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STUDY OF NUCLEAR DATA AND APPLIED NUCLEAR PHYSICS AT THE DALAT INSTITUTE FOR NUCLEAR RESEARCH (VIETNAM)

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ABSTRACT

The Dalat Institute for Nuclear Research (DINR) is the main nuclear research establishment of Vietnam National Atomic Energy Commission (VINATOM). The activity of DINR in neutron activation analysis (NAA), radioisotope production and radiation technology has begun since 1980s using nuclear reactor and Co-60 radiation source. The safe operation and efficient exploitation of the Dalat nuclear reactor have required researches on nuclear data and reactor physics. This report presents study of nuclear data and applied nuclear physics at the Dalat Institute for Nuclear Research using filtered neutron beams and the thermal column of the reactor. The information presented is based mainly on the results of the National Research Contracts 50A-01-01-03, KT-04-3.2.3 and KC-09-08 for the period 1985-1995.

I. INTRODUCTION

Nuclear energy will play a significant role in the growing economy and energy demands of developing countries. It is essential for any country which has any reactor program to maintain a nuclear data group who can provide reliable data for input to their reactor group, even when the reactors are commercially supplied with fixed period guarantees or are copies of well tested working model put up with technical collaboration. Moreover, the safe operation and efficient exploitation of nuclear reactors require a wide spectrum of scientific and engineering personnel. These people must be so trained that they can understand the physics principles of nuclear reactions and of particle transport, as well as all engineering and safety principles needed to make nuclear reactors a full available and economic source of energy, within widely accepted constraints of safety and environmental protection. Besides, these people must also supply data required for calculations of optimal conditions for radioisotope production and activation analysis, and for calculations of radiation protection to radiation facilities and radiation therapy, and so on. With this policy,

Vietnam National Atomic Energy Commission and The Vietnam National Research Programs on Nuclear Science and Technology, and on Fundamental Sciences have supported nuclear data activities at the Dalat Institute for Nuclear Research in the framework of the National Research Contracts 50A-01-01-03, KT-04-3.2.3 and KC-09-08. In this paper we will present the main activity of Nuclear Data Sector (DINR) in the field of nuclear data calculations, measurements and applied nuclear physics using filtered neutron beams and the thermal column of the Dalat reactor. Nuclear data processing, reactor physics calculations and reactor physics experiments that are an important activity of DINR will not be included in this report.

II. NUCLEAR DATA CALCULATIONS

2.2. The exciton model calculation of the (n,p) cross sections:

We have carried out investigations on preequilibrium emission of protons and isotopic effect in the fast neutron-induced (n,p) reactions on heavy elements at the neutron energy of 14 MeV/1/. The (n,p) cross sections, contributions of both evaporation and preequilibrium exciton mechanisms and the emitted proton spectra have been calculated for series of Sm, Dy and Er isotopes. By fitting the experimental data the exciton model free parameter K characterizing the transition rate between exciton states has been determined for each isotope chain (see Fig.1). It has been found that more than 85% of the preequilibrium protons are emitted from the exciton state n=3. On the basis of this result a rather simple formula has been found and can be used for the evaluation of the (n,p) cross sections on heavy nuclei.

2.1. Modified statistical calculations of neutron radiative capture cross sections:

The precision of neutron capture cross section evaluations for the keV-MeV region is still not enough to satisfy the required accuracy of 10-30%. It seems likely that the uncertainty might partly come from the gamma ray strength functions and partly from the neutron transmission coefficients used in compound-nucleus model calculations. So, we have made a modification of the statistical approach to the neutron capture problem in which the energy dependence of the average total electric dipole radiative width is connected to the relative variance of the exciton number D_n/n. On the basic of this modification, the calculations of the average neutron radiative capture cross sections carried out for a number of nuclei in the mass region A=50-250 and for neutron energies up to 2 MeV with using experimental neutron strength functions for s- and p-waves to estimate transmission coefficients have shown a good agreement with experimental data /2/. Therefore, we have developed the code for analyze of average neutron radiative capture cross sections $\sigma_{n\gamma}$ allowing estimate the average radiative width and neutron strength functions from experimental data of $\sigma_{n\gamma}$ /3/.

III. NUCLEAR DATA MEASUREMENTS

3.1. Filtered neutron beams:

Since the pioneer work of Sympson and his co-workers /4/, neutron transmission filters have been successfully used to produce quasi-monoenergetic neutrons for nuclear physics experiments. The Dalat IVV-9 reactor is a 500 kW pool-type reactor with distilled water serving as moderator and coolant. The horizontal section scheme of the Dalat reactor is given in Fig.2. Experimental set up at the piercing beam port No.4 of the Dalat reactor using the neutron filter technique is given in Fig.3 The neutron flux at this beam port is $6x10^8$ n/cm^2/s, and about one tenth of which are epithermal neutrons. Single crystal silicon (980 mm long), aluminum (1023 mm long), iron (200 mm long) and sulfur (45 g/cm^2) filters with possibility for insertion of additional filters like ^{10}B, Ti have recently been installed to produce neutrons of 24 keV, 25 keV, 55 keV, 75 keV, 144 keV as well as thermal neutrons /5/. The fluxes of quasi-monoenergetic neutrons measured at 25 cm from the beam port outlet by activation of Au-foils together with other characteristics of filtered neutron beams are given in Table 1. For performance in Fig.4,5 were shown spectra of the filtered neutron beams of 55 keV and 144 keV at the Dalat reactor. In the near future other types of filters using Sc, U, Pb and polyethylene permitting transmission of 2 keV, 186 eV, 1.2 MeV and 2 MeV neutrons will expectedly be installed.

3.2. Measurement of the thermal neutron absorption cross section for small samples by poissoning method:

The knowledge of the macroscopic thermal neutron absorption cross section is indispensable in the quantitative interpretation of the neutron lifetime logs. We have developed the new approach to the problem of its determination /6/. The experiments were carried out in the thermal column of the reactor where the neutron flux in the sample center was measured by activation Au-foils at different values of absorption cross section Σ_a obtained by poissoning with suitable chemicals. The absorption cross section $\Sigma_{a,s}$ of the unknown sample is found from the intersection of the measured curve of relative fluxes Φ/Φ_o and the line $\Phi/\Phi_o=1$, it is corresponding to the negative poissoning so that the neutron flux at the measusrement position is not disturbed by the sample. For performance in Fig.6 were plotted the measured ratio Φ/Φ_o vs. added possioning absorption macroscopic cross section together with the fitting curve by logarithmic function to receive an linear dependence of the two variables. The value of the macroscopic absorption cross section for H_2O obtained in this work $\Sigma_a=(1.66+-0.30)x10^{-2}$ cm^{-1} is in good agreement with the averaged value of different authors $\sum_a=1.67.10^{-2}$ cm^{-1}.

3.3.Total neutron cross sections:

It is well known that the total neutron cross section studies in the keV-energy region for fissile, breeding, cooling and shielding materials are immediate

important to fast reactor technology because the average kinetic energy of neutrons in fast reactors lies in the keV region /7/. Besides, average neutron resonance parameters can be evaluated if resonance self-shielding effect in total neutron cross sections is studied /8/. It is neutron resonance existence that makes the observed total cross section to be dependent upon sample thickness. At the Dalat reactor, the system for total neutron cross section measurements was set up and experiments for ^{238}U and ^{12}C on the 55 keV and 144 keV filtered neutron beams have been carried out /9/. Fig.7 shows our experimental data (σ_t = 11.45 +- 0.10 b for 144 keV and σ_t = 13.38 +- 0.07 b for 55 keV) obtained by fitting using Monte-Carlo IBM program /10/ with the account of both Porter-Thomas and Wigner distributions and Dopler-broading and data of other authors taken from /22/. The Comparison of total neutron cross sections and average resonance parameters obtained in our work with the values of other authors are given in /11/.

3.4. Average neutron radiative capture cross sections:

The keV neutron radiative capture cross sections are of interest to astro-physics for calculating the nuclear abudances of heavy elements and also to nuclear reactor design and nuclear reaction theory. Experiments for measurement of average neutron radiative capture cross sections of ^{238}U and ^{98}Mo were carried out at the Dalat reactor by activation method. Fig.8 shows our experimental data for ^{238}U together with the results of other authors taken from /12/. In the frame of experimental errors, our data ($\sigma_{n\gamma}$=292.3+-8.5 mb for 55 keV neutrons and $\sigma_{n\gamma}$=152.5+-4.6 mb for 144 keV neutrons) are in good agreement with the results of the work /13/, but the accuracy of our data is better (approximately 3%). The detail information about these experiments is given in /14/.

3.5. Gamma spectra from neutron capture for reactor materials:

In order to assess gamma ray production in a fast reactor and thereby estimate the shielding requirements, it is necessary to know the prompt gamma ray spectrum varies with neutron capture energy. These prompt capture gamma rays will constitute much of the "hard" component of the reactor photon spectrum and will therefore have the most stringent shielding requirement. Besides, these data are also needed for radiation damage estimate and for radiation heating calculations. However, the data are scanty, especially in the keV neutron region /15/. So, we have carried out measurements of capture gamma ray spectra for materials like Si, Ti, C, Al, Fe, Cr on the filtered keV-neutron beams. Capture gamma ray spectra were measured by the Compton-suppressed and pair spectrometer consisting of HPGe-90 cc detector and 3 NaI(Tl)-scintillators (see Fig. 9). Gamma spectra of the Na-22 source and the activated NaCl sample in the Compton-suppressed and pair modes were shown in Fig.10,11. Our measurements presented in /16/ shows that the intensities and energies of the keV neutron capture gamma rays change substantially as neutron energy increases.

