e ; E^*_e ; $p_{//e}$; $p_{\perp e}$
primary fission fragment
A'_i ; Z'_i ; $E^{*\prime}_i$; $p'_{//i}$; $p'_{\perp i}$; T'_i ; T'_{tot}
nuclear evaporation
n
p
(clusters)
secondary fission product
A_i ; Z_i ; E^*_i ; $p_{//i}$; $p_{\perp i}$; T_i ; T_{tot}
β-decay
final fission product (stable)

The experimental method to be used in the proposed experiment is that of semiconductor detectors for energy-energy-velocity measurements on complementary fission fragments. A simplified situation is shown in fig. 1:2 where detector 2 is placed far from the target and detector 1 as close as possible.

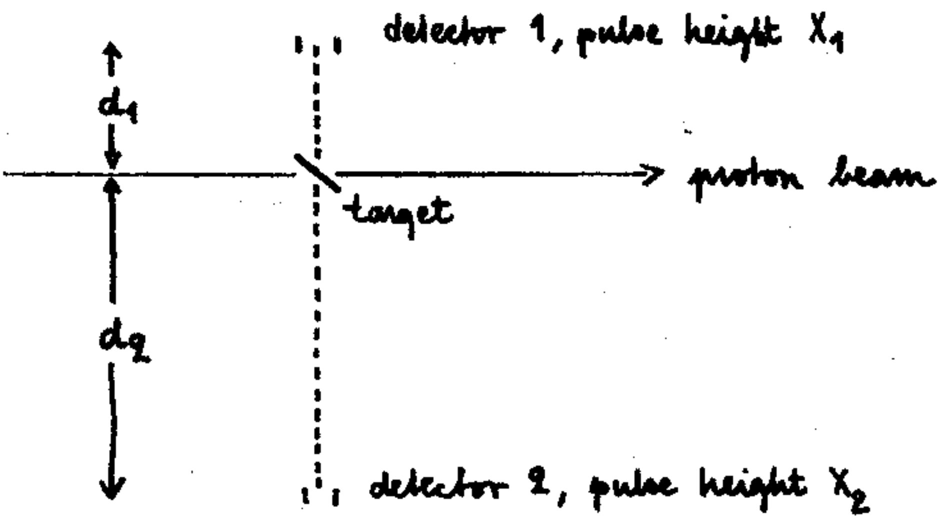


FIGURE 1:2

From the pulse height X_i in detector i the corresponding kinetic energy of the fragment may be calculated according to

$$E_{i,n} = (a_i + a_i' M_{i,n-1}) \cdot X_i + b_i + b_i' M_{i,n-1} \qquad (1.1)$$

where the constants a_i, a_i', b_i, b_i' may be determined for each detector using fission fragments from ^{252}Cf. As the calibration equation depends on the mass of the fission fragment, M_i, iteration has to be used. From the time difference Δt between the complementary fragments one may calculate the velocity $V_{2,n}$ from

$$V_{2,n} = \frac{d_2}{\Delta t}\left[1 - \left(\frac{d_1^2}{d_2^2} \cdot \frac{M_{1,n-1}}{M_{2,n-1}} \cdot \frac{E_{2,n}}{E_{1,n}}\right)^{1/2}\right] \qquad (1.2)$$

where the term in the square bracket is a correction for the flight time to the near detector 1. Fragment masses may be calculated from

$$M_{2,n} = 2\,E_{2,n} / V_{2,n}^2 \qquad (1.3)$$

$$M_{1,n} = M - M_{2,n} \qquad (1.4)$$

where M is an estimated average total mass of the two fragments. The iteration is continued until $|M_{2,n}-M_{2,n-1}|$ reaches some predetermined limit.

To a large extent the design of the proposed experiment is based on the work of Remsberg et al.$^{1)}$. These authors studied 2.9 GeV proton induced fission in uranium and bismuth, obtaining an energy resolution of about 1 MeV, a time resolution of about 0.5 nsec and the resulting mass resolution was approximately 4 amu.

The method of semiconductor detectors has several advantages compared to the other methods given in table 1:2. It is possible to study for each event the correlations between single fragment mass and kinetic energy or total kinetic energy. These quantities may be observed at different correlation angles between the fragments, corresponding to different center of mass velocities for the fissioning nucleus (or equivalent different excitation energies). Another advantage of the method is the detection of all fragments, i.e. also those with extremely long or short half-lives (including stable fragments). Finally, both fragments of the binary process are registered, thus there is no doubt that a complementary fragment exists.

The disadvantages of the method compared to radiochemical methods are mainly connected with the poor mass resolution and the fact that charge numbers are not recognized by the method. A severe disadvantage compared to solid state detectors is the low counting rate due to small solid angles, and compared to radiochemical methods the limited target thickness in order to avoid large energy loss in the target.

