TOF : proposal for a neutron time of flight facility, European collaboration for high-resolution measurements of neutron cross sections between 1eV and 250 MeV

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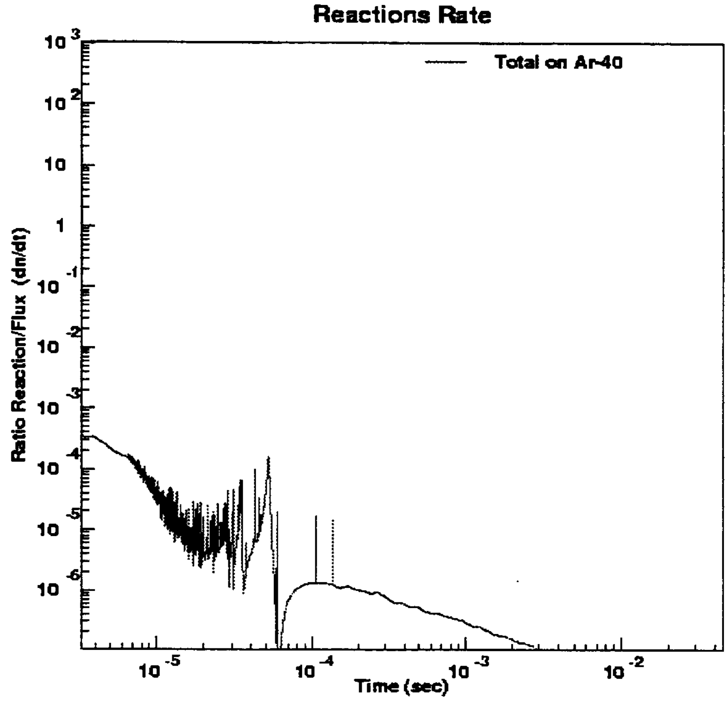

Figure 5.13: Relative Event Rates in 4 mm Argon at 2 bars over 1000 cm² surface.

Unfortunately the composition of the two materials being $C_5 H_4 O_2$ for Mylar® and $C_{14} N_2 H_{14} O_2$ for Kevlar®, the large quantity of Hydrogen will produce more than 1% events due to elastic scattering. To avoid this problem the Mylar® can be purchased in a form where the Hydrogen is replaced by Deuterium and the reinforcement could be made with Carbon fibers showing the same mechanical properties of Kevlar®. The total mass budget of materials, others than the gas, introduced on the neutron path can be fixed as follow: the Carbon fibre walls (2 x 0.75 mm), the Mylar® supports (4 x 10 µm) and the Aluminum metallization (15 µm). In figure 5.14 are reported the insertion losses produced on the neutron beam by the two Carbon walls of 0.75 mm.

Being the contribution of the Mylar® (Deuterium loaded) < 0.2% and that of the metallization < 0.1%, we can conclude that the insertion losses are around 1% of the neutron flux and are produced only by the Carbon walls. This situation is very satisfactory because the assumption to implement a counter with an active circular surface of ø=40 cm is probably only an academic exercise because a so large detector could not be built for reasons others than those concerning a stand alone FF detector.

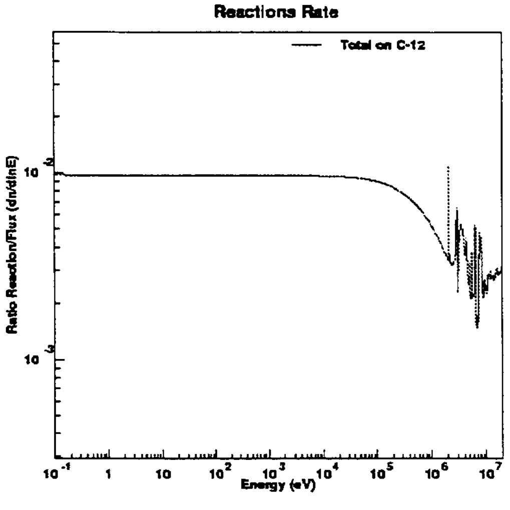

Figure 5.14: Absorption losses in Carbon walls (ø=40 cm)

We have now to evaluate the induced signal available on the chamber electrode. The high voltage is applied to the Anode through a resistor of several MΩ. and the decoupling to the Amplifier input is made with a high voltage capacitor. In response to the ionisation produced by the FFs in the gas, the current rises immediately to a value proportional to the ionisation while its shape and duration are depending on the track angle with respect to the electric field. For the detector filled with Argon, the instantaneous peak current for a FF of 40 MeV becomes:

$$I_{max}=\{(e_{FF}/w) \times q\}/t_d\} =\sim 5.3\ \mu A$$

where: e_{FF} = FF energy = 40 MeV, w = energy necessary to produce a free electron =~ 30 eV, q =electron charge = $1.6\text{x}10^{-19}$ C, t_d = drift time = $40\text{x}10^{-9}$ s. This current is sufficient to produce a large noise-less signal after amplification.

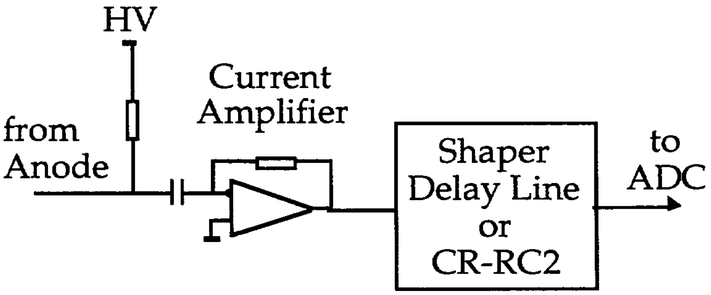

Figure 5.15: Front-end Electronics.

In figure 5.15 is presented a sketch of the front-end. The role of the Shaper is to subtract the base-line eventually introduced by the large background expected for radioactive targets. The analog signal at the Shaper output can be sent to the Analog to Digital Conversion for digital storage. This information can be used, after discrimination, to veto the capture cross section detectors and, therefore, avoid the background induced by the gamma flash produced by the fission reaction.

As already mentioned it will be certainly necessary to fragment the detector surface to avoid a too large event rate for both fission reactions or back-ground. If we consider the problem of the detector fragmentation from a strict geometrical point of view, it appears that is possible to reach a fragmentation up to 128 cells with a detector surface occupancy of ~1000 cm^2 corresponding to 80 % of that of the nominal neutron spot.

Let's now consider the detector fragmentation from a physical point of view. The simulations reported in [5.11] [5.12] normalised to a single PS shot of ~ 0.75×10^{13} protons for the small lead target followed by a hydrogenous moderator, are helping to define the event rates. Following the results reported in [5.6] obtained on a detector used in a previous experiment and based on the same principle proposed here, the target density should not exceeds 0.3 mg/cm^2 to guarantee the clear separation of the FF from back-ground. In Table 5.1 are reported the expected yields for some interesting low radioactive elements. The high density of events appears, as expected, in the high part of the energy spectrum during the first 10-15 µs after the beam shot. A fragmentation of ~20 is sufficient to avoid the pile-up on a single channel.

Element	Max. Fission Rates [MHz]	Fission Reactions [per shot]	Fission Reactions [per day]
^{233}U	18	1.2×10^4	6×10^7
^{235}U	12	7.2×10^3	4×10^4
^{247}Cm	18	5.1×10^3	2.5×10^7
^{237}Np	15	1.6×10^2	8×10^5
^{239}Pu	18	2.3×10^4	1.1×10^8
^{242}Pu	14	1.3×10^2	6.5×10^5

Table 5.1 *Expected Yields for 1000 cm^2 Targets of 300 mg.*

The situation is completely different for highly radioactive elements reported in Table 5.2, for which the constraints are of two kinds: the max. background that allows the FF recognition in the counter and the radiation safety rules. Concerning the detector running, a radioactivity of 5 mCi seems the upper limit for a single counter (see fig.5.12). The limitations given by the safety must be considered for each element and are depending on radioactivity other than alpha.