3.6. The energy dependence of isomeric ratio:

Measurements of neutron cross sections for formation of ground state σ^g and isomeric state σ^m or isomeric ratio $R=\sigma^m/(\sigma^m+\sigma^g)$ are useful for description of nuclear reaction characteristics. The nuclear level density plays an important role in statistical theory of nuclear reaction. One of the procedures to get more accurate information about the nuclear level density, its energy and spin dependences is to analyze nuclear reactions with formation of isomeric states /17/. So, we have carried out this research. Fig.12 shows the decay of the 828 keV gamma line of $^{82g,m}Br$ after irradiation of NH_4Br-sample on the 144 keV filtered neutron beam. Calculation curves are given with different values of ratio σ^m/σ^g /18/. Experiments for the other nuclei and on the other filtered neutron beams are going on.

3.7. Average resonance capture (ARC):

Discrete resonance capture may be studied by neutron time-of-flight method, but the statistical accuracy of this method is limited by low intensity of pulsed neutron beams. Another limitation stems from the distribution of partial radiative widths for the statistical decay /19/. The ARC technique greatly reduces the statistical fluctuations in primary intensities that would arise in single resonance or thermal neutron capture. That is the results of the spread in the energy of filtered neutron beams, which encompasses a large number of individual resonances /20/. These results are very valuable for the completeness of level schemes because all levels of given spin-parity groups are equally populated and identified. At the Dalat reactor ARC investigations are being carried out on the filtered neutron beams using Compton-suppressed and pair spectrometer. Fig.13 shows relative reduced gamma transition intensities from neutron capture resonances to low lying levels of ^{239}U in the reaction $^{238}U(n,\gamma)^{239}U$ on the 55 keV filtered neutron beam. It was seen that the p-wave neutron radiative capture cross section of ^{238}U at the 55 keV neutron energy is significantly larger than s-wave neutrons. Other ARC experiments are being carried out at the Dalat reactor.

3.8. (n,2γ) reactions:

For excited levels below 2 MeV their detail spectroscopic information were known very well from investigations of (n,γ), (n,e), (d,p),... reactions. However, for higher excited levels the information is not enough because of low intensity of transitions and bad resolution of detectors with increasing energy of transitions. In this case, the method of summation of amplitudes of coinciding pulses (SACP) from two Ge(Li) detectors for detecting gamma rays emitted in (n,2γ) reaction allows obtaining the spectroscopic information for higher excited levels /21/. The schema of the SACP spectrometer designed by ourselves is given in Fig.14. The experiments are being prepared for some nuclei of rare earth region, for which possibility of cascade transitions in the (n,2γ) reaction is high enough. Besides, the SACP spectrometer is also used to study complex

decay schemes of radioactive nuclei and in neutron activation analysis thanks to its very low gamma backgrounds.

IV. APPLICATIONS

4.1. Prompt gamma neutron activation analysis (PGNAA):

The PGNAA facility is a new multielement analytical tool in Vietnam complementary to the existing INAA techniques with delayed gamma rays measurements for which major elements, mainly light elements, in environmental samples can not be analyzed. This facility was established at the tangential beam port of the Dalat reactor and used in many application fields such as boron analysis in agricultural and biological samples, nitrogen analysis in oil samples, determinations of Fe, Cr, Ni, Mn, B in stainless steel and iron ore samples, analysis for Si, Ca, Fe, Al contents in cement samples, determination of Gd, Sm, Nd in uranium ores, analysis for Sm, Gd contents in rare earth ores,... /23,24/. In Table 2 are listed the sensitivities of our PGNAA facility expressed in (c/g/s) and obtained by irradiation of pure elements or compounds in the forms of foils or pellets. On the basic of these data, the K-factors representing sensitivity ratios relative to Si, Cl and K were calculated (columns 3,4,5 in Table 2) and used in analysis by relative method. Fig.15 shows the prompt gamma spectra of the same rock sample recorded without and with using the monocrystall silicon filter. Fig.16,17 show a portion of prompt gamma spectra of two biological and non-biological standard reference materials (SRM): Bowen's Kale (Fig.16) and IAEA-SL-1 (Fig.17). In recent time, the use of the more intensive filtered thermal neutron beam at the piercing horizontal channel ($1.2x10^7 n/cm^2/s$) and the Compton-suppressed spectrometer has improved the sensitivities by factors of 4-6. At the present time we are developing a method for in vivo measurements on Cd in the body making use of activation analysis with 24 keV neutrons from an iron filter.

4.2. Neutron radiography (NR):

The neutron radiography is a new NDT tool in Vietnam complementary to the existing other NDT techniques using X-ray or gamma ray radiations. The important parameters of the NR facility established at the Dalat reactor are given in Table 3 /25,26,27/. In order to assess the quality of the facility and to prove the capacity of neutron radiography in comparison with other radiographic methods, we have concentrated on objects as following: Electrical and Electronic products; Mechanical devices and Biological samples. The results obtained here show that the neutron radiography on the tangential beam port of the Dalat reactor could be applied in reality.

4.3. Neutron dose calibrations:

A basic radiobiological problem is to clarify to what extent bond-breakage of molecules following elastic collisions of neutrons of different energies contributes to the biological effectiveness (RBE). Knowledge of this becomes

especially important, making it possible to perform risk estimations at exposure of the human body to neutrons, accidentally or by medical treatment. In such case, the filtered quasi-monoenergetic neutron beams at the Dalat reactor become a unique tool in Vietnam allowing to carry out this research. Besides, they were also used in the calibration of neutron dosimeters. In this research the flux and spectrum of the filtered neutron beams were determined by the foil's activation method and gamma doses were obtained by the TLD technique. The result of these researches are given in /28/.

V. POSSIBILITIES AND PROSPECTS IN THE FUTURE

5.1. The main methods and equipments:

The main methods and equipments for exploitation of filtered neutron beams were produced as following:

- The filtered neutron beams: thermal, 24 keV, 25 keV, 55 keV, 75 keV and 144 keV.
- The method and equipment for total neutron cross section measurements.
- The method of average neutron radiative capture cross section measurements.
- The facility for ARC research.
- The method for research of energy dependence of isomeric ratio.
- The Compton-suppressed and pair spectrometer for neutron in-beam research.
- The spectrometer of summation of amplitudes of coinciding pulses.
- The method and equipment for neutron radiography.
- The method and equipment for PGNAA.

5.2. The fundamental and applied nuclear physics researches:

On the basic of received results, we have planed to expand research subjects on nuclear data and applied nuclear physics using filtered neutron beams. The five following research directions are included in the next five year plan:

- Nuclear data required for the Nuclear Power Reactor Program of Vietnam (calculation, evaluation and processing).
- Developing other filtered neutron beams.
- Investigation of average characteristics of some nuclei in the energy region of filtered neutron beams.
- Investigation of nuclear structure and nuclear spectroscopy.
- Applied nuclear physics researches such as prompt gamma neutron activation analysis (PGNAA), neutron radiography (NR), neutron therapy (NT) and small angle neutron scattering (SANS).

VI. CONCLUSIONS AND DISCUSSIONS

In the condition of limited finance, the production of the filtered neutron beams at the reactor with available channel is a remarkable success. For the first time in Vietnam and in the South-East Asian region the filtered neutron beams

obtained at the Dalat nuclear research reactor allow us to carry out basic investigations in the field of nuclear data measurements at the world level. Besides many applications such as neutron radiography, prompt gamma neutron activation analysis, neutron dose calibrations were also developed on these filtered neutron beams. This allows us to take part in regional cooperation on nuclear research reactors utilization, especially in the field of education and training, sharing of research reactors experimental facilities and establishment of a regional nuclear data program.

To further promote nuclear data activity in Vietnam, it is necessary to join all physicists working in the field of nuclear data from different institutes and universities in the country and to improve international collaboration with the advanced nuclear data centers like OECD/NEA Nuclear Data Bank, Nuclear Data Section (IAEA), Nuclear Data Center (JAERI), Brookhaven National Nuclear Data Center (USA), Nuclear Data Center (Obninsk, RF) .... We consider a regional nuclear data center for Asia and Pacific being the most important promotion in the nuclear data activity in the region. Under the circumstances the scientists from developing countries in the region like Vietnam can make active contributions in the international nuclear data activity.

We would like to thank the Director Boards of the Dalat Institute for Nuclear Research and the Vietnam National Research Programs on Nuclear Science and Technology and on Fundamental Sciences for financial support in carrying out investigations on nuclear data and applied nuclear physics at the Dalat reactor. We are very grateful to Prof. P.Z. Hien for his strong support and permanent interest. We would like to thank Dr. Tr. H. Anh, Director of DINR, for his interest in this work. The fruitful cooperation of Drs. Murzin A.V. and Litvinski L.L. from the Kiev Institute for Nuclear Research (KINR, Ukraine) in the field of neutron filters is highly appreciated.