Below, the three parts of the proposed experiment is described, the estimates of beam time and details about detector configurations may be found in section 3.

Experiment 1 (Uranium)

The purpose of this part is to study in detail the 600 MeV proton induced fission in natural uranium.The parameters aimed to be determined are those studied by Remsberg et al.[1] at 2.9 GeV. Thus the angular correlation between fission fragment pairs, the energies of the two fragments, the velocity of one fragment and the mass of this fragment will be studied. It will be possible to deduce the excitation energies and momenta of the fissioning systems.

With solid state detectors the angular correlation between fission fragments has been obtained at 590 MeV protons incident on U, Pb and Ag by Brandt et al. [2]. For limited parts of the fission mass region the charge dispersion curve and mass yield has been obtained (see for instance refs. 3 and 4). Also, for some regions the recoil parameters has been studied at the proton energy 600 MeV.

However, the variation of and correlation between the quantities obtainable with semiconductor detectors is not known for the entire fission mass region. Thus it would for instance be of interest to obtain a total mass distribution curve, and to study the competition between symmetric and asymmetric fission as a function of excitation energy.

In conclusion: The proposed experiment 1 would constitue a valuable complement to the experiments already performed with other experimental methods at the CERN SC.

Experiment 2 (Lead)

The purpose of this part is to study in detail the 600 MeV proton induced fission in natural composition lead. The parameters aimed to be determined are the same as those given above in connection with the uranium-experiment. In the case of lead the information already available do not, as far as we know, include fragment kinetic energies, excitation energies and momenta of the fissioning systems. The entire mass distribution has been determined with radiochemical methods $^{5)}$, however this fact will be used to overcome some of the difficulties mentioned earlier in connection with primary fission fragments and secondary fission products. Thus, it will be possible to generate the average number of neutrons emitted as a function of fragment mass using the cumulative-yield method $^{6)}$. Such information is not available , at the proton energy considered, leading to uncertainties in the estimate of neutron emission from the primary fragments.

Another purpose of the lead-study is to compare the experimentally obtained kinetic energy- and mass distributions with calculated ones. In the calculations, the cascade step will be treated with Monte Carlo Methods, similar for the two different evaporation steps. The formation of primary fragments may be calculated with the "dynamic" liquid drop model 7). As properties of primary and secondary products may be extracted from the experiment, it will be possible to test the calculations in some detail with respect to the assumptions made. Such calculations are commonly used to interprete experimental results obtained with intermediate- and high-energy protons.

In conclusion: The proposed experiment 2 would, in addition to the parameters also obtained for uranium, yield the average number of neutrons emitted from the primary fragments. It will also be possible to test some of the assumptions inherent in fission-spallation competition calculations.

Experiment 3 (Pr, Ag, Sr and Cu)

The purpose of this part is to study the fission process induced by 600 MeV protons in some light elements. Here our main interests are angular correlations between fission fragments, differential- and total fission cross sections. The kinetic energy-, velocity- and mass-distributions will only be estimated due to the low counting rates expected.

In fig. 1:3 , the nuclear fissility, i.e. the fission cross section divided with the total cross section, is shown versus Z^2/A for some fissioning systems. (The references given may be found elsewhere 8).) Above $Z^2/A \approx 25$ there is general agreement between γ-, p- and α-induced fission, but below this value considerable scatter occurs. When comparing the experimental values shown in fig. 1:3 it must be noticed that differences exists in the absorption cross sections for the three projectiles. In the case of γ-induced fission the plateau-values in the fission cross sections occur at lower energies than the corresponding plateaus in p- and α-induced fission. Below $Z^2/A \approx 20$ (i.e. Ag) the experimenters have not studied complementary fragments, thus it has not been established that the cross sections given refer to binary fission events or even fission events. The solid curves shown has been calculated by Nix and Sassi 9). The different curves correspond to different values of parameters involved in the calculations.

The proposed experiment aims to determine the angular distribution and total fission cross section for binary fission events. In the experiment, however, also those events giving pulse heights in the fission fragment region but without complementary fragments will be registered. Thus it might be possible to determine the character of the events registered in the γ-induced fission at low Z^2/A values.

The mass distribution in the target mass region considered is unknown. The width of the distribution is expected to be "infinite" 7). The fission fragments might loose their indentity making it impossible to distinguish between fission fragments, spallation- and fragmentation products.

The estimates of counting rates (see section 3) is for natural reasons very uncertain in the cases of Sr and Cu.