Element	Weight [mg]	Fission Reactions [per shot]	Fission Reactions [per day]
^{241}Am	1.46	1.5	7.5x10^{3}
^{242m}Am	0.47	17x10^{2}	8.5x10^{6}
^{243}Am	25	1.2x10^{1}	6x10^{4}
^{243}Cm	0.1	6.4	3.2x10^{4}
^{244}Cm	0.06	0.05	2.5x10^{2}
^{245}Cm	29.4	1.5x10^{4}	7.5x10^{7}
^{246}Cm	16.1	9.2	4.6x10^{4}
^{238}Pu	0.3	0.57	2.8x10^{3}
^{240}Pu	21.7	1.4x10^{1}	7x10^{4}
^{241}Pu	0.05	0.38	1.9x10^{3}

***Table** 5.2 Expected Yields for 5 mCi Targets .*

For highly radioactive elements, the solution to reach a satisfactory statistic while keeping the total target radioactivity at reasonable levels, will be to measure these elements at a shorter distance. More generally all these parameters have to be carefully evaluated concerning the background produced by other ionizing particles than alphas and also concerning the spontaneous fissions that must be low compared to the neutron induced events.

To conclude, the proposed detector seems to be very well suited for measuring the shape of the FF cross section in the range 1 eV to 250 MeV. The time resolution of ~2 ns, consistent with the timing of the proton source and the $\Delta\lambda$ of the lead target, allows an energy resolution better than 10^{-3} at 1 MeV. The large signal produced by the ionization allows the use of a very simple front-end electronics and, therefore, the possibility to have a large detector fragmentation to enhance the statistics in case of highly radioactive elements. The low mass and the efficiency close to 100 %, are making this kind of detectors ideal as a part of a complex assembly for the measurement of the capture cross section.

5.B.3 – FISSION CROSS SECTION MEASUREMENTS IN YEAR 2000.

The groups of CERN and Orsay have proposed two types of detectors for fission (see 5.B.1 and 5.B.2). These detectors can be ready and calibrated at ILL-Grenoble by April 2000. They can perform the first cross section measurements on standard targets : ^{235}U and ^{233}U and possibly on ^{239}Pu. For neutron energies below 100 keV, they will serve to establish the overall perfomances of the neutron beam, the energy resolution of the TOF and the background levels at the depths between the resonances. These elements will also serve to have the first spectroscopy of the resonances in the unresolved region above 100 keV. Fission measurements will be done also on some so called non fissile elements as ^{238}U, ^{232}Th, ^{237}Np, allowing to explore the higher neutron energy region through their threshold cross sections. Using 0.3 mg/cm^2 on 50 cm^2, the counting rate per day and per energy bin corresponding to a resolution of 2x10^{-4} are shown in Figure 5.16.

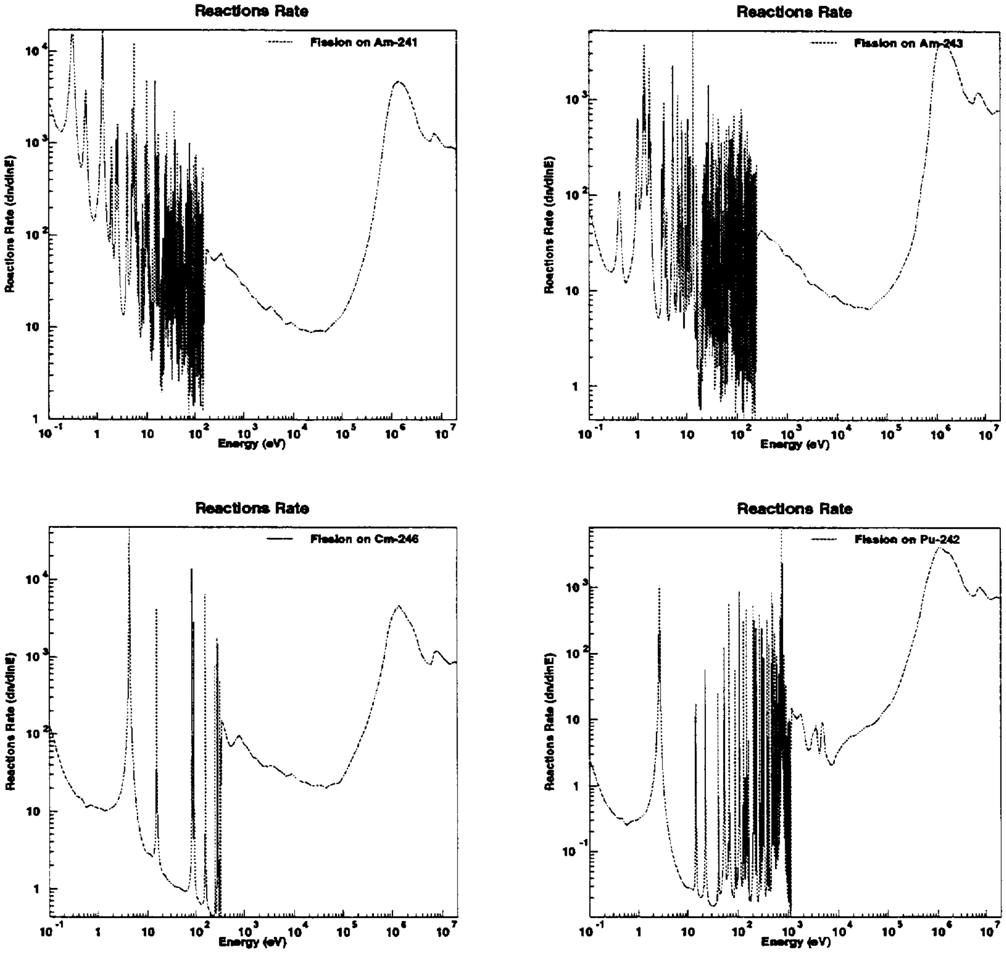

Figure *5.16 : The simulated fission rates for a 10 days run and per energy bin corresponding to a bin-width of 0.05*E_n or 50 bins per energy decade.*

Neutron-induced fission cross sections of minor actinides like Am, Pu or Cm are important for justification of different ways of nuclear waste transmutation and deep burn-up strategies for modern fuel cycle. Those are also necessary as an input information for creation of complete fission cross section systematics (FCS). Experimental data are available only in relatively narrow energy regions and have large discrepancies. The main part of the evaluations is based on statistical models tested with only low energy data. Therefore, any predictions of FCS cannot be done with satisfactory accuracy without special systematical measurements of FCS. There exist two measurements of ^{243}Am cross section below 50 eV, by Knitter et al [5.13] at GELINA and by Zamyatnin et al. [5.14] in Dubna. Fission widths extracted from these two measurements contradict with each other by a large factor. The background difficulties have been attributed to the spontaneous fission (SF) of the ^{244}Cm (0.05 atoms per cent) contamination and, mainly, to the characteristics of the IBR-30 booster, having permanent background between pulses (due to the multiplication of the delayed neutrons into the plutonium core of the booster). This type of background will be absent at the CERN-PS beam. The flight time of a 0.1 eV neutron for 200m is about 50 ms, resulting in a suppression of a factor of more than 300 of the background related to the ^{244}Cm contamination.

For ^{242}Pu there are no measurements below 50 eV, while data below 1 keV differ by an order of magnitude [5.15, 5.16]. In the ^{242}Pu measurements the main background will be caused by the fission of the ^{241}Pu (0.3%) contamination, but the very high resolution of the CERN-PS gives the possibility to separate the resonances of the two plutonium isotopes by time of flight.

EXPERIMENTAL METHOD	Multiplate/multisectional fast ionization chamber with alpha background suppression
ENERGY REGION	1 MeV — 200 MeV
TARGETS	Circular layers of high-purity Neptunium, Americium, Plutonium and Curium isotopes 10-100 μg/cm^2 thick, covered with 30 μg/cm^2 thick gold
ISOTOPES	^{237}Np, ^{241}Am, ^{243}Am, ^{242}Pu, ^{246}Cm (available in 2000-2001)
MONITOR	^{235}U or ^{239}Pu ; back-to-back geometry
CALIBRATION	Preliminary measurements at IPPE, Obninsk, EGP-15 accelerator with t(d,n) pulsed neutron source with energy up to 30 MeV; determination of numbers of nuclei in fissile targets with isotopic dilution method and alpha-spectrometry.

Like other even actinide isotopes, the fission cross sections of ^{242}Pu and ^{243}Am exhibit a threshold-type energy dependence, resulting to very small cross sections, typically barns for the strongest resonances. The high flux and the resolution of the CERN-PS source gives the possibility to study the level structure in the sub-barrier region and extract the parameters of the levels in the second potential well.