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Table 1: The characteristics of filtered neutron beams at the Dalat nuclear reactor

Neutron	Filter combination	Flux[n/cm^2/s]	R_{Cd} or FWHM
Thermal	98^{cm}Si+10^{cm}Ti+ 35g/cm^{2}S	1.8x10^7	143
144 keV	98^{cm}Si+10^{cm}Ti+ 0.2g/cm^{2}B^{10}	1.2x10^7	22 keV
55 keV	98^{cm}Si+35g/cm^{2}S+ 0.2g/cm^{2}B^{10}	4.0x10^6	8 keV
25 keV	102.3^{cm}Al+0.2g/cm^2 B^{10}	1.2x10^6	
24 keV	20^{cm}Al+20^{cm}Fe+25 g/cm^{2}S+0.2g/cm^{2}B^{10}	1.0x10^6	
75 keV	45g/cm^{2}S+0.2g/cm^2 B^{10}	1.1x10^6	

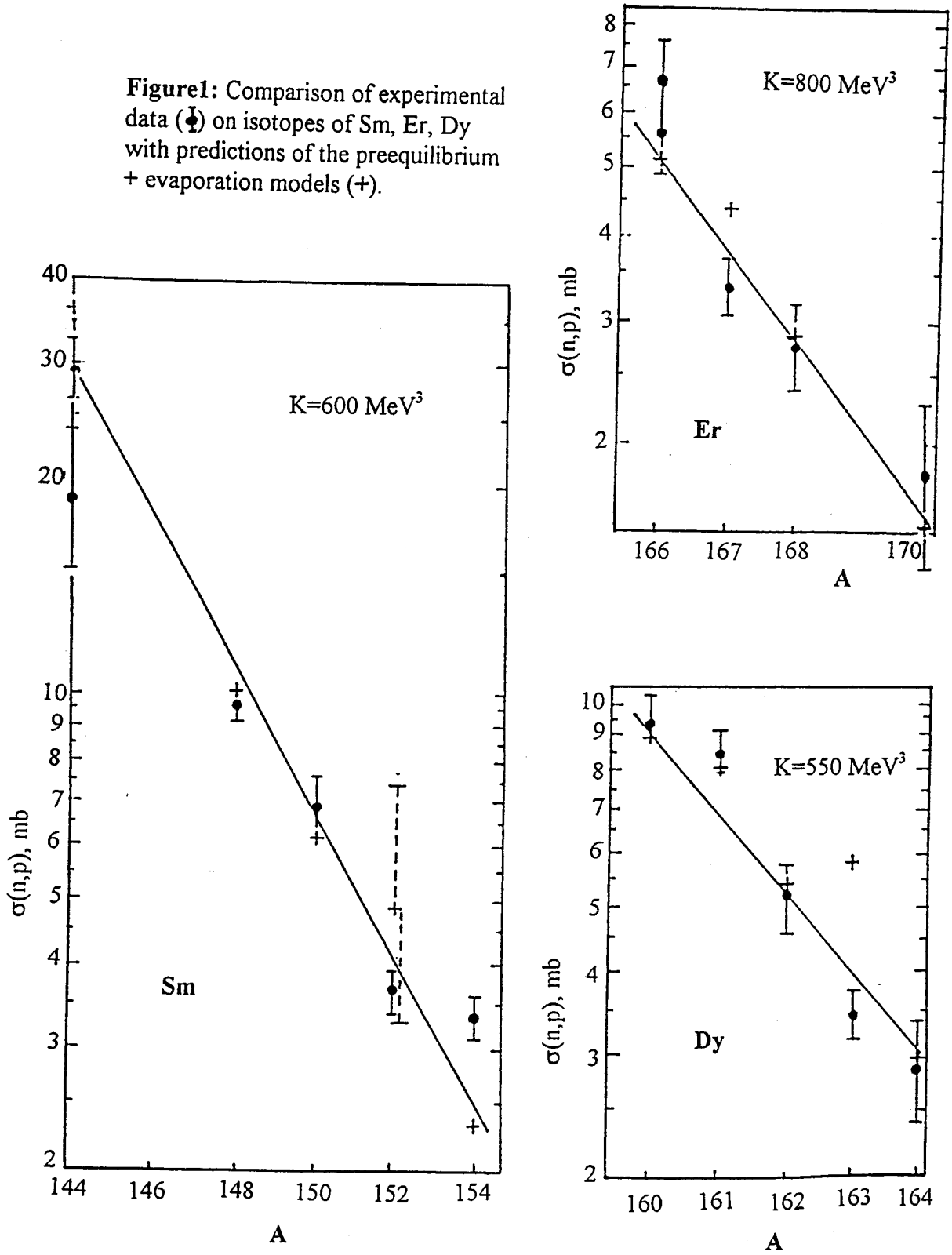
Table 2: The sensitivities and K-factors obtained by PGNAA at the Dalat nuclear reactor

Element	E_γ (keV)	Sensitivity (c/g/s)	K-factor (%) K_{Si}(3539keV)	K-factor (%) K_{Cl}(788keV)	K-factor (%) K_K(771keV)
H	2223	5.61	95.3(3)	1.399(2)	13.4(2)
C	4945	0.0022	0.037(7)	0.00055(10)	0.0052(8)
N	1884	0.021	0.356(5)	0.0052(8)	0.050(6)
Al	1778	0.244	4.14(4)	0.0610(6)	0.581(5)
Si	3539	0.059	1.0	0.0147(4)	0.140(4)
P	3900	0.016	0.271(7)	0.0040(8)	0.0381(6)
S	2380	0.11	1.86(6)	0.0275(8)	0.2619(5)
Cl	778	4.01	67.9(4)	1.0	9.55(2)
K	771	0.42	7.12(4)	0.1047(2)	1.0
Ca	1943	0.112	1.90(5)	0.028(3)	0.267(4)
Ti	342	0.082	1.39(4)	0.0204(3)	0.195(3)
Mn	847	0.861	14.6(5)	0.215(3)	2.05(4)
Fe	1725	0.112	1.90(6)	0.028(6)	0.267(6)

Table 3: The main characteristics of the neutron radiography facility at the Dalat nuclear reactor

Parameter	Value
Useful beam area	120x120 mm^2
Thermal neutron flux	$2.5x10^6 n/cm^2/s$
Gamma radiation level	200 mR/h
Cadmium ratio	120
Neutron exposure for 0.5 optical density on Crystallex film	$2x10^8$ n/cm^2 for Gd convertor

Figure1: Comparison of experimental data (⊕) on isotopes of Sm, Er, Dy with predictions of the preequilibrium + evaporation models (+).