In conclusion: The proposed experiment 3 would yield information in a region where the fission process is little understood, and even data with poor statistics could be used to make interesting comparisions with theoretical predictions about the fission cross section, the kinetic energy- and mass-distributions.

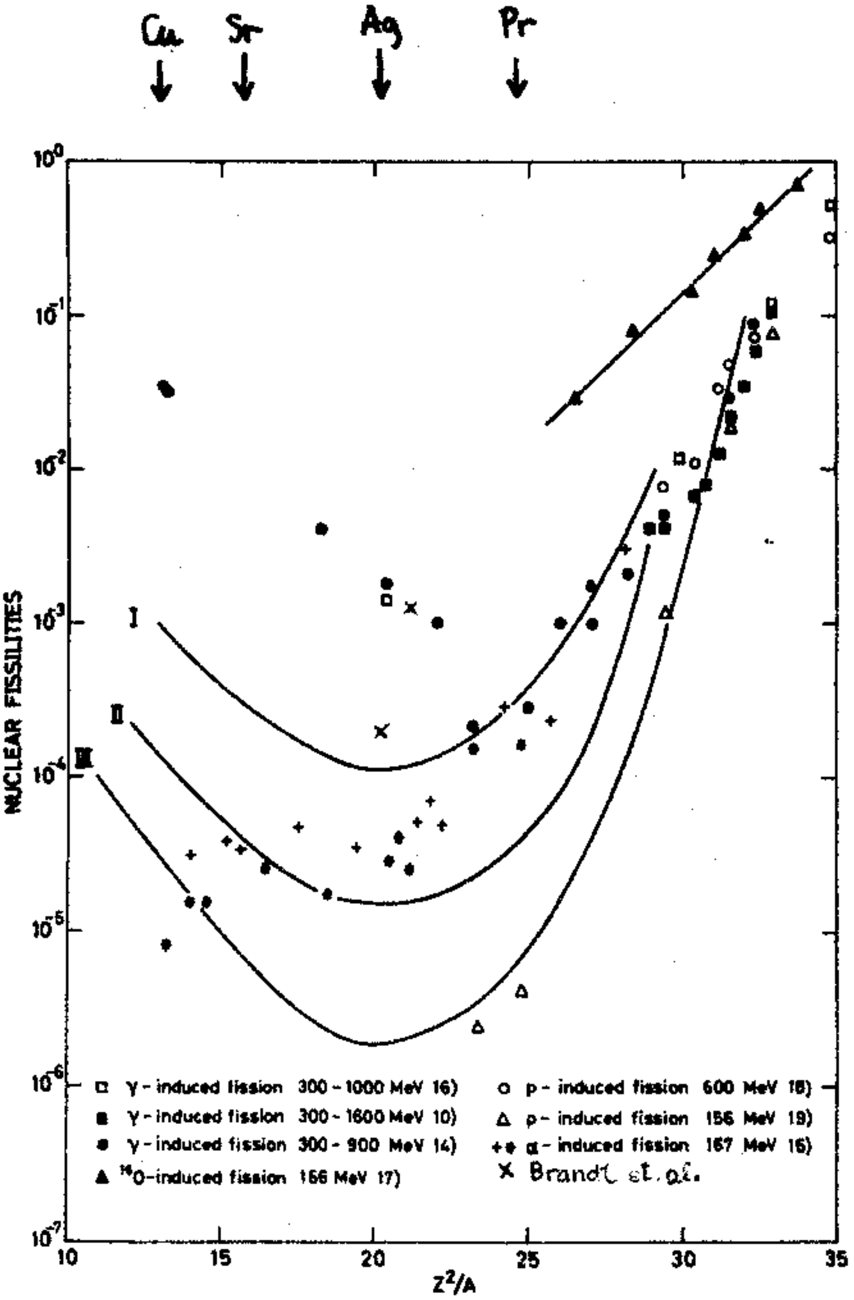

Cu
Sr
Ag
Pr
NUCLEAR FISSILITIES
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
I
II
III
10
15
20
25
30
35
Z^2/A
□ γ - induced fission 300 - 1000 MeV 16)
■ γ - induced fission 300 - 1600 MeV 10)
● γ - induced fission 300 - 900 MeV 14)
▲ ^{16}O-induced fission 166 MeV 17)
○ p - induced fission 600 MeV 18)
△ p - induced fission 156 MeV 19)
+● α - induced fission 167 MeV 15)
× Brandt et.al.