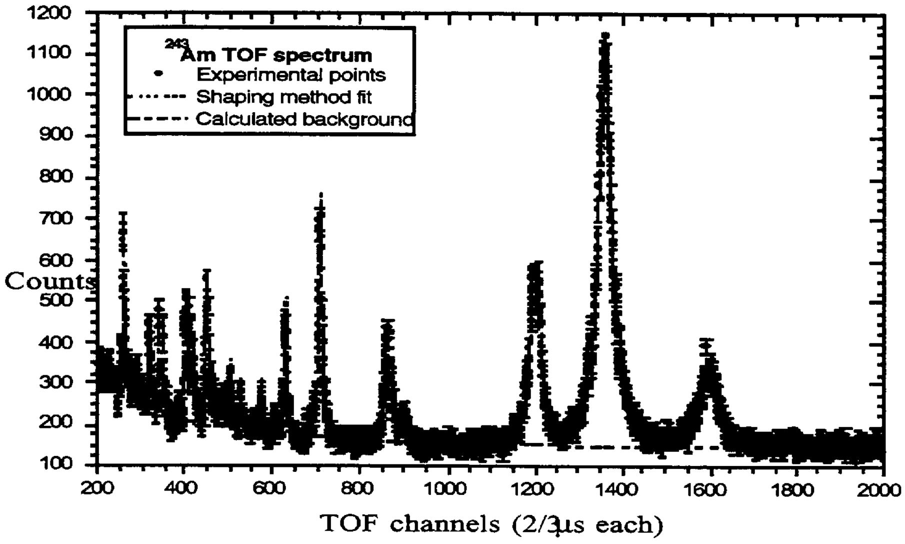

***Figure** 5.17. The ^{243}Am TOF spectrum measured at the IBR-30 booster in Dubna for a flight path of 15 m. The shown part of the spectrum covers the neutron energy interval from 0.8 to 50 eV.*

The FLNP/JINR and the Obninsk groups intend to measure in the next 2 years the five nuclides listed below using an experimental technique developed already at IPPE and used in the measurements done at the IBR-30 reactor in Dubna for ^{243}Am [5.14]. In these experiments, the mass of the sample was about 2 mg and about 10^5 events in the energy interval from 1 eV to 10 eV were recorded (see Figure 5.17). "*Fresh*" targets will be prepared in 1999 and the experimental set-up will be adopted to better match the CERN TOF conditions. Moreover, they propose for the year 2000 to measure the fission cross sections ratio ^{237}Np/^{235}U in the neutron energy range 1-200 MeV. The experimental equipment will be tested using the ns-pulsed fast neutron sources of the IPPE in the energy range from 0.5 to 30 MeV and the IBR-30 resonance µs-neutron source of the Frank Laboratory of Neutron Physics. Target layers of ^{243}Am, with a total mass of 10 mg (5 layers of 2 mg each) are already available, while the ^{242}Pu sample has a mass of 30 mg.

5.C - NEUTRON CAPTURE REACTIONS.

When an (n,γ) reaction occurs, a cascade of gamma-rays is promptly emitted. Depending on the atomic mass of the nucleus, there can be from ~102 to ~104 possible de-excitation channels with gamma multiplicity averaging around 3 or 4. The cross section of the process can be determined by counting the number of cascades resulting from the target irradiated with a known neutron flux assuming that the detector efficiency is also known. The efficiency is usually measured in a calibration experiment with ^{197}Au as a target.

The most important feature of such measurements is that capture events have to be detected independent of the multiplicities of the repective gamma-ray cascades. Therefore, the following two extreme experimental approaches are possible: a) to use a detector with nearly 100% efficiency for all gamma-rays (total absorption detectors), and b) to detect only one gamma-photon from each cascade (then a detector with a very low efficiency, ~1%, is needed) but with the efficiency proportional to the gamma-ray energy (Moxon-Rae method [5.17]). An intermediate solution is also known. It assumes the use of a detector with ~10% efficiency and correction of each pulse amplitude with a weighting function [5.18].

Among other parameters, low sensitivity of the detector to neutron background is very important. This implies a careful choice of the detecting medium, as well as the capability to distinguish between (n,γ) and (n,f) reactions. The latter can be achieved, although not with a 100% efficiency, by measuring the cascade multiplicity (it is possible in some total absorption detectors that enable detection of the individual gamma-rays) or by anticoincidences with an additional fission fragment detector surrounding the target (see section on fission fragment detectors).

A time resolution better than ~10 ns and counting rate up to ~1 MHz are also desirable to profit from the high neutron flux and the good neutron TOF resolution. When radioactive target isotopes are investigated, the corresponding gamma-ray background will distort the measurements. However, it can be rejected if the detector energy resolution is good enough.

Among the existing capture detectors we consider the following :

1) For stable isotopes available in large quantities (~some mg to grams), those based on the Moxon-Rae principle ([5.19] is an example) seem to be

the most suitable due to the low sensitivity to neutrons and the potential possibility to operate them in current mode thus enabling high data acquisition rates.

2) For stable isotopes in small quantities or samples with low radioactivity, the liquid C_6D_6 scintillation detector with pulse height weighting can be used [Geel] as it enables, to some extent, rejection of gamma-ray background and is also very little sensitive to neutrons.
3) In the case of highly radioactive and fissile isotopes, the total absorption detectors, such as BaF_2 Crystal Ball [5.20] and NaI(Tl) "Romashka" [5.21,5.22] with good energy resolution would be the best choice. The HPGe 4π cluster detector with excellent energy resolution should also be considered [5.23]. New developments combining Micromegas photodetectors [5.24] with BaF_2 scintillators seem to offer a promising and rational path for the solution of high instantaneous rates, with the additional advantage of a low sensitivity to scattered neutrons.

Also new detection techniques may significantly contribute to improve the detector setup for neutron capture measurements. Far from pretending to mention all of them, we would refer new developments on a CeF_3 scintillator which has a very low sensitivity to neutrons [5.25] and total absorption liquid xenon gamma-ray detectors: a 4π segmented TPC with high position resolution or a very fast scintillation calorimeter with high energy resolution [5.26,5.27], especially advantageous for the experiments when a large detector is required.

5.C.1 – CAPTURE CROSS SECTION MEASUREMENTS IN 2000.

A neutron capture measurement to be performed in the first starting phase of the CERN TOF facility, i.e. in the years 2000 to 2001, should possibly comply with the following characteristics :

- The chosen isotope should be important for one of the research fields mentioned in Ch. 3. Since the funding of the detector station and associated infrastructure would be provided by the EC Fifth Framework Programme, the ADS field should be privileged.
- The measurement should emphasize the "added value" of the facility in comparison with the present ones.
- The gamma detectors should be the simplest of the existing detectors under operation at other TOF facilities.
- For checking purposes, at least part of the cross sections and/or resonance parameters of the chosen nuclide should already be rather well known.

- The measurement should be rather straightforward, thus avoiding the most difficult cases such as fissile or very radioactive isotopes .
- The sample should be readily available.

A possible candidate would be ^{232}Th, of interest for ADS and thorium fuel cycle in general. There are at least two reasons for this choice : first, the isotopes of interest for the Th fuel cycle have not received the same attention as those of the U-cycle. In the data files released in the nineties, the resolved region for ^{232}Th extends only up to 4 keV as compared to 10 keV for the case of ^{238}U, which however has a comparable level density. A capture measurement at 200 m flight path with a resolution of $1.5\text{x}10^{-4}$ would fill this gap. Secondly, there are even discrepancies up to 15% between the average ^{232}Th capture cross sections in the various data files above ~50keV.

The ^{232}Th (n,γ) reaction from thermal up to 200 keV is presently measured by a collaboration between FZK Karlsruhe and IRMM Geel. The CERN measurement, besides providing the better resolution as already stated, has also the advantage of being unaffected by the γ-activity of the sample which is a serious problem for the Geel measurement. Finally it should be noted that an extension of the resolved region up to 10 keV will probably require also a high resolution transmission measurement considered in section 5.E. Similarly, the capture cross sections for the elements ^{238}U, ^{237}Np, ^{99}Tc, ^{93}Zr, of interest for the ADS studies, are considered together with the well known targets used as standards, like ^{nat}Ag and ^{197}Au.