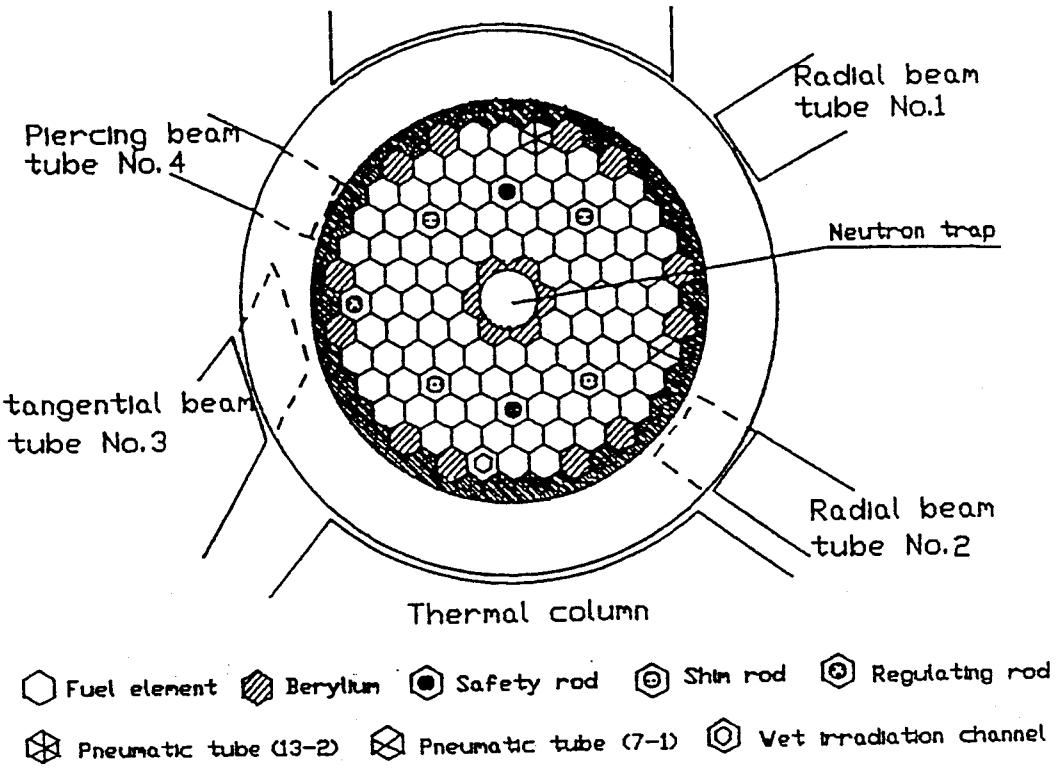


Figure 2: The horizontal section scheme of the Dalat reactor

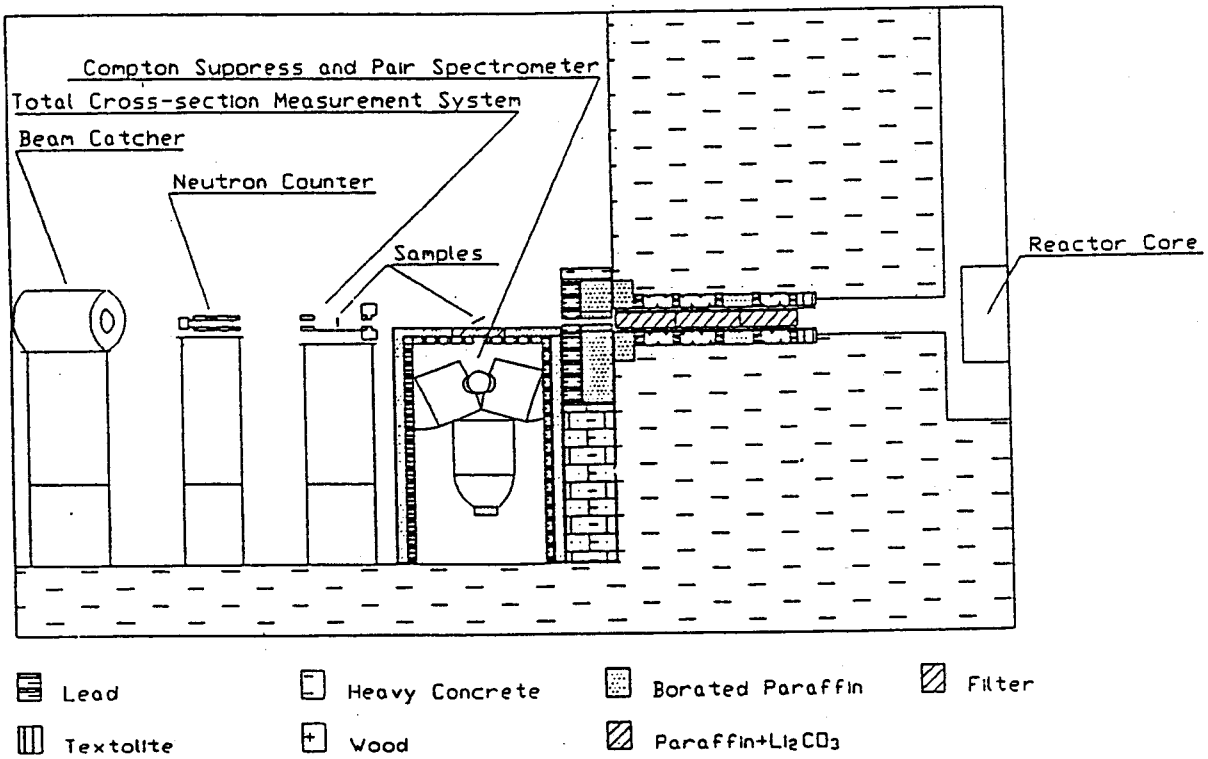


Figure 3: Experimental setup at the piercing beam port No.4 of the Dalat reactor

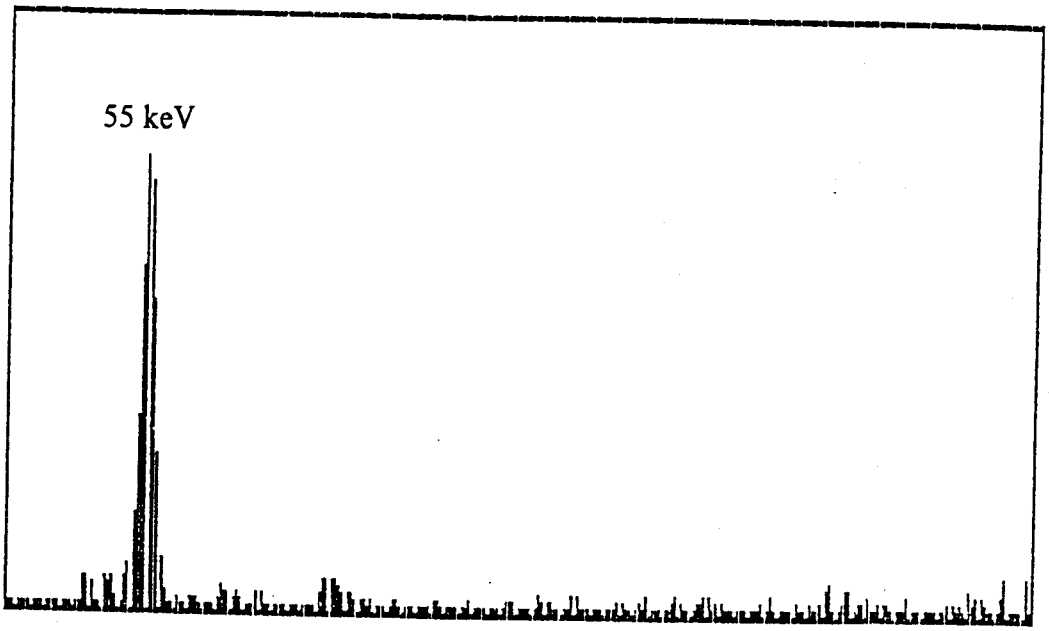


Figure 4: The spectrum of the 55 keV filtered neutron beam at the Dalat reactor

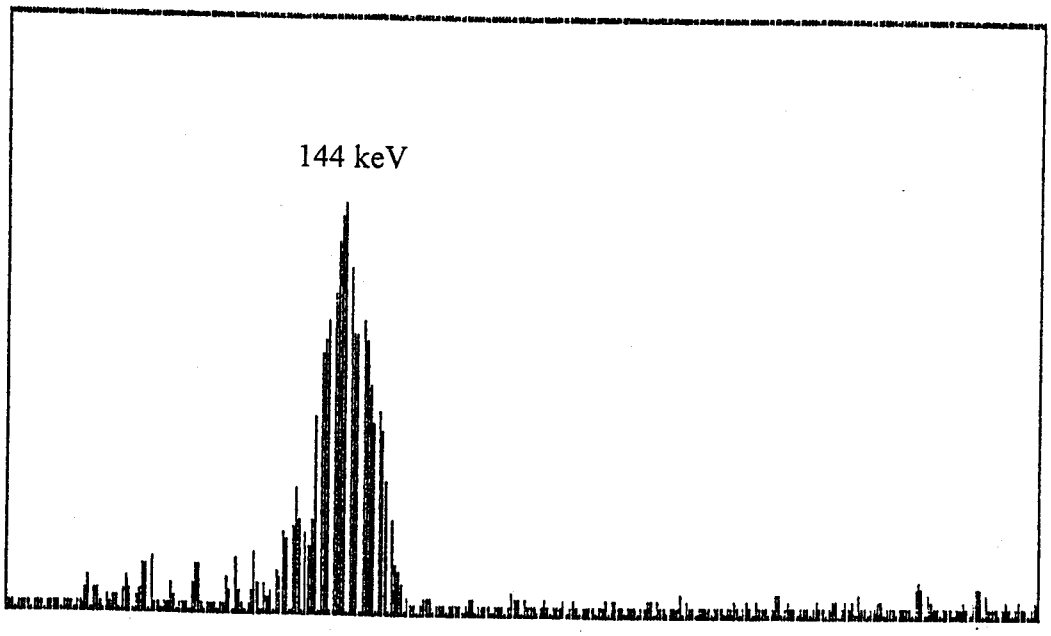


Figure 5: The spectrum of the 144 keV filtered neutron beam at the Dalat reactor