FIGURE 1:3

2 Experimental arrangements

The scattering chamber with detectors is shown in fig. 2:1. Detectors D_4 and D_5 are placed on detector holders, which may be moved to obtain different angles, with respect to the proton beam, as well as different distances to the target. Detectors D_1- D_3 are at fixed positions. The moveable arm for target holders makes it possible to change target element easily and also to calibrate the detectors with ^{252}Cf fission fragments. The options above may be choosen without breaking the vacuum (approximately 10^{-5} torr). When changes of detectors and detector collimators have to be made it is necessary to break vacuum, however, and each such break means an irradiation stop of about 4 hours. It is thus necessary to have a number of pauses during the irradiation, short pauses to change angles, distances and target elements, and longer stops to change detectors and collimators. The approximate area needed to build up the experiment is shown in fig. 2:2, where one part of the electronic system is placed too. In fig. 2:3 a possible location of the experiment in the particle physics area of UR2 is shown as the hatched area.

The electronic system is designed approximately as the system used by Remsberg et al. [1], and most of the components are commercial ones (ORTEC). The fast timing signals needed to obtain the time-of-flight are derived with time-pickoff units inserted directly between the detectors and the preamplifiers. From the experimental area in UR2 5 signals will be obtained: 3 analog signals describing the two energies and th time-of-flight, and 2 logic signals used for gating purposes and to determine from which one of the detectors D_1-D_3 the event originates. These 5 signals may be transported in normal coaxial cables to a remote place where the 3 ADC-units, the interface-unit and the computer used to collect data are situated.