For these first measurements it is proposed to use "total energy" detectors, i.e. scintillators in which the proportionality of the detection efficiency to the total radiative energy emitted is achieved via a pulse-height weighting method. If the primary goal is a very low efficiency to scattered neutrons, the best choice is a deuterated hexabenzene (C_6D_6) based liquid scintillator : this kind of detector is currently used at the main existing TOF facilities, namely ORELA (Oak Ridge), LANSCE (Los Alamos) and GELINA (Geel). It is advisable to use scintillators canned in thin aluminium cylinders of 10 cm internal diameter and 7.5 cm height : for such a size, a pulse-height weighting function has been experimentally measured, and tested, at Geel.

The main experimental parameters would be as follows :

- Flight distance : 230 m.
- Beam and sample size : circular, 8 cm diameter corresponding to 50 cm^2.
- Sample thickness and type : ~10 mg /cm^2 .

- Detectors : four C_6D_6 scintillators of size as above, placed with their axis perpendicular to the neutron beam and with the entrance windows at ~6.5 cm from the sample centre.
- Neutron flux monitor in-beam, e.g. thin ^{10}B ionization chamber available at Geel, placed ~0.8m upstream.

The counting rates are estimated by simulation and compared to the results of a similar capture run performed at Gelina on a considerably shorter flight path, taking into account that in the year 2000 the proton pulse will consist of a single burst every 14.4s. Under this assumption, one can estimate (Fig. 5.1) that the total capture rate amounts to 7.5×10^6 and 17×10^6 per day for a 50 cm^2 and 100 mg/cm^2 sample of ^{232}Th and ^{233}U, respectively.

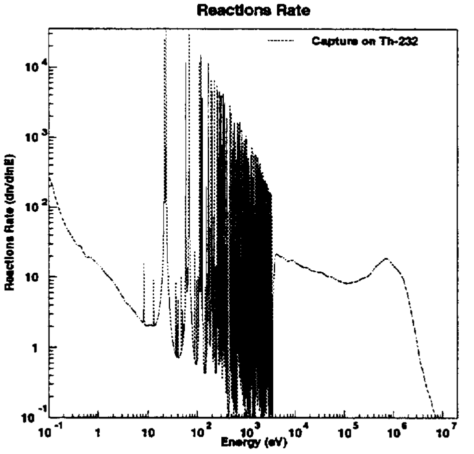

Figure 5.18: The simulated capture rates per day and per energy bin corresponding to a resolution of 2×10^{-4} or 12'000 bins per energy decade.

The instantaneous counting rate of the CERN TOF facility at 200 m flight path do not exceed 10 MHz for the example of ^{232}Th. The very fast decay time of the scintillator (3 ns) combined with fast photomultipliers and a standard Particle Physics FADC-VME data acquisition system allows this measurement without rate problems.

5.C.2 - SECOND PHASE MEASUREMENTS.

The desirable features of an ideal gamma ray detector for use in neutron capture cross section measurements, particularly by TOF techniques are :

- an efficiency for the detection of a capture event, which is independent of the particular gamma ray cascade emitted.
- low sensitivity to the scattered neutrons.
- fast response.
- low intrinsic background and ease of shielding.

In general, the main criteria in the choice of the type of such a calorimeter are its sensitivity to direct but also to scattered neutrons, its pulse rise time and the speed of the readout devices.

The best identification of neutron capture events is provided by the total energy of the capture γ-cascade. This requires a large solid angle (>90% of 4π) detector that operates as a calorimeter. With a γ-ray efficiency of better than 90% in the entire energy range below 10 MeV, capture events can be registered with almost 100 % probability. A typical example of such a detector is the design of the Karlsruhe 4π BaF_2 detector [5.20]. A similar large solid calorimeter, consisting of CeF_3 crystals, has been discussed by the Grenoble group [5.25]. The main arguments for the CeF_3 crystals are the faster decay time and the four times smaller sensitivity to the prompt neutron reactions.

New developments on particle detection techniques can contribute significantly to improve performance of the gamma-ray detection system. Liquid noble gases are very suitable for the detection of gamma-rays with high efficiency, especially liquid xenon due to large atomic number (Z=54), high density (3g/cm^3), excellent scintillation properties and the possibility to collect free electrons released by an ionising particle. Therefore, two types of a 4π liquid xenon total absorption detector are considered. First, a liquid xenon scintillation calorimeter with full direct light collection, similar to the one proposed in [5.27], can provide high energy resolution (about 4% at 1 MeV), time resolution better than 1 ns and counting rates up to several times 10^6 Bq. On the other hand, the experience accumulated on liquid xenon ionisation detectors self-triggered by xenon scintillation [5.26,5.28] allow also a highly segmented liquid TPC to be considered. Although limited in counting rate to ~10^5 Bq, its precise position resolution and the possibility of the whole event reconstruction makes the latter device a powerful tool for active neutron background rejection. Liquid argon should also be considered due to exceptionally low neutron capture cross section of its principal isotope, ^{40}Ar, that makes such a detector incomparably superior to any other 4π gamma-detector in terms of sensitivity to neutron background.

A key problem in the experiments with radioactive samples is the efficient detection of multiple gamma rays induced by neutrons in the presence of a large background of low energy gamma rays from radioactive targets. With values foreseen for the background intensity, like 10^9 Bq, we are naturally inclined to look into the potential opened by recent research on fast detectors for the high luminosity colliders. The application of fast photosensitive chambers, e.g. Micromegas, as massless photomultipliers has been considered by the group of G. Charpak for both crystal and liquid calorimeters. A combination of the Micromegas detector [5.24] as a photon detector with solid BaF_2 (CeF_3) or liquid noble gas scintillators seems to offer a promising and rational path for the solution of the problem, with the additional property of offering a low sensitivity to the background of scattered neutrons.

Concerning the gamma spectroscopy, the contribution of the ILL group [5.23] supplying a HPGe-detector array has been studied in relation to shielding and neutron background problems with encouraging results. The utilisation of this detector array would be particularly interesting for the gamma spectroscopy of fission fragments from (n,f) reactions, in particular for targets with small inherent gamma radioactivity.

Neutron capture studies on radioactive targets are hampered by the background from the sample activity. Although spallation neutron sources have not often been used for measurements of radioactive samples so far, their huge fluxes allow to reduce the sample mass by a factor of more than few 10^3 compared to the traditional facilities. In the case of a radioactive sample, the following background sources can be distinguished. a) Gamma-rays from the nuclear decay, typically with energies below ~1 MeV and fluorescent X-rays below 100 keV and b) Bremsstrahlung from beta activity (both internal, IB, and external due to passage of the beta particle in the surrounding materials).

Beta particles are slowed down by radiative processes as well as by collisional Coulomb interactions (ionisation and excitation). Radiative losses are always a small fraction of the energy losses due to ionisation and excitation and are insignificant in absorber materials of low atomic mass. The ratio of the specific energy losses of beta particles is given approximately by :

$$\frac{\left({}^{dE}\!/_{dx}\right)_{Brems.}}{\left({}^{dE}\!/_{dx}\right)_{Coll.}} \cong \frac{E \times Z}{700}$$

where E is in units of MeV. The cross section for radiative losses is given by

$$\frac{d\sigma}{dE_\gamma} \approx 5\frac{e^2}{\hbar c} Z^2 \frac{1}{\beta^2} \frac{r_e^2}{E_\gamma} \ln \frac{m_e c^2 \beta^2 \gamma^2}{E_\gamma}$$

where β (γ) is the velocity of the incident electron and Z is the charge of the nucleus. Note, that the cross section falls off with increasing photon energy roughly as 1/E. For the majority of the radioactive elements of interest, the maximum energy of the electrons does not exceed 1 MeV and therefore the bremsstrahlung in the sample is not expected to contribute significantly to the background rates seen by the calorimeter. On the other hand, the detector can be easily shielded from beta-particles with a low mass material without taking a risk to produce bremsstrahlung (for example, 2 mm of Be is enough to stop 1 MeV electron).

In respect to radioactive samples with inherent gamma emission, the mass of the sample depends on the specific activity of the isotope under study and the pileup rejection of the detectors and readout electronics. The probability that a given count is formed from the pileup of x+1 gammas is :

$$P(x) = e^{-R\tau}(1-e^{-R\tau})^x \approx \frac{x}{x!} R\tau \cdot e^{-R\tau}$$

where R and τ are the rate and the scintillation decay time, respectively. For a pileup level of 3%, each calorimeter module would accept a rate of ~10 MHz, ~0.5 MHz, ~50 kHz and ~25 kHz for a $(BaF_2)_{fast}$, a CeF_3 or LXe, a BGO and a $(BaF_2)_{slow}$ scintillator, respectively. Taking the BaF_2 Crystal Ball as an example of the 4π detector design reference, one can estimate that for a capture event with the average multiplicity of 3 about 7% of the individual detectors are hit. This allows the maximum sample activity to be estimated to ~4 mCi, ~200 μCi, ~20 μCi and ~10 μCi for the equivalent scintillator materials.