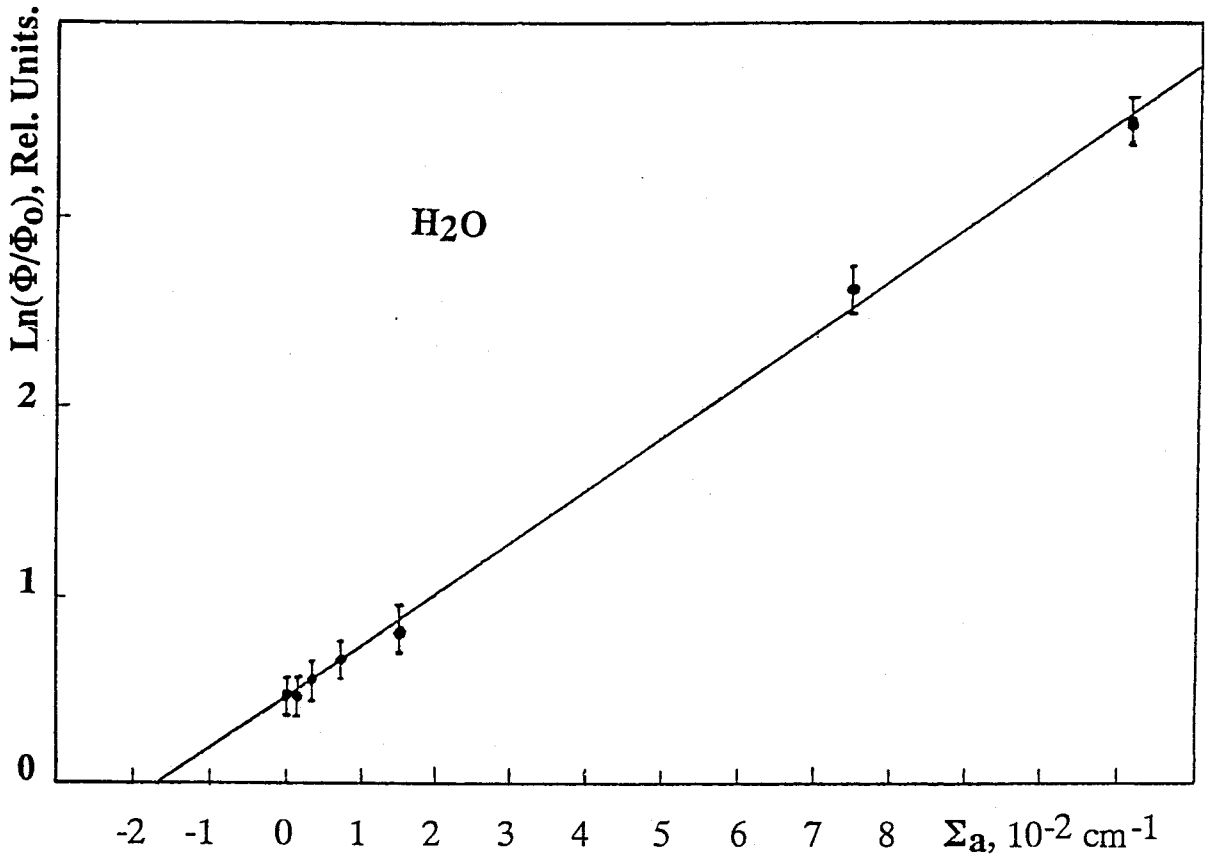


Figure 6: The measured ratio $Ln(\Phi/\Phi_o)$ vs. added possioning absorption macroscopic cross section for H_2O sample

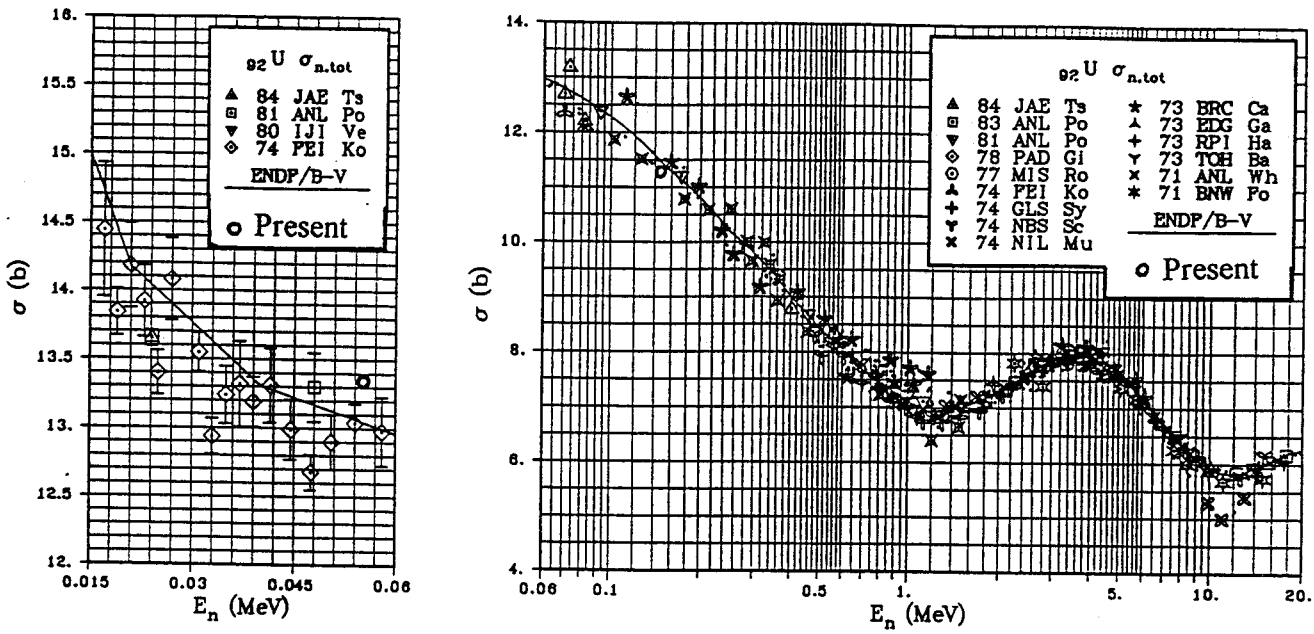


Figure 7: The total neutron cross sections of uranium

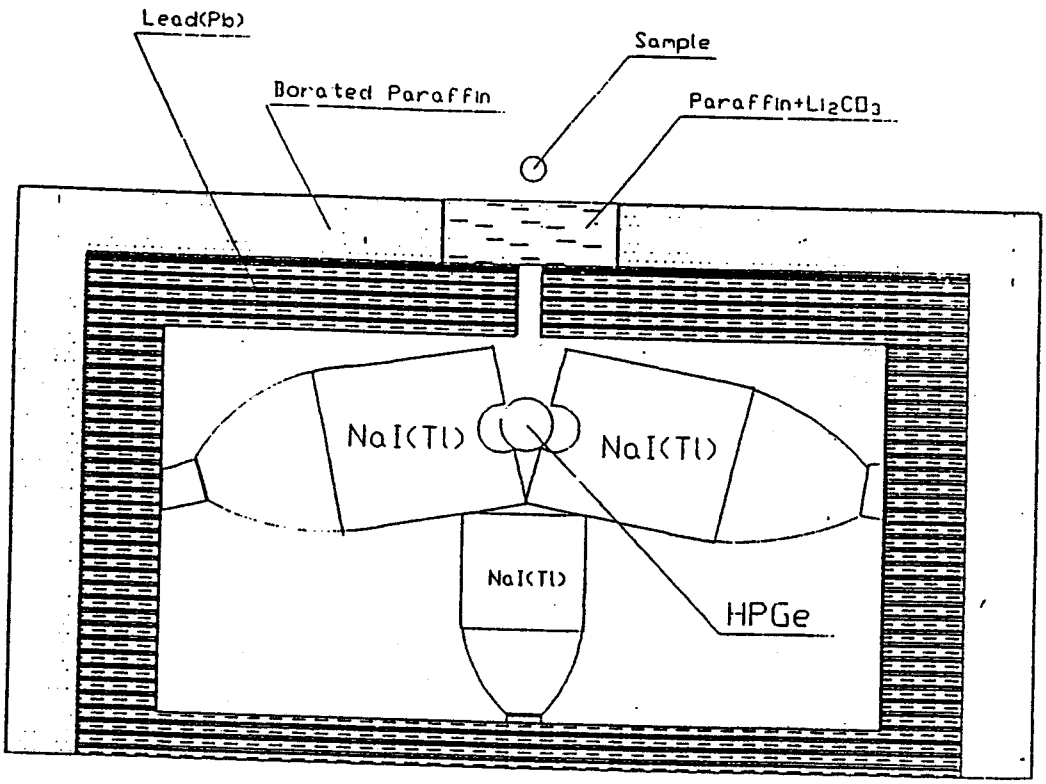


Figure 9: The scheme of the Compton-suppressed and pair spectrometer at the Dalat Nuclear Research Reactor