Scattering chamber

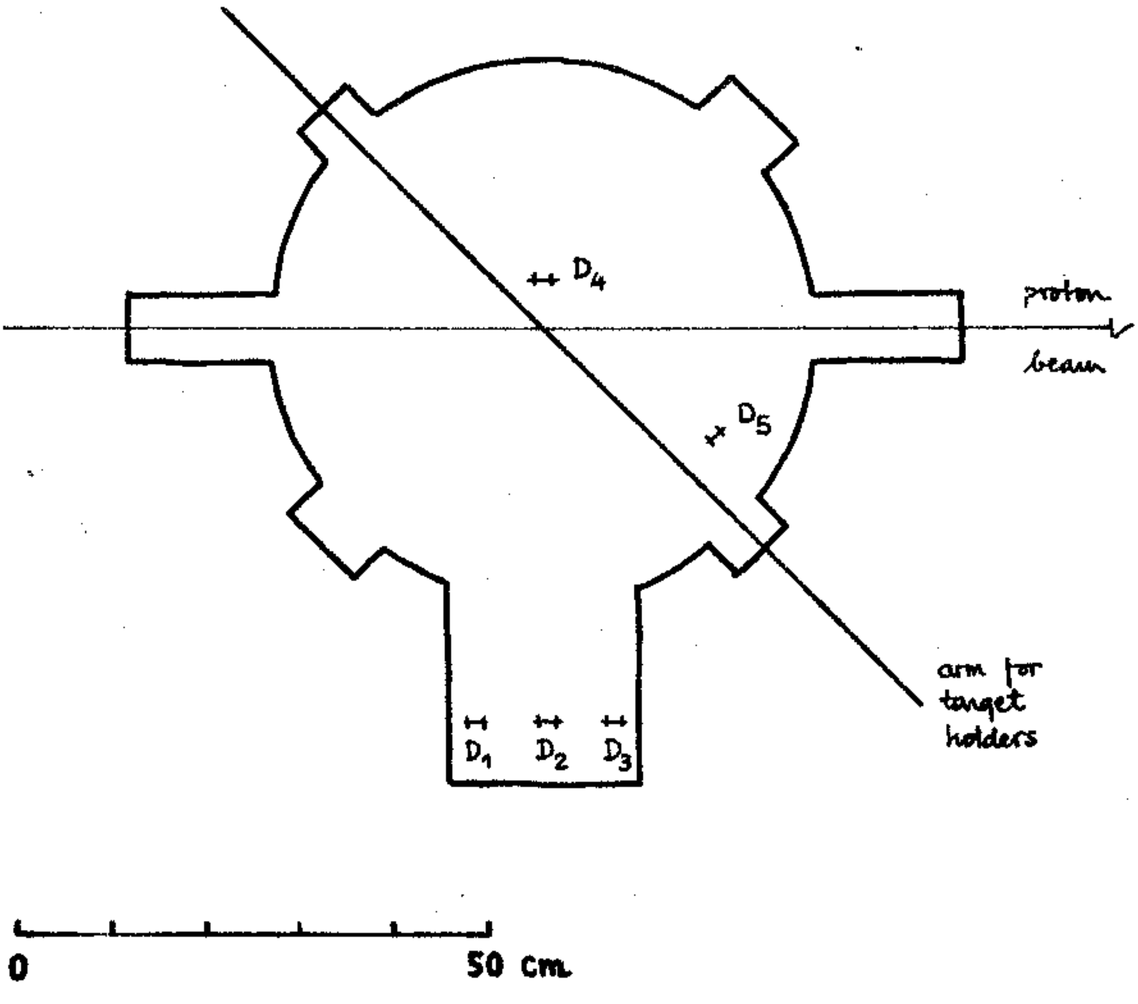


FIGURE 2:1

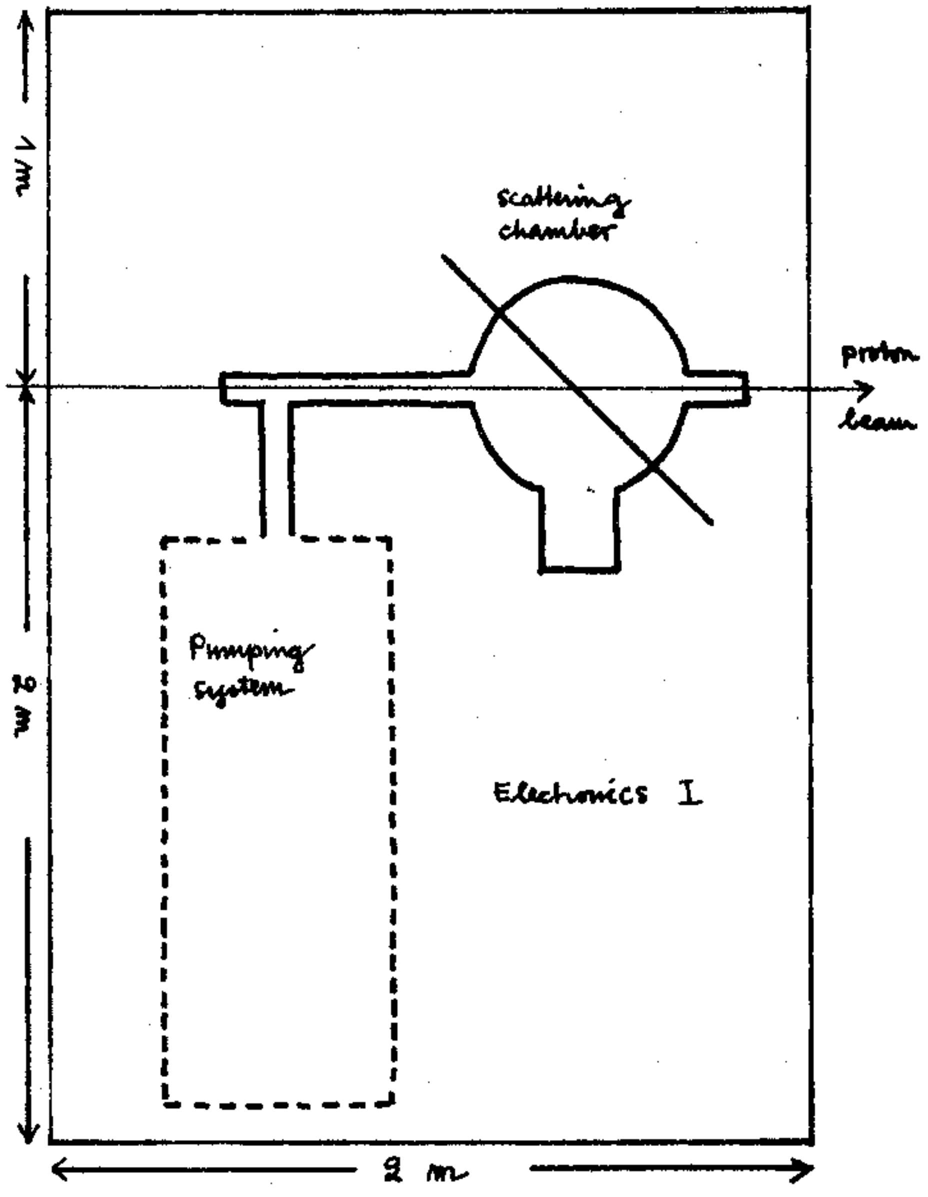
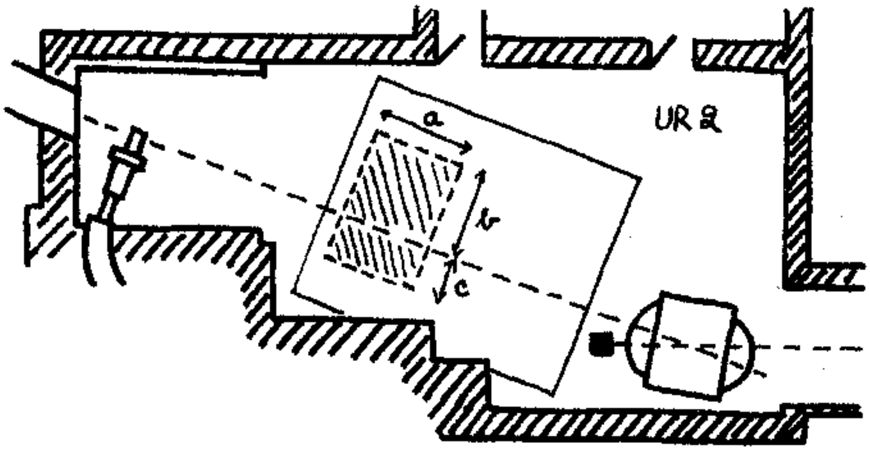