MATERIAL	Density [g/cc]	Attenuation length, AL, at 6 MeV [cm]	Decay time [ns]	Rel. light output	n-captures in 5 AL per pulse / cm^2 at 200 m
$PbWO_4$	8.28	2.98	5 - 15	0.01	28'833
BaF_2	4.89	6.01	0.7 (20%,fast) 620 (80%,slow)	0.05 0.20	8'613
$Bi_4Ge_3O_{12}$	7.13	3.59	300	0.15	4'145
CeF_3	6.16	4.77	10-30	0.10	2'138
LXe	2.95	9.18	27	0.90	

***Table** 5.1: Properties of several inorganic crystal scintillators. The number of captures correspond to an energy range between 0.1 to 2x10^7 eV according to the neutron spectrum at the CERN TOF Facility.*

However, the well known pulse-shape of the two slow scintillators BGO and a $(BaF_2)_{slow}$ can be off-line reconstructed, once the first part of the pulse is free of pileups and measured at several points. The utilisation of flash ADC's with 10 ns clock allows to have 10 points in the first 100 ns of each pulse. By fitting the known pulse shape the corresponding gamma energy can be extracted by resolving the pileup pulses. This off-line analysis would correspond then to a pileup resolution of ~100 ns. In particular the BGO and $(BaF_2)_{slow}$ crystals with long decay times would run with higher sample activity, i.e. 120 μCi, at the same 3% pileup level, which is determined now exclusively by the 100 ns pileup resolution of the electronics.

In conclusion, the intrinsic activity of the radioactive samples in the case of nanosecond fast calorimeters, as $(BaF_2)_{fast}$, can be 4 mCi, whereas for the BGO and $(BaF_2)_{slow}$ it should not exceed ~5 MHz or 120 μCi per detector module. This means that the total acceptable rate would increase with the granularity of the detector.

Most of the radioactive targets under consideration have appreciable yields only for gamma energies below 100 keV. For these cases the activity of the radioactive sample could be even higher than estimated above. Firstly, such low energy gammas can be absorbed by a set of appropriate adsorbers (filters), for instance 1 mm Cd and 0.25 mm Cu for 70 keV gammas. Secondly, it can be seen that the pileups of such low energy gammas will induce an overall baseline, which can electronically be eliminated, because its level is much smaller compared to the total gamma energy deposited in the calorimeter from (n,γ) events ($\Sigma E_\gamma >$ 1-2 MeV). The total gamma energy of (n,γ) events equals the binding energy of a neutron in the compound nucleus being studied, plus the kinetic energy of the incident neutron. In such cases, the sample activity can reach the level of 30 mCi where the gammas of the ^{135}Cs with E_γ<30 keV arise from internal and external bremsstrahlung and the 662 keV gammas are due to the ^{137}Cs contamination amounting to 10^{-3} (see chapter 4).

Since the statistical fluctuations of the baseline appear at the lower frequency spectrum than the pulses of the true capture events, the use of a highpass filter would reduce and smoothen these baseline fluctuations. In conclusion, for radioactive targets with gammas below ~100 keV, pileups can be tolerated without deteriorating the measurement of neutron capture events by detecting the total energy of the capture gamma cascade ($\Sigma E_\gamma >$ 1-2 MeV) in a large solid angle (90% of 4π) calorimeter.

In respect to the photosensitive readout device, recent tests at Saclay and Collège de France have shown that the Micromegas, with a He gas filling with 6% of isobutane at atmospheric pressure, permits to detect single photoelectrons, with a gain of 10^7, and a good pulse height resolution - for single electrons in a proportional mode - which is reached by no other detectors. The timing of the detector has been shown to be of the order of one nanosecond. In particular, the combination of BaF_2 and CsI has already been studied by J. Seguinot et al. [5.29]. We will have to choose between two strategies:

a) Reflective photocathodes deposited on the outer side of the thin grid, of 4μm thickness, which limits the amplification volume of Micromegas.
b) CsI photo cathodes deposited directly on the exit face of the BaF_2 crystal.

The BaF_2 crystals have a fast emission of VUV light, peaked at 225 nm, with a yield of 560 photons per MeV. With a reflective photocathode the maximum observable signal is limited, by total internal reflection to about 11.6% per face, i.e. 4.6 photoelectrons per MeV per face. But an additional loss by a factor two due to transparency of the grid has to be taken into account. Notice that the face can be placed at a distance of 100μm from the entrance grid of the amplifying space. With crystals of $1x1cm^2$ section practically all electrons ejected from the CsI photo cathode deposited on the grid are detected. We may then expect a 100% efficiency for gammas above 1 MeV and a reduced efficiency for photons with an energy of the order of 0.2 MeV from the radioactive targets. A transmission photocathode, deposited directly on the crystals surface, would avoid the problem of losses due to internal reflection, but it would not increase the detected signal because its quantum yield is only 10% of the reflective cathode yield.

We are then lead to the study of a well defined detector:

- Crystals of BaF_2 of 8 cm length and 1x1 cm^2 section with about 1 m^2 surface.
- A mosaic of Micromegas detectors of 20x20 cm^2 with a gas filling of He and 6% of Isobutane.
- The VUV light pulses have a duration of 0.6 ns and the Micromegas detector has a time resolution of about 1ns.
- For a gamma energy of 1 MeV there are 3 photoelectrons detected
- The counting rate per crystal and per pad, due to a 10 GHz background, is 100 kHz which is rather low and permits the use of low noise amplifiers for each of the 10^4 pads which are collecting the avalanche of the counters.

In this respect Micromegas offers rather unique properties, where the events are selected from the background through two physical effects :

- The efficiency of the BaF_2 crystals for the capture gamma rays is higher than the efficiency for the gammas rays emitted by the radioactive targets.

- The multiplicity of the gammas produced by neutron capture is measured with a time resolution of 1ns leading to a rejection of the background. The accidental rate will depend on the limit set for the multiplicity and on the time resolution of the detector.

Physicists at Saclay and Coimbra would participate in the development and the construction of this Micromegas counter.

5.D – NEUTRON INDUCED (n,X) REACTIONS .

Any ADS project relies heavily on the cross sections of the (n,n') and (n,xn) reactions, since these reactions govern largely the flux and the energy spectrum of the neutrons in any reactor. To avoid model-dependent analyses, such reactions should be investigated with the help of neutron detectors.

With white neutron beams, such reactions have mostly been investigated by detecting not the neutrons, but discrete γ-rays which are produced in the final nucleus. Technically, this method is relatively straightforward since γ detectors can have a good time resolution, which allows to measure precisely the TOF of the neutron projectile, and a good energy resolution which allows to identify the final nucleus and thus the number of emitted neutrons. Measuring the excitation function of any of these reactions consists experimentally in registering the γ-spectrum as a function of E_n. The basic assumption of this method is that the cross section for production of secondary neutrons without emission of any γ-ray is negligible.

However, this method cannot be generalised to all possible nuclei. The final nucleus should preferably be an even-even nucleus. Indeed, in this case the γ ray which is used to identify the reaction channel is the transition from the first 2^+ state to the ground state. For even-even nuclei, often more than 90% of the γ-cascade proceeds via this transition [5.30]. Thus Vonach et al. for example have investigated ^{207}Pb (n,xn) reactions and have given cross sections for (n,2n), (n,6n) and (n,8n) reactions on ^{207}Pb, and for (n,n'), (n,2n), (n,3n), (n,5n), (n,7n) and (n,9n) reactions on ^{208}Pb.