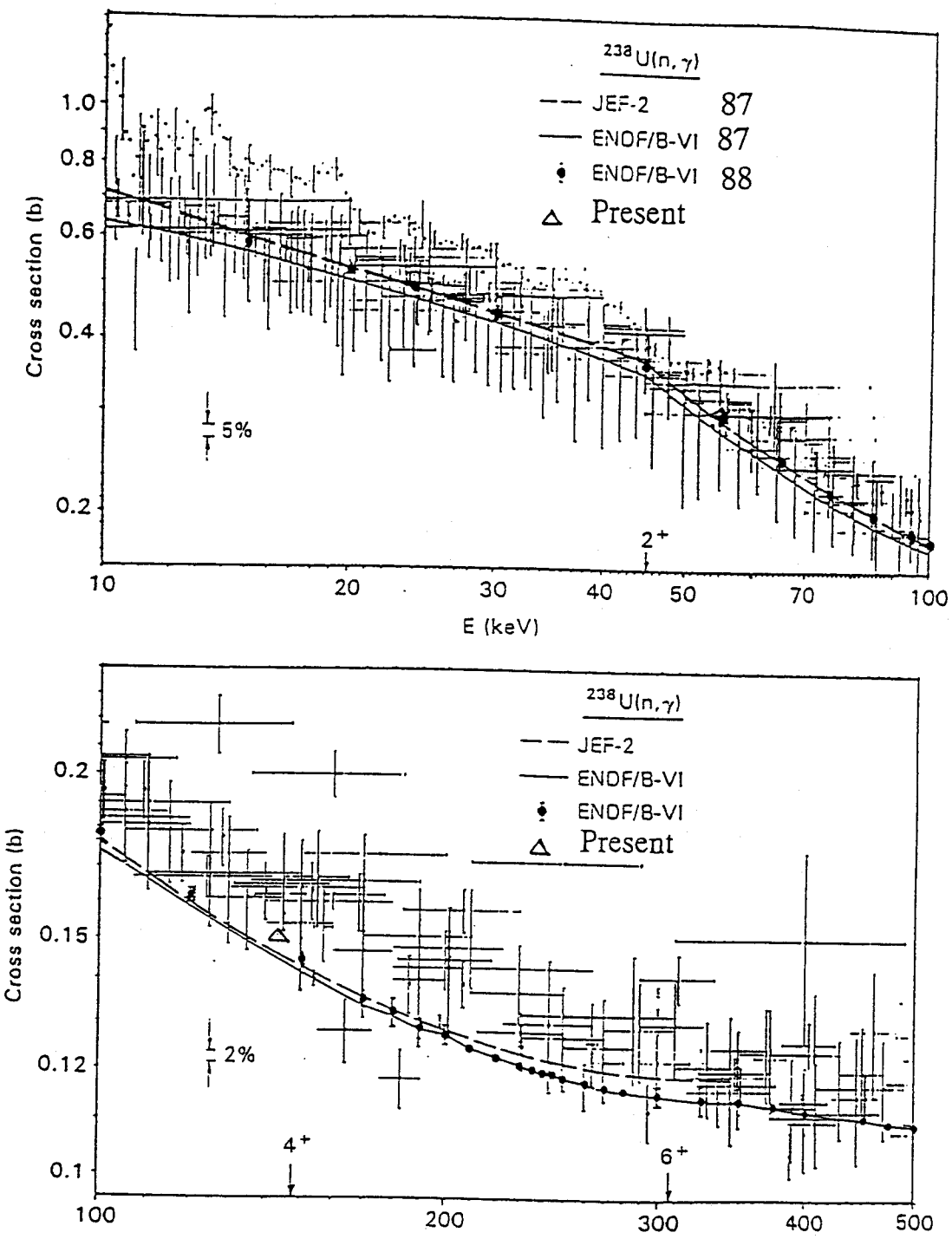


Figure 8: Average neutron radiative capture cross sections of U-238

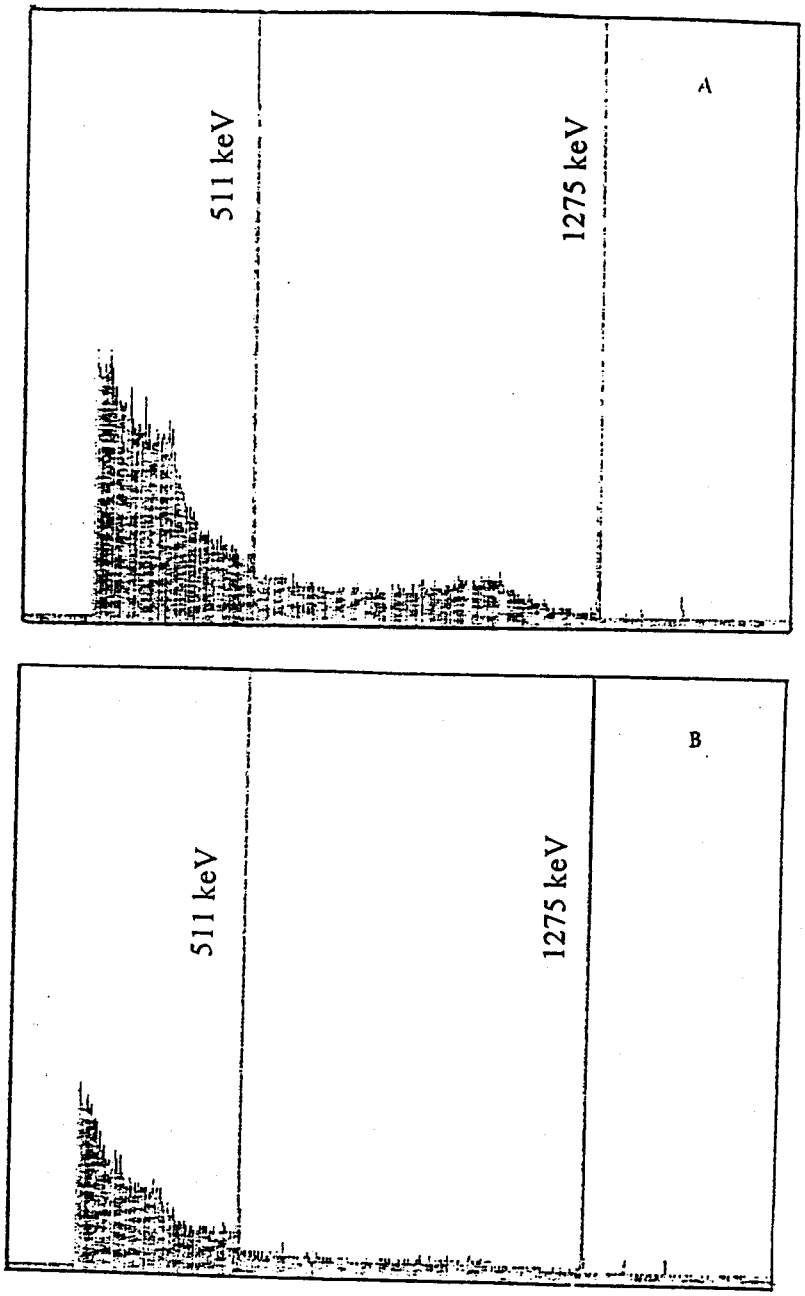


Figure 10: Gamma spectra of the Na-22 source measured by HPGe-detector in direct (A) and Compton-suppressed (B) modes

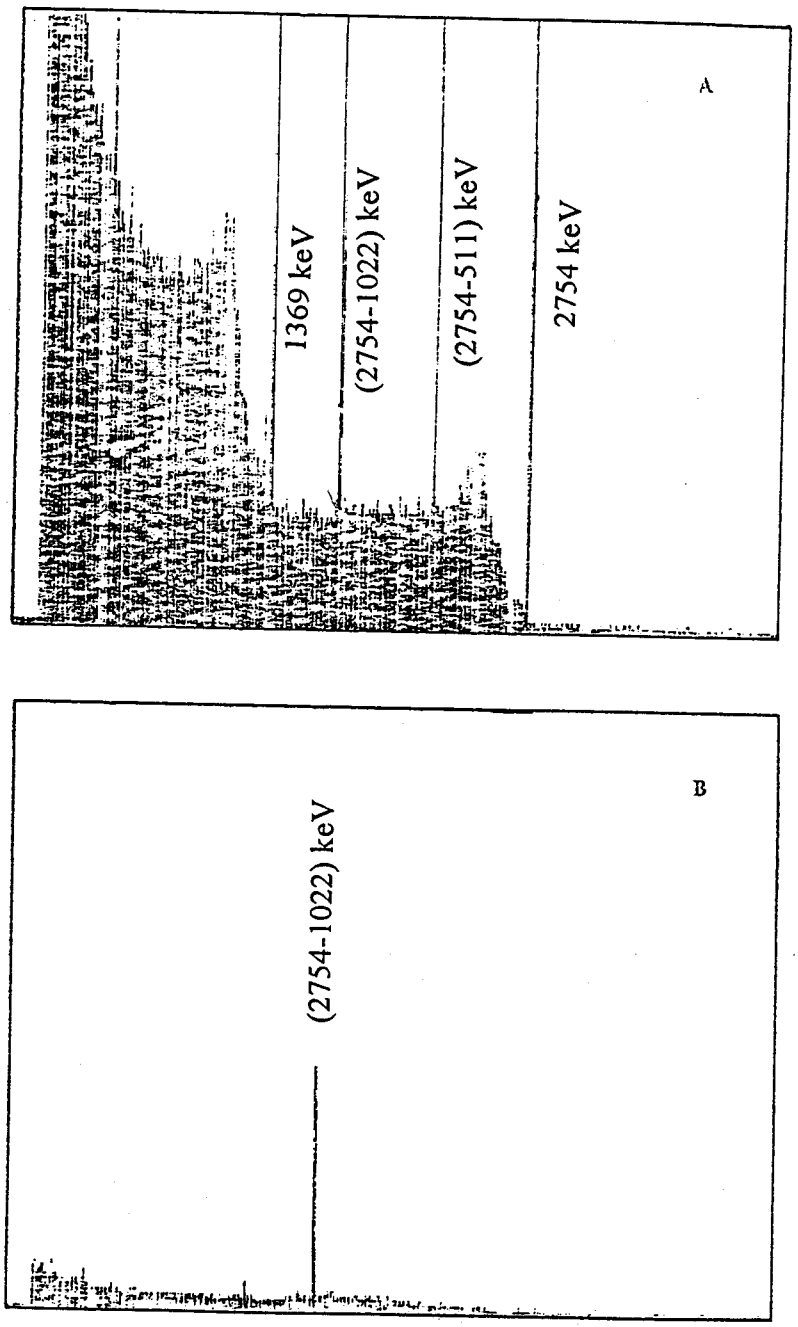


Figure 11: Gamma spectra of the activated NaCl sample measured by HPGe-detector in direct (A) and pair (B) modes