1 m
scattering chamber
proton beam
Pumping system
2 m
Electronics I
2 m

FIGURE 2:2

As we cannot move the IBM 1800 computer used, when the experiment is performed in Lund, it is necessary to have a small computer with a magnetic tape unit accessible during the running period. Also, it is desireable to have some room (preferably with the computer in it) from where we can run the experiment.
Finally, it is desireable to be able to test our equipment, if the experiment is accepted, some time (say half a year) before the actual running period. During this test we would like to observe the behaviour of the detectors when placed close to the beam,,and also to check the interface-unit. The data taking will be simulated in order to test computer programs etc..



a: 2 m
b: 2 m
c: 1 m

FIGURE 2:3

3. Estimates of beam-time

The number of fission fragments registered in a detector D_i, placed at θ° with respect to the beam, may be calculated according to

$$n_i = \frac{q \cdot \Delta\Omega_i \cdot n_p \cdot n_{at}}{\sin\alpha} \cdot \left(\frac{d\sigma}{d\Omega}\right)_\theta \qquad (3.1)$$

where

$\Delta\Omega_i$: solid angle subtended by the detector
n_p : number of projectiles per second
n_{at} : number of target nuclei per cm^2
α : angle between target and beam
$(d\sigma/d\Omega)_\theta$: differential cross section at θ

According to Remsberg et. al. 1) the following relation is approximately true,

$$(d\sigma/d\Omega)_{90^\circ} = \sigma/4\pi \qquad (3.2)$$

not only for fission products but also for other reactions having products in the fission mass region. Thus, at 90° the fragments observed are expected to be an unbiased sample of all products in the mass region characteristic for fission fragments.

The total fission cross sections measured by Brandt et al.2) were used for U, Pb and Ag. For Pr the general relation between the nuclear fissility and the quantity Z^2/A was employed, and for Sr and Cu we simply assume the counting rates to equal those of silver.

In table 3:1 the values of n_{at} (calculated for target thicknesses of 200 $\mu g/cm^2$), σ_f and $\sigma_f/4\pi$ are given. The proton intensity (with duty factor 1) has been limited to $5 \cdot 10^{11}$ protons/sec in order to minimize pile-up effects. A beam spot of 1 cm^2 is used below.

Table 3:1

Target	n_{at}(atoms cm^{-2})	σ_f(mb)	$\sigma_f/4\pi$ (mb sterad^{-1})
UF_4	3.85 10^{17}	1060	84
Pb	5.82	144	11.5
Pr	8.55	1.4	0.11
Ag	11.2	0.4	0.032
Sr	13.8		
Cu	18.9		

For different solid angles it is possible to calculate the counting rate, n_i, according to eq. (3.1). This value of n_i refer to registrations without coincidence-requirements. In order to calculate the coincidence rate the distribution of correlation angles φ between complementary fragments must be estimated. For U, Pb and Ag these distributions have been measured by Brandt et al.$^{2)}$. The coincidence rate in detector D_k within the angle interval φ in relation to detector D_i is then given by

$$n_k^c = n_i \cdot k_\varphi \cdot \frac{\Delta\Omega_k}{\Delta\Omega_\varphi} \qquad (3.3)$$

where k_φ is the fraction of coincident fragments emitted into interval φ and $\Delta\Omega_\varphi$ is the solid angle into which these fragments are emitted.
The different detector configurations used, will be described in the more detailed calculations given below for the different parts of the proposed experiment.

Experiment 1 (Uranium)
This part may be devided into three subexperiments. The angular correlation between complementary fragments is studied in a), the kinetic energy-, velocity- and mass-distributions are investigated for two different φ-values in b), and in c) these quantities are measured with good statistics integrated over all φ-angles.

a) Detector D_4 (see fig. 2:1) at the distance R_4=10 cm from the target center and with diameter d_4 = 5 mm subtends the solid angle $1.95 \cdot 10^{-3}$ sterad. Detectors D_k (D_1, D_2 and D_3) at R_k = 42 cm with d_k = 30 mm subtend the solid angles $4.1 \cdot 10^{-3}$ sterad.