The method consists in detecting γ-rays in a large solid angle set of scintillator modules, and the neutrons in coincidence in a number of DEMON [5.32 -5.36] modules. The events are triggered by the detection of any γ-ray. The γ-detectors must have a good time resolution, so that the projectile energy is precisely determined. It must also have a high efficiency and a low threshold to allow the measurement of coincidences to be triggered by low energy transitions which are important at the threshold. It may also have a good energy resolution, which would help identifying given channels and a low neutron sensitivity. The Total Energy Spectrometer which is being brought in operation at CERN by the Isolde collaboration [5.31] would be a suitable candidate. However, the first experiments will be performed with 9 modules of the BaF_2 Karlsruhe Ball, corresponding to 1π solid angle. The neutrons will be detected in about 24 DEMON modules, each consisting of a NE213 cell 16 cm in diameter and 20 cm deep, with the n-γ discrimination performed by pulse-shape analysis. They will be located at about 1 m from the target. This geometry allows the determination of the time of flight of the detected neutrons, and thus their energy. This energy information is essential for the knowledge of the detection efficiency. It would also allow to measure double-differential cross sections of emitted neutrons in a later stage.

The principle of the method is based on the fact that any reaction leads to the emission of at least one detectable γ–ray. Then the detection of this γ-ray can be used as a trigger for the reaction, providing in addition the time of the collision and thus the energy of the projectile and the start for the time of flight of the neutron detection. Fission reactions must also be included in the trigger, since they contribute to the cross section of (n,xn) reactions. The measurement will be more simple for the fissile targets, by replacing the gamma detectors by fission ones, triggering thus on fission fragments instead of the prompt gammas.

If only (n,xn) reactions contributed to the trigger, the neutron multiplicity would be :

$$\nu = \frac{\sigma(n,n') + 2\sigma(n,2n) + \dots}{\sigma(n,n') + \sigma(n,2n) + \dots}$$

For instance, just above the threshold for the (n,n') reaction, ν must be found equal to 1. The method can be checked with the elements having well known σ(n,n'). When the (n,2n) channel opens, ν will increase in proportion to the relative cross sections for the (n,n') and (n,2n) reactions. Therefore, the measurement of ν reveals the opening of each new channel. In the example of ^{208}Pb, the method can be checked until the threshold of the 4n channel, and then it would allow to measure the σ(n,4n) until the (n,6n) channel opens. At higher bombarding energies, where the (n,xn) channels with large values of x open, it is no more possible to separate the cross sections for the different values of x but the results are still valuable for the comparison of the different model predictions.

Up to now we have made the assumption that each collision will produce at least one γ-ray. This hypothesis has increasing validity when the mass of the target becomes heavier, the neutron multiplicity larger and the bombarding energy higher, but is not valid in the vicinity of the threshold of any channel with two consequences. The first one is the shift of the threshold by the energy of the first excited level, being of the order of a few hundred keV in the most heavy nuclei but much larger for magic or double-magic nuclei. This effect clearly can be corrected from the known Nuclear Data. The second consequence is the decrease of the trigger efficiency for low excitation energies. This effect has to be corrected by statistical model calculations including the discrete level scheme of the nucleus.

The method is valid only for the trigger acting on the (n,xn) reactions. But gamma rays are emitted also by the capture and the fission reactions which, however, have very small cross sections as soon as the bombarding energy reach the threshold of the (n,xn) channels at few MeV. Such contaminating reactions will therefore contribute very little in the trigger rate. The cross sections of such reactions are either sufficiently well known or will be independently measured, allowing thus the correction, if necessary, of such contaminations.

A GeLi detector will also be included in the set-up in order to test the possibility to measure (n,n′γ) to the lowest excited state at TOF. The neutron background will determine the closest distance at which this detector can be placed, and thus the counting rate.

Despite the fact that this method is not universal, its simplicity is such that it should remain an essential tool at the TOF facility. The main limitations come from the thresholds of the detectors, which are around 100 keV for gamma detection and 1 MeV for the neutron one. Thus the possibility to place a GeLi detector close to the target at TOF should be checked immediately. This method based on n-γ coincidences may even extend the interest of the GeLi measurements. More precisely, it would:

- Fill in some of the gaps corresponding to non even-even final nuclei;
- Select a given channel, even in the case that γ-lines corresponding to other mechanisms like capture, overlap with the line of interest;
- Allow to test the different theoretical models by investigating directly the neutron multiplicity as a function of bombarding energy. Actually, one of the aims of measuring σ(n,xn) is to allow to calculate the neutron multiplicity ν , and the Strasbourg group proposes to measure it directly;
- Provide experimental informations on the angular distributions and possibly on the energy distributions of the γ– and n-emission. These

informations are of course of great interest in conceiving the ADS prototype.

The identification of charged particles in the reactions with charged particles in the final state is mandatory, i.e. separate protons from α particles, but also from ^{2}H's, ^{3}He's and ^{3}H's. Because the cross sections for charged particle production are generally less than 100 mb, the target must have a large total mass. The measurement of low energy particles, like protons at 1 MeV or α particles at 5 MeV, implies very thin (< 1 mg/cm^{2}) targets, which means that such targets must cover a large surface, i.e. have a radius of several tens of cm. Therefore, the CERN TOF facility is of importance for such measurements.

The method for charged particle identification consisting in the measurement of the energy or the energy loss and the particle velocity is not possible at the TOF beam, since the time measurement is just used to determine the projectile energy. Combinations of gas detectors, thin and thick scintillators etc., have been used in other laboratories, but the probability to produce several particles in a single collision makes tracking indispensable. Moreover, It seems quite difficult to meet all these requirements with one single detector set.

It seems reasonable to define two regions for the energy of the detected particles. The one region extends from 1 to some tens of MeV for protons, and from 5 to ~100 MeV for the α particles. In this region, detectors must obviously be placed in vacuum. The second region will cover the higher energies. Classical nuclear physics detectors are, indeed, not suited for the time structure of the TOF beam, at least at high bombarding energies. Identifying the charged particles implies several measurements of their energy loss. The angular distribution for the charged particle emission is sometimes strongly forward peaked, implying the exposition of the detector to the neutron beam. The use of a combination of high-energy tracking detectors (MWPC, MSGC, drift chambers) seems to be mostly adequate. In particular, the use of radiation resistant Si-microstip detectors is very promising mostly for the charged particles produced with small angles. However, the decision on the final charged particle detector for charged particles requires more further discussion inside the collaboration.

5.E– ELASTIC AND INELASTIC NEUTRON SCATTERING.

Elastic scattering is a key process for understanding the great variety of nuclear reactions. Although it is the simplest collision process its study has yielded important insights into the nature of the nuclear many-body problem. Investigation of inelastic and reaction channels gives specific information on the structure of the collision partners. Before any of the below mentioned experiments can be performed a detailed characterisation of the beam of the TOF facility is required. Specifically the time energy correlation function, the spectrum of the beam, the absolute flux and the background at the measurement stations must be determined by standard measurements.

The study of elastic scattering below the first inelastic threshold can easily be performed with the white beam of the TOF facility because there is only one neutron exit channel and the TOF measurement directly gives the neutron energy. The measurements presented in 5.E.1 as well as elastic scattering in the resonance region, which is usually below the first inelastic threshhold, belong to this type of experiments.

Above the first inelastic threshold, there are several energy groups in the exit channels, and therefore the energy of the incident neutron cannot be extracted uniquely from the TOF. Additional information is needed to determine the energies of the incident and scattered neutrons. For instance a direct measurement of the energy of the scattered neutron can be perfomed with a neutron spectrometer. This technique, which can work only at sufficiently high energies (few tens of MeV), has been sucessfully used at the LAMPF/WNR facility and could be also implemented at the CERN TOF facility.

5.E.1 MEASUREMENTS ON THE ELECTROMAGNETIC STRUCTURE OF THE NEUTRON.

This section comprises measurements of the neutron-electron scattering length and the electric polarizability of the neutron. Two complementary experimental schemes are envisaged, i.e., angular scattering and transmission experiments. The following program of measurements is planned for the first phase of operation of the TOF facility.

- **MEASUREMENT OF THE NEUTRON-ELECTRON SCATTERING LENGTH BY ANGULAR SCATTERING:**

Recent measurements of b_{ne} by Kopecky *et al.* [3.69, 3.71] and Koester *et al.* [3.70] are based on transmission experiments on ^{208}Pb and ^{209}Bi. To end the ongoing discussion and to eliminate the discrepancies between these measurements and those of [3.66, 3.67] an independent determination using angular scattering techniques (similarly to Krohn and Ringo [3.62, 3.64]) is planned at the TOF facility in the beginning phase. A setup suitable for high precision angular scattering experiments is required [3.62, 3.64] using the modern techniques of data acquisition. The key parameters of the experiment are:

Proposed samples: Xe, Ar , thorogenic ^{208}Pb (liquid)

Sample position: at the 230m measurement station a beam collimation of a few cm^2 is necessary for the definition of the scattering volume and the scattering geometry.