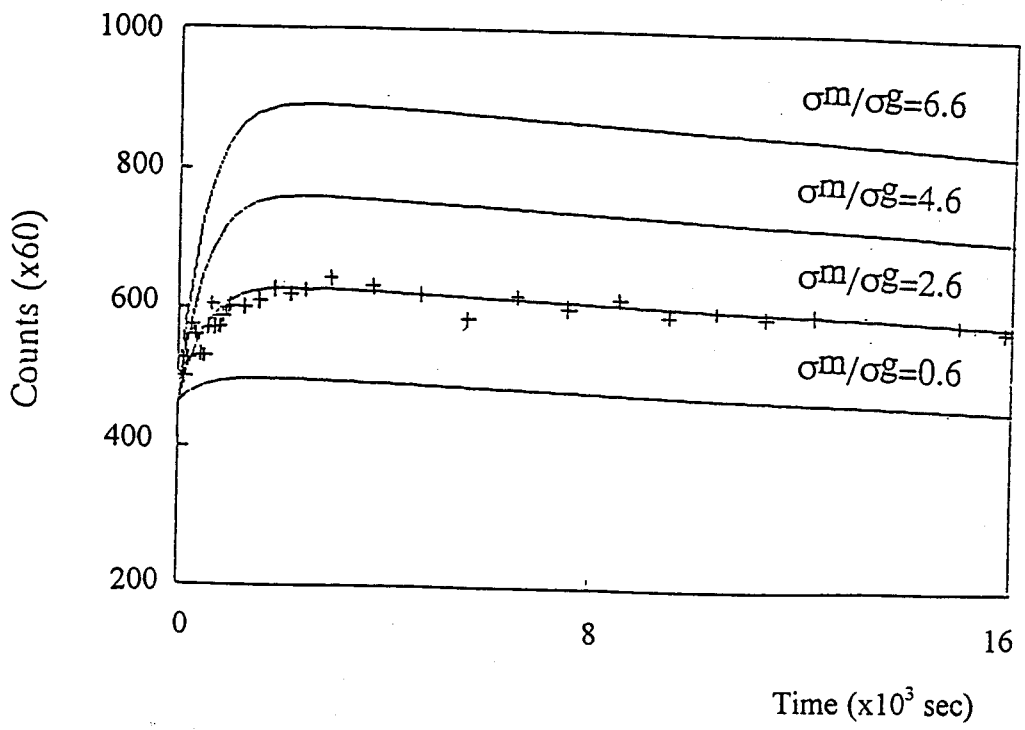


Figure 12: The time decay of the 828 keV gamma ray intensity of ^{82g,m}Br

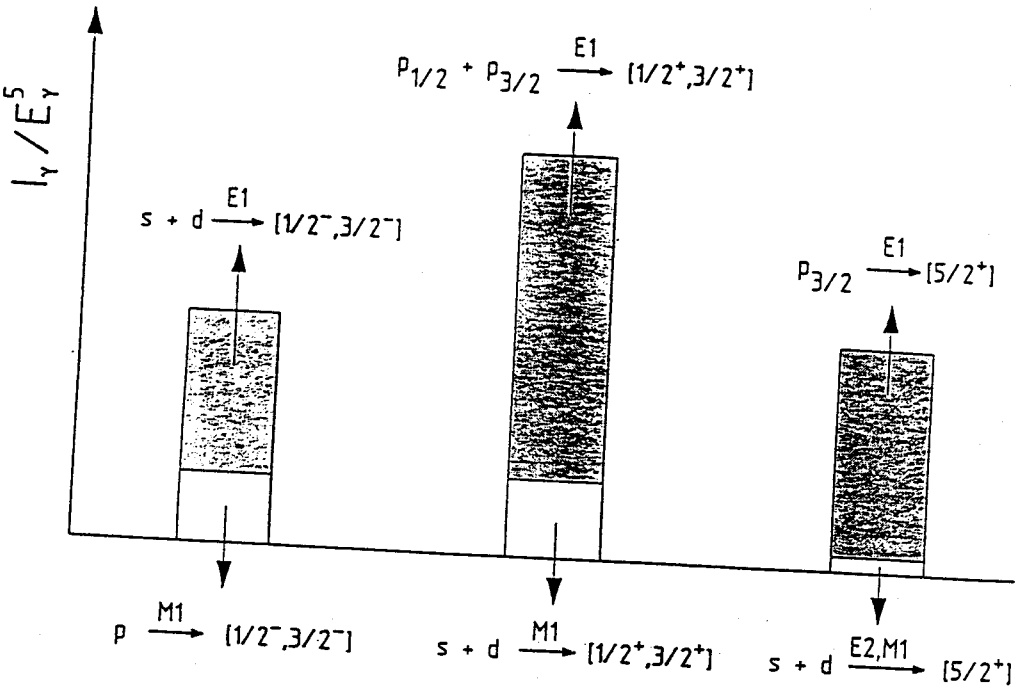


Figure 13: The relative reduced gamma transition intensities of ^{239}U

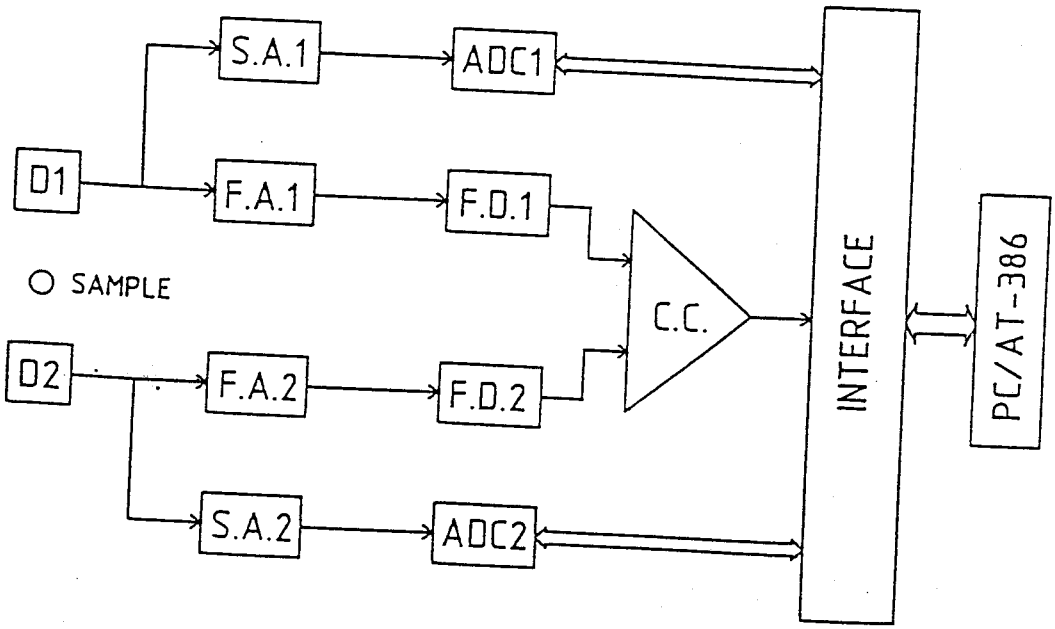


Figure 14: The scheme of the SCAP spectrometer at the Dalat reactor

D - HPGe-detector.
F.A. - Fast Amplifier.
C.C. - Coinciding Circuit.

S.A. - Spectroscopy Amplifier.
F.D. - Fast Discriminator.
A.D.C. - Analog Digital Convertor.