According to eqs. (3.1) and (3.2) the counting rates for the detectors D_k and D_4, without coincidence-requirements, are

$$n_k = 11100 \text{ counts min}^{-1}$$
$$n_4 = 5300 \text{ counts min}^{-1}$$

In this subexperiment the aim is to study the angular correlation function $I(\varphi)$, with detector D_4 at approximately 90°. The estimates are based on a 5° bin width for φ-angles (see ref. 2). Furthermore, we assume that for φ-angles less than 175° the velocity of the center of mass causes the fragment to be emitted only into the shaded parts of the solid angles as shown in fig. 3:1. These shaded areas have been used in the calculations assuming equal probability within each area ($\Delta\Omega_\varphi$). This is not quite correct, but from the experimental results of Remsberg et al. 1) it can be seen, that the procedure used is a good approximation.

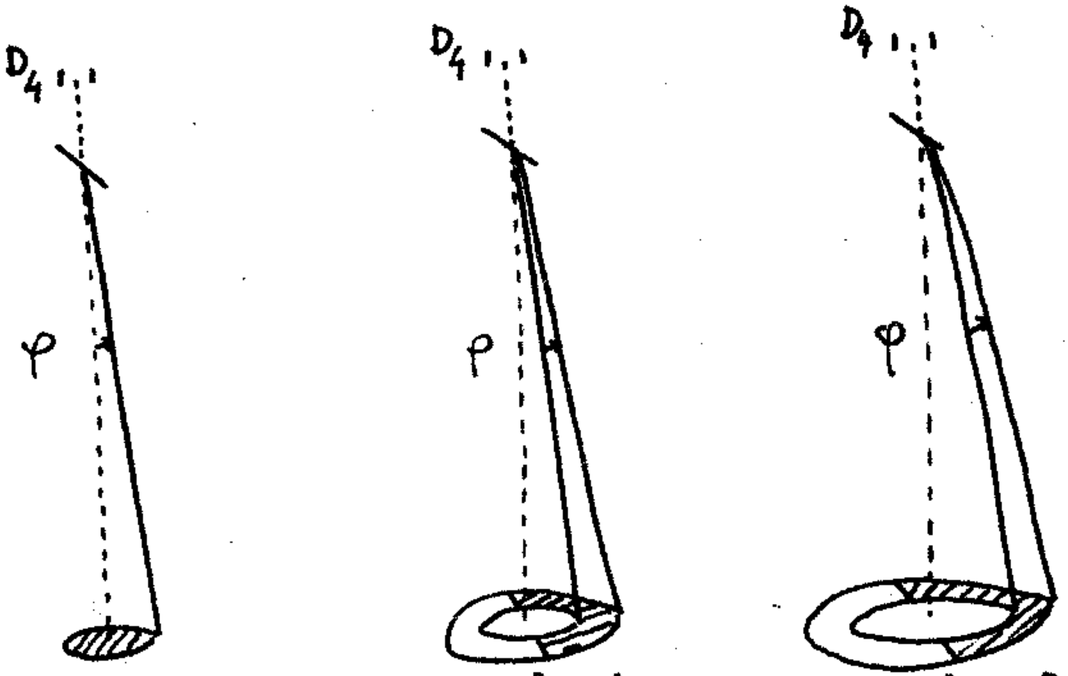
In table 3:2 the estimated coincidence rates are given.

Table 3:2

φ-interval	k_φ	$\Delta\Omega_K/\Delta\Omega_\varphi$	n_k^c (counts$\cdot$min^{-1})
180–175	0.52	0.166	460
174–170	0.28	0.111	170
169–165	0.12	0.067	44
164–160	0.06	0.048	16
159–155	0.02	0.038	5

The total run time for a) is estimated to 8 hours including pauses for changes of angles.

b) Detectors and other parameters as in a). The aim here is to study the distributions of E_k,E_4 and Δt, where E are kinetic energies and Δt the time-of-flight for fragments entering detector D_k. Additional data (with respect to a)) will be taken in the angles φ=180° and 170°. With 4 hours run time, one will obtain approximately 10^4 event for φ = 170°, which should be sufficiently good for our purpose.



180°-175°   174°-170°   169°-165°

FIGURE 3:1

c) Detector D_4 is replaced with a detector having d_4 = 30 mm and R_4 = 5 cm resulting in the solid angle 2.66 10^{-1} sterad, and covering an angle of approximately 32° from the target center.