Range of energies: 0.05 eV to 100 eV

Detectors: Neutron detectors (e.g. ^{3}He or ^{10}B loaded liquid scintillator detectors) at well defined angles.

Required accuracy: better than $5 \cdot 10^{-4}$

Expected use of beam time: starting with year 2000; this experiment is the first in a series of measurements concerning the fundamental properties of the neutron and could be scheduled in the group of first experiments at the TOF facility.

The challenge of this experiment lies in the precision which must be achieved. This implies that a detailed study of the background for the specific geometry of the setup is required. Small contributions which influence the *q*-dependence (e.g. nuclear resonances, effects due to the status of the target, etc.) must be taken into account carefully.

In the beginning phase complementary measurements of the neutron-electron scattering length via transmission experiments will be proposed. They will consider the energy dependence of the total cross sections of ^{208}Pb and ^{209}Bi to compare with the previous results at ORELA [3.71] but also of ^{86}Kr. In principle this experiment uses a standard setup for transmission measurements .

Again it is characterized by the challenging requirement of accuracy. The key parameters are:

Proposed samples: ^{86}Kr, thorogenic ^{208}Pb, ^{209}Bi

Range of neutron energies: 0.05eV - 100eV

Expected accuracy: about 10^{-4}

At present this transmission experiment (detector located in the primary beam axis) cannot be performed at the TOF facility because no adequate detection system is available which can handle the high peak flux. However, neutron peak fluxes of this magnitude will also occur in future spallation sources (e.g. AUSTRON, ESS) and therefore it is of great interest to develop the techniques of high rate neutron detectors. A possible direction might be based on current mode detectors (using fast scintillation materials) with segmentation of the detection volume and ultra-fast data acquisition electronics. With the availability of such a detector system the feasibility of transmission experiments at such high peak rates should be demonstrated first at the TOF facility.

- **MEASUREMENT OF THE ELECTRIC POLARIZABILITY BY SCATTERING OUT OF THE FORWARD DIRECTION :**

The determination of the electric polarizability requires experiments typically of accuracy 10^{-4}. This can be achieved in transmission experiments but is beyond the limits of angular scattering experiments nowadays. Therefore the best available data on the electric polarizability of the neutron have been obtained by transmission [3.73]. As already mentioned it appears now feasible to perform measurements which reduce the uncertainty in a_n to 10^{-4} fm^3.

It is the goal of the TOF collaboration to achieve this accuracy. The experiment, however, has not to be designed as a standard transmission experiment because of the high peak flux of about 20 neutrons/cm^2 ns at 500 keV (an energy which has to be included in these experiments). Positioning the detector out of the forward direction at a well defined angle will yield a similar information, i.e., a linearly k-dependent term of the cross section. Because of the high intensity of the beam the statistics can be optimized by the design of the setup. In particular it will depend on the status of the development of the high rate detector. The key parameters of the experiment are:

Proposed samples: thorogenic ^{208}Pb (compensated with radiogenic ^{206}Pb)

Sample position: at the 230m measurement station; a beam collimation of a few cm^2 at the sample is necessary for the definition of the scattering volume and the scattering geometry.

Range of energies: 100 eV to 500 keV

Detectors: Neutron detectors (e.g. ^{10}B loaded liquid scintilator detectors and plastic scintillators) at well defined angles.

Required accuracy: relative accuracy about 10^{-4}

Expected use of beam time: this experiment is scheduled as a follow-up experiment to the neutron-electron scattering length measurement by the angular scattering method.

At the accuracy required it will be of particular emphasis to have a good knowledge of all resonances and their parameters. Especially the occurence of resonances near the continuum threshold must be checked because they can influence the low energy behaviour. A good background determination is also required although they are expected to be smaller than in standard transmission experiments.

A complementary measurement of the electric polarizability via a transmission experiment on thorogenic ^{208}Pb will be proposed at GELINA in parallel. In principle it will be an adapted version of the ORELA experiment [3.C42] aiming an improved accuracy.

- **MEASURING THE PHOTO- AND MESON PRODUCTION IN np SCATTERING:**

As already mentioned there will be a considerable flux of neutrons up to energies of 1GeV at the CERN TOF facility. It is very promising that this unique feature of the CERN neutron source offers the possibility of direct measurements of the *np*-bremsstrahlung as well as of meson production. These experiments are challenging and are therefore envisaged as second phase measurements. The key parameters of these experiments are:

Proposed samples: H_2

Sample position: at the 230m measurement station.

Range of energies: 100 MeV to about 1GeV with emphasis on energies beyon the pion threshold

Scheduled start: 2002

In the beginning phase simulations will be performed to clarify the achievable accuracy at a given energy resolution. This can be followed by a detailed design of the detector structure. Particular attention will be focussed on the option of measuring the analysing power in *np*-bremsstrahlung experiments. In the beginning phase only preparatory works are planned within the collaboration.

6 – THE FIRST CROSS SECTION MEASUREMENTS.

6.A. – ASTROPHYSICS RELATED MEASUREMENTS.

In the first year of operation, the Astrophysics measurements of neutron capture cross sections at the CERN TOF facility will concentrate on a number of *tests* in order to verify the computer simulations of different experiments, to understand the backgrounds, and to master the data acquisition techniques as well as on *measurements* of resonance-dominated cross sections of stable light nuclei, which are important for the interpretation of isotopic anomalies in meteoritic material. All these experiments require a narrow beam with a diameter of 30 or less.

6.A.1. – BACKGROUND STUDIES AND DETECTOR TESTS.

These studies are of mutual interest for other groups as well and can, therefore, be carried out in close collaboration with Geel, Saclay, and Grenoble. The following measurements are planned for the period from May to July:

- **Conventional detectors** (C_6D_6 liquid scintillator and Moxon-Rae type) have to be tested with respect to sensitivity for scattered neutrons and for beam-induced backgrounds. A series of TOF measurements on different ^{197}Au samples with masses between 100 mg and 1 mg is proposed to investigate the achievable signal/background ratio and the count rate problem. These runs can be performed with rates between 10^3 and 10^6 true counts/day. Given the unavoidable backgrounds, the measurements have to be performed in a (sample in)/(sample out) mode using a low mass sample changer and will require acquisition times between 1 and 3 days, accumulating to a total duration of 2 weeks. The tests with gold samples have to be complemented by measurements of (n,γ) resonances in ^{27}Al and ^{19}F with different Γ_γ/Γ_n ratios. While the respective resonance areas yield detailed information on the prompt sensitivity for scattered neutrons, the deep cross section minima between resonances indicate the general background level and the occurrence of delayed components. Since the small cross sections between resonances require longer runs, an additional period of 2 weeks is required for this part.

- **The test of a BaF_2 array** covering about 1π solid angle is planned for comparison with detailed simulations of (n,γ) experiments with this detector. The simulations will be carried out with the GEANT and FLUKA software, using a true model of the detector geometry and assuming different scintillator materials and different granularities. These simulations and the complementary measurements with the BaF_2 setup will subsequently be used for developing an improved 4π detector array for neutron capture studies by the end of 2000.

6.A.2. - CROSS SECTION MEASUREMENTS.

^{103}Rh : We propose to start in the fall of 2000 with a first TOF measurement on ^{103}Rh by using conventional techniques. This case has the following advantages:

(i) In the keV region, this (n,γ) cross section is well established by a number of independent data sets, where the results can be checked (and normalized if necessary).

(ii) The resonance region is poorly known. Therefore, the proposed experiment would provide new information at lower energies. Since Rh is a mono-isotopic metal, the preparation and definition of suited samples is straightforward. The required measuring time will, therefore, not exceed a period of one week.

$^{24-26}$Mg: Given the experience from the tests and from the ^{103}Rh experiment, the first actual measurement of immediate astrophysical interest is proposed for the stable isotopes of magnesium. This experiment is difficult because of the small cross sections of these nuclei, for which only rudimentary experimental data exist so far. The differential cross sections are dominated by few resonances, and the respective stellar averages are as small as a few millibarns. These cases could not be studied so far because of the limited fluxes at traditional neutron sources. The stellar (n,γ) rates of the Mg isotopes are important to analyze the isotopic composition of presolar inclusions in meteorites. Since a variety of such inclusions were found to represent pure s-process material, the isotopic pattern of s-process magnesium provides insight into the role of the ^{22}Ne(α,n)^{25}Mg and ^{21}Ne(α,n)^{24}Mg reactions as neutron sources for the s-process. These measurements are estimated to last for about 3 weeks.

