Method of Measurement of Cross Sections of Heavy Nuclei Fission Induced by Intermediate Energy Protons

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The purpose of this work is experimental studies of the energy dependence of the fission cross sections of heavy nuclei, ^{nat}Pb, ^{209}Bi, ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np and ^{239}Pu, by protons at the energies from 200 to 1000 MeV. At present experiment the method based on use of the gas parallel plate avalanche counters (PPACs) for registration of complementary fission fragments in coincidence and the telescope of scintillation counters for direct counting of the incident protons on the target has been used. First preliminary results of the energy dependences of proton induced fission cross sections for ^{nat}Pb, ^{209}Bi, ^{235}U and ^{238}U are reported.

1. Introduction

The interest in fission cross section measurements is coming both from fundamental (nuclear properties of highly excited nuclei, such as temperature dependence of level density and fission barriers) and applied nuclear physics (new energy production concepts based on accelerator driven systems, for nuclear waste transmutation technologies). All existing experimental data on total cross sections of fission process induced in heavy nuclei by protons are dispersed in the range which exceeds the declared accuracy of measurements. For some nuclei total fission cross sections are absent in the chosen energy range.

The purpose of this work is experimental studies of the energy dependence of the fission cross sections of heavy nuclei, ^{nat}Pb, ^{209}Bi, ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{237}Np and ^{239}Pu, by protons at the energies from 200 to 1000 MeV. At present experiment the method based on use of gas parallel plate avalanche counters (PPACs) for registration of complementary fission fragments in coincidence and the telescope of scintillation counters for direct counting of the incident protons on the target has been used. The PPACs for detection of fission events together with target are placed on the way of the proton beam providing very large solid angle acceptance. This allowed to provide high precision measurements at the intensity of proton beam about 10^5-10^7 p/s that is important for precise monitoring of the proton flux by scintillation counters. First preliminary results of the energy dependences of proton induced fission cross sections for ^{nat}Pb, ^{209}Bi, ^{235}U and ^{238}U are reported.

2. Experiment

The experiment was carried out at the 1 GeV proton synchrocyclotron of Petersburg Nuclear Physics Institute (Gatchina, PNPI). The targets were irradiated with protons and two resulting fission fragments were detected for each fission event. Having the number of fission events as well as the number of protons passed through the target, solid angle of registration and thickness of the target, the total fission cross sections have been determined.

2.1 Proton Beams

The synchrocyclotron of PNPI provides the external proton beam with the fixed energy of 1000 MeV and the intensity up to 1 μA. To obtain the proton beams with energies from 900 MeV to 200 MeV at intervals 100 MeV the method of degrading of the initial 1000 MeV proton beam has been chosen. It is based on the direct beam dumping on the appropriate set of copper degraders. The appropriate system of beam transportation from the degrader (installed at the accelerator outlet) to the experimental setup has been created. The system of the beam transportation and focusing consisting of two doublets of magnetic quadrupole and a bending magnet represents a magnetic spectrometer with a high momentum resolution $\Delta p/p \sim 0.008$ (FWHM). The measurements of the intensity at all energies showed that the beam intensities up to 10^7 p/s on the area $2x2cm^2$ can be reached even for 200 MeV proton beam that is more than enough for purpose of our experiment. The energies of the proton beams were determined by the time-of-flight method. The analysis of TOF spectra enabled us to conclude that an admixture of π^+ mesons in proton beams is practically absent. Maximum admixture does not exceed 1% for 200 MeV proton beam.

2.2 Registration of Fission Events

In this experiment, the detectors of choice were gas parallel plate avalanche counters since they are known to be very efficient in registering fission fragments. They are also ideal for experiments at accelerators because they have good timing properties (time resolution is better than 300 ps), and they are practically insensitive to neutrons, photons and light charged particles with minimum specific energy losses.

The detector for registration coincident fission fragments represents an assemblage consisting of two identical PPACs and the target to be studied. The electrodes of PPAC were made of thin stretched aluminized Mylar foils (300 $\mu g/cm^2$) and spaced at 1 mm. The assemblage was placed in the reaction chamber filled by saturated heptane gas at the pressure 6-10 Torr. The schematic drawing of the assemblage and related electronics is shown in Fig.1. Both fission fragments produced in the target are detected in coincidence by two PPACs with active areas of 80 mm in diameter located at a short distance at opposite sides of investigated target, providing a large solid angle acceptance of nearly 10 sr.

The pulse height from PPAC depends on specific energy losses of registered particles and gas amplification which can be changed by proper choice of applied anode-cathode potential. Thus at the fixed threshold of the discriminator the registration efficiency of PPAC can be modified by changing applied high voltage. The possibility to discriminate light particles with low specific energy losses and the good timing properties of PPACs[1] allowed us to use this assemblage directly in the incident proton beam, providing a large solid angle acceptance at 100% detection efficiency of fission fragments. However, in real beam conditions the use of the threshold criterion is not enough. The amplitude spectra derived from single PPAC show some contribution of the background events with low amplitude. These events come from the products of other nuclear reactions mainly induced by protons in the electrodes of PPACs, backing and different media on the way of the beam. If the coincidence condition is turned on, this component is strongly suppressed.

It should also be pointed out that the assemblage is quite transparent to intermediate energy protons, allowing the location of the several assemblages one after another on the way of the proton beam. This is very important in order to increase the statistics of the measurements. In our experiment we placed five similar assemblages with the investigated targets in reaction chamber. Schematic view of the experimental setup together with the set of scintillation counters is given in Fig.2.

2.3 Targets

The investigated target represents the thin layer of fissioning material laid by vacuum evaporation method of on thin backing foil (50-80 mkg/cm^2) made of alumina-Al_2O_3. The diameter of backing foils is equal to 50 mm while the diameter of target spot in the center of backing is 40 mm. The thicknesses of targets were in the range from 100 to 450 μg/cm^2.

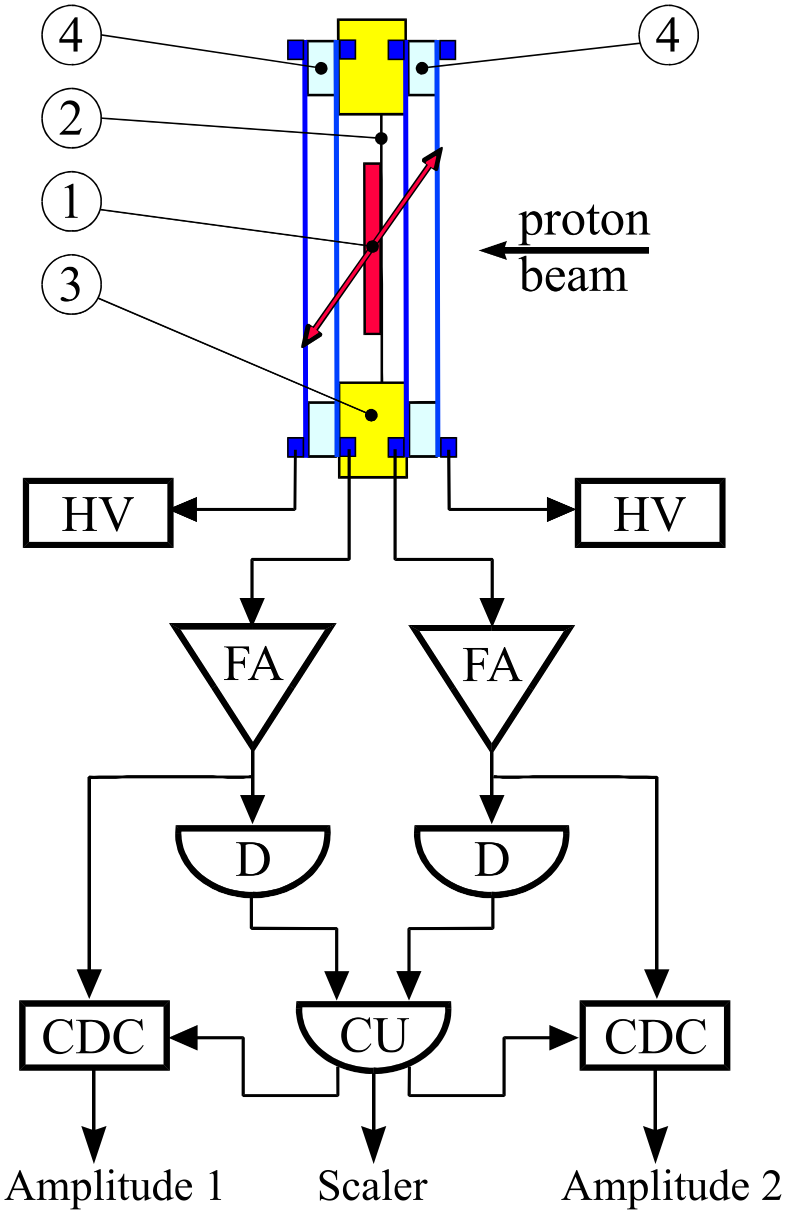

Fig.1. Schematic drawing of the fission fragment registration method

1. target; 2. target backing; 3. target support; 4. PPACs; HV– high voltage;FA- fast amplifier; D- discriminator; CDC- charge to digital converter; CU- coincidence unit;