Detector D_2 at 90° with d_2 = 10 mm and R_2 = 42 cm subtends the solid angle 4.50 10^{-4} sterad. Placing D_4 in an optimal angle (determined in 1a) with respect to D_2, it will be possible to register in D_4 approximately 90 % of the complementary fragments to the ones detected in D_2.

$$n_2 = 1260 \text{ counts}\cdot\text{min}^{-1}$$

With 8 hours beam-time (including vacuum break) about 250 000 events may be collected.

Experiment 2 (Lead)
The program for lead is indentical to the uranium-study described above. With all parameters (distances, diameters etc.) it turns out that the counting rates for lead are about 5 times smaller those for uranium.
Thus, for the same three subexperiments the estimated run-times are (taking stops and pauses into consideration):

a) and b) 28 hours
c) 24 hours

Experiment 3 (Pr, Ag, Sr and Cu)
As mentioned before, the estimated run-times given below are by neccessity uncertain. This part of the proposed experiment may be divided into two parts. First the angular correlation between fission fragments will be studied, and in the second subexperiment the angular distribution of fission fragments (and other fragments giving detector-responses equal to those obtained with coincident fragments) will be investigated. At the different angles the distributions of kinetic energies, velocities and masses will be measured or rather estimated. At 90° somewhat better statistics will be collected.

a) With D_4 at $R_4 = 5$ cm and $d_4 = 20$ mm the solid angle subtended is $1.22 \cdot 10^{-1}$ sterad. Detectors D_k are in experiment 3 placed at $R_k = 20$ cm and $d_k = 30$ mm yielding the solid angle $1.80 \cdot 10^{-2}$ sterad.

$n_4 = 1000$ counts min^{-1} for Pr
$n_4 = 370$ counts min^{-1} for Ag, Sr and Cu

without coincidence-requirements. The distributions of angle-intervals φ are binned in 10° intervals.
In table 3:3 the coincidence-rates in D_1 are presented with k_{φ} according to Brandt et al.$^{2)}$ (the value for Ag were used for all four elements).
With approximately 10^3 events for each target in the φ -interval 159-150 , the estimated beam-time amounts to 48 hours.

Table 3:3

φ-interval	k_φ	$\Delta\Omega_k/\Delta\Omega_\varphi$	n_k^c (counts min^{-1})	
			Pr	Ag,Sr,Cu
180–170	0.45	0.183	70	27
169–160	0.19	0.123	20	8
159–150	0.15	0.076	10	4
149–140	0.11	0.053	5	1.9
139–130	0.10	0.047	4	1.5

b) The angles choosen for the investigation of angular distributions of fission fragments are: 20°, 45°, 90°, 135° and 160°. These angles refer to the position of D_5. The solid angle for this detector is $1.77\cdot10^{-2}$ sterad for R_5 = 20 cm and d_5 = 30 mm. Detector D_4, placed in an optimal angle with respect to D_5, subtends the solid angle $2.66\cdot10^{-1}$ sterad from R_4 = 50 mm and d_4 = 30 mm. The detector D_4 subtend an angle of about 32° and approximately 80 % of the fragments in coincidence with those registered in detector D_5 will enter D_4.

n_5 = 140 counts min^{-1} for Pr
n_5 = 55 counts min^{-1} for Ag, Sr and Cu

All events in detector D_5 will be registered, i.e. also those without complementary fragments in D_4. For approximately 5000 events for each target in the angles 45°–135° and about half this number in 20° and 160° (R_4 = 10 cm) we will need about 56 hours of beam-time.

Summary

A summary of the estimated beam-time and the subjects investigated is given in table 3:4.

Table 3:4

Experiment	Target	Subject of interest	Beam-time
1a	U	$I(\varphi)$ for coincident fragments	8 hours
1b	U	E_i, v_i, m_i versus φ	4 "
1c	U	E_i, v_i, m_i total	8 "
2a	Pb	$I(\varphi)$ for coincident fragments	28 "
2b	Pb	E_i, v_i, m_i versus φ	
2c	Pb	E_i, v_i, m_i total	24 "
3a	Pr,Ag, Sr,Cu	$I(\varphi)$ for coincident fragments	48 "
3b	Pr,Ag, Sr,Cu	$I(\theta)$, E_i, v_i, m_i versus θ	56 "
Tests			6 "
		Total	182 hours

Preliminary time-schedule

Day 1 Access to UR2, 2 hours beam-time, experiment set up
2 Tests
3 Tests with 2 hours irradiation time
4 Tests
5 Tests
6 Tests with 2 hours irradiation time
7
8–15 Experiments in the following order 1a,1b,2a,2b,3a,1c,2c,3b
16 Access to UR2 for packing and cleaning
17 " " " " " " "

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