^{151}Sm : By summer 1999, a sample for neutron capture studies of about 300 mg ^{151}Sm is being prepared by a joint Oak Ridge/Karlsruhe effort. If the total activity of about 2.5x10^{11} Bq (7 Ci) can be accepted, the sample could also be used for a neutron capture measurement at the CERN TOF facility. This project would provide an important extension of the results from a planned experiment with the 4π BaF$_2$ detector at Karlsruhe in the energy range between 5 and 220 keV. The measurement – which is equally interesting for waste transmutation – would require beam time for about 10 days.

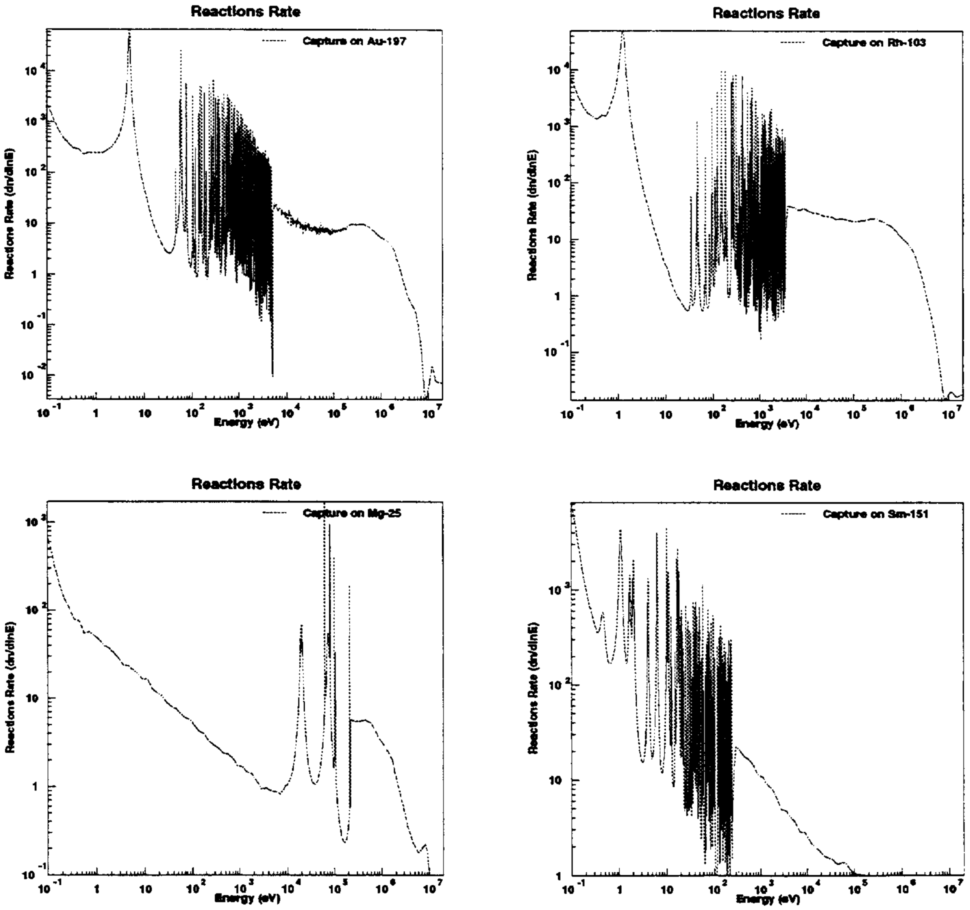

Figure 6.1. The expected capture rates per day and energy bin of 2x10^{-4}xE_n for a gamma detector efficiency of 10%.

6.B. – CROSS SECTION MEASUREMENTS RELATED TO ADS.

In the first stage of operation of the CERN-PS TOF Facility, cross section measurements should concentrate on the most important isotopes relevant to the Thorium fuel cycle and transmutation of long-lived radioactive waste from NPPs (Nuclear Power Plants). The measurements will rely on the use of standard techniques.

^{197}Au and ^{Nat}Ag: we propose to start in the fall of 2000 with a first **(n,γ)** measurements on the well known ^{197}Au and ^{Nat}Ag as a check of the reliability of the techniques used. The advantage of these elements is the well known cross sections in the resonance region. We have identified in the evaluated data files some 260 and 950 resolved resonances between 1 eV and 10 KeV for ^{197}Au and ^{Nat}Ag respectively;

^{238}U and ^{235}U: **(n,γ)** and **(n,f)** measurements for these two nuclides are necessary for normalization purposes. The resonace region is well known for both isotopes: for instance we have identified some 2000 resolved resonances up to 20 KeV for ^{238}U and some 3500 for ^{235}U up to 3.5 KeV. There is, however, some incentive to extend the resolved resonance region of ^{235}U beyond this value.

^{232}Th and ^{233}U: They are the base of the Thorium fuel cycle. The requirement for the nuclear data accuracy for these two nuclides are most stringent and include all types of neutron interactions.

(i) **(n,γ)** cross sections for ^{232}Th are badly known in the resonance region: only 300 resonance between 5 eV and 3.5 keV are resolved. We estimate some 40% discrepancy in the experimental data and 30% for the evaluated data.

(ii) For ^{233}U, **(n,γ)** measurements are badly needed: the resolved resonance region extends only to a few 100 eV and there is no direct experimental data. In the energy region between 0.1 and 1.0 MeV, the data are derived from α-measurements. Comparison between evaluated data show a considerable discrepancy between 100 eV and 10 keV, and above 1 MeV.

(iii) **(n,f)** measurements for ^{233}U are also required since the situation is similar to that of capture. The resolved resonance region has to be extended from 100 eV to a few keV. The comparison between experimental data shows some 5–10% discrepancy in the energy region between 0.1 and 10 MeV, where a target accuracy of about 1% is required for the EA. Furthermore, above 10 MeV, only one measurement exists. When comparing the evaluated data files, the discrepancy rises to ~ 10%.

(v) **(n,f)** measurements with ^{232}Th are required in the energy range between 6 and 20 MeV. Enough measured data exist below 6 MeV, however, above 6 MeV the discrepancy rises to values close to 15–30%.

(vi) **(n,2n)** measurements on ^{232}Th and ^{233}U are needed to estimate the production of ^{231}Pa and ^{232}U, which are the main nuclides responsible for the long-term and short-term radiotoxicity of the Th-based fuel cycle respectively. In thecase of ^{232}Th, experimental data exist in some energy intervals but with 15–20% discrepancy, where a target accuracy of at least 5% is required. For ^{233}U, they are no experimental data available and upto 8 MeV the discrepancy between the different evaluations reaches a factor 5. Therfore, reference experimental data are very much needed.

(vii) **(n,n')** measurements on ^{232}Th and ^{233}U will be also carried out since this reaction is important in estimating the average neutron flux spectrum in the fuel. Target accuracies for this reaction are of the order of 5–10%. Seldom data exist for ^{232}Th even though it is the dominant reaction (together with elastic scattering) after a few keV (i.e. 4 barn at 1 MeV versus 0.3 barn for capture). This is also true for ^{233}U, where both inelastic and fission processes are dominant above a few 100 keV, 1 barn versus 3 barn respectively.

Concerning the transmutation of minor actinide waste, important cross sections to be measured are **(n,γ)** and **(n,f)** for ^{241}Am, ^{243}Am, ^{244}Cm. **(n,γ)** measurements for ^{242}Pu and ^{246}Cm are also very interesting since these two nuclides are responsible for the production of a major part of Am and Cm isotopes in the case of ^{242}Pu and higher actinides such as Bk and Cf in the case of ^{246}Cm. Moreover, these two nuclides present abnormally small capture cross sections compared to the other actinides.

Regarding the transmutation of long-lived fission products, the **(n,γ)** cross sections of ^{99}Tc and ^{93}Zr should be remeasured with emphasis on the unresolved region above 1 keV.

Equally important to ADS studies, are the **(n,xn)** cross section measurements for structural and coolant materials such as ^{56}Fe, ^{208}Pb and ^{209}Bi.

7 – REFERENCES.

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