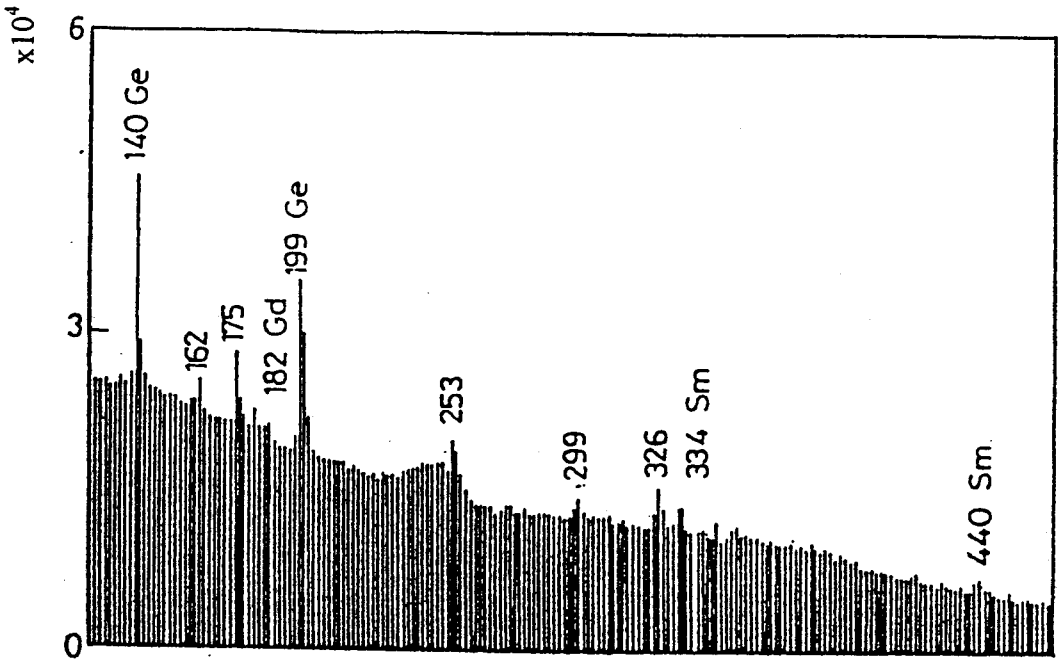


Figure 15a: A portion of the prompt gamma-spectrum of a rare earth sample irradiated by the neutron beam without a silicon filter

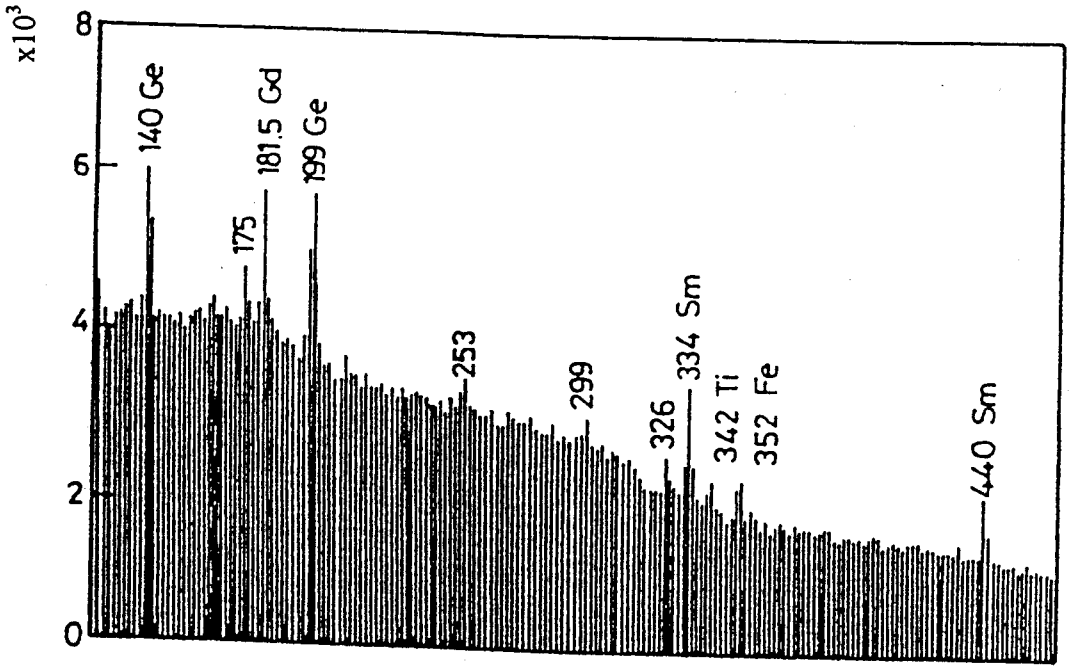


Figure 15b: The corresponding spectrum portion of the same sample irradiated by the neutron beam with a 366 mm single crystal silicon filter

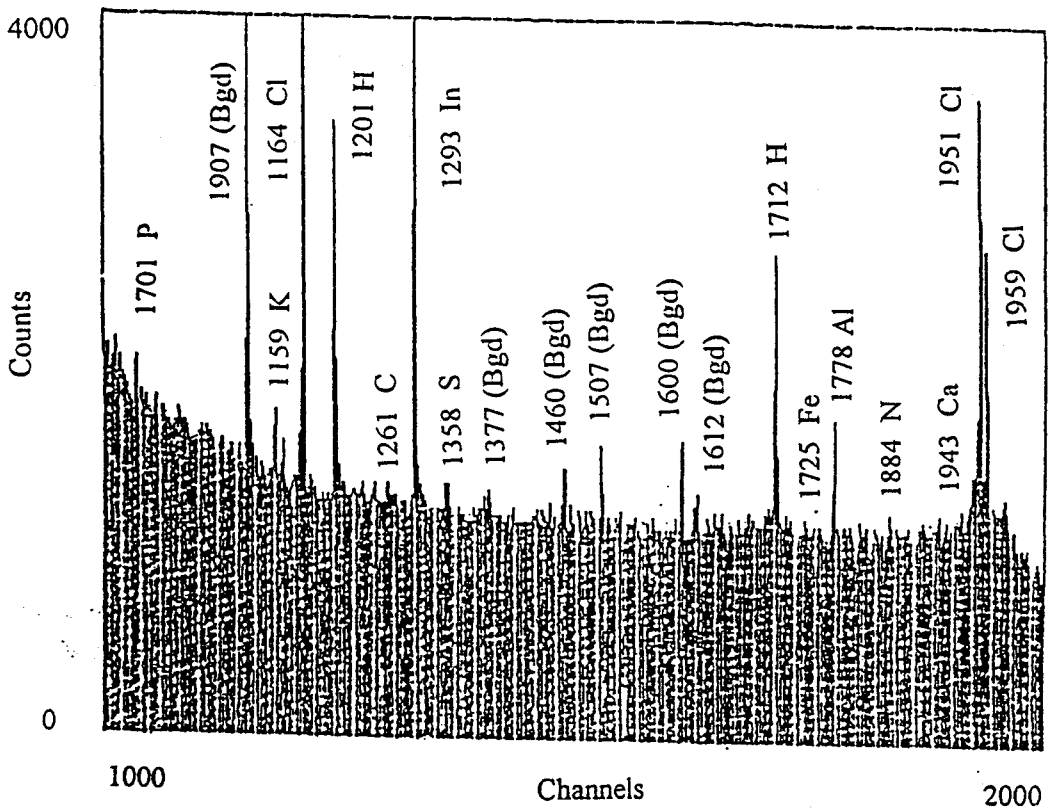


Figure 16: A portion of the prompt gamma spectrum of the Bowen's Kale sample

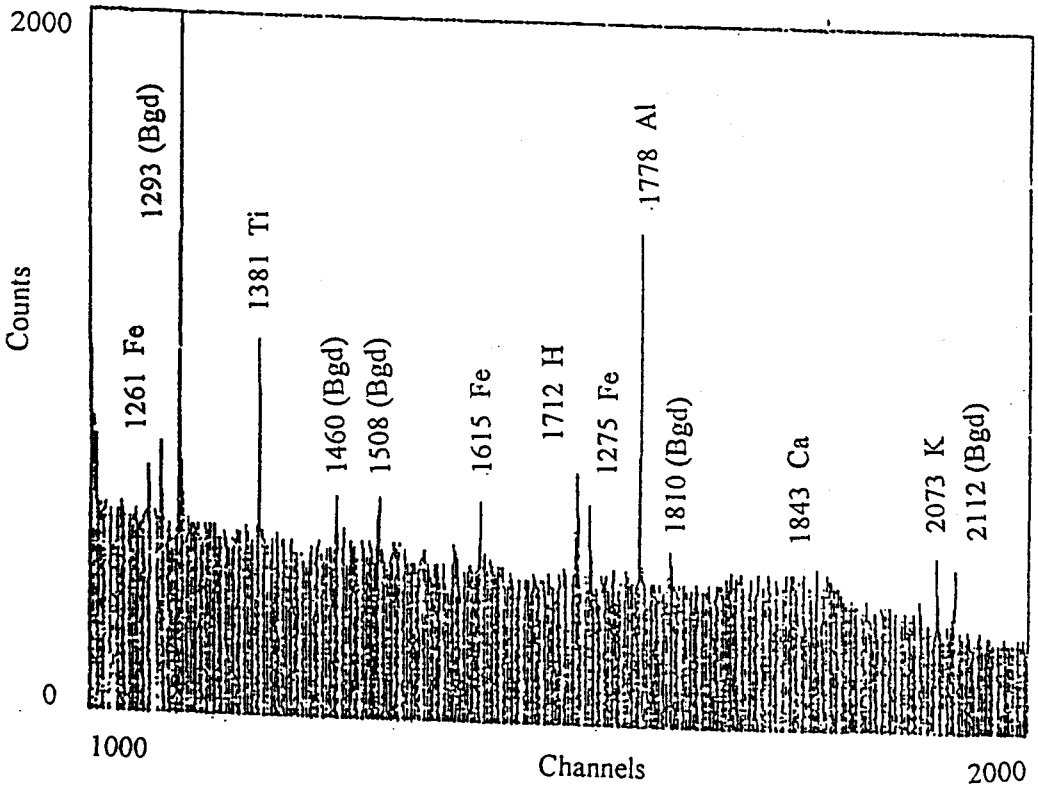


Figure 17: A portion of the prompt gamma spectrum of the SL-1 sediment sample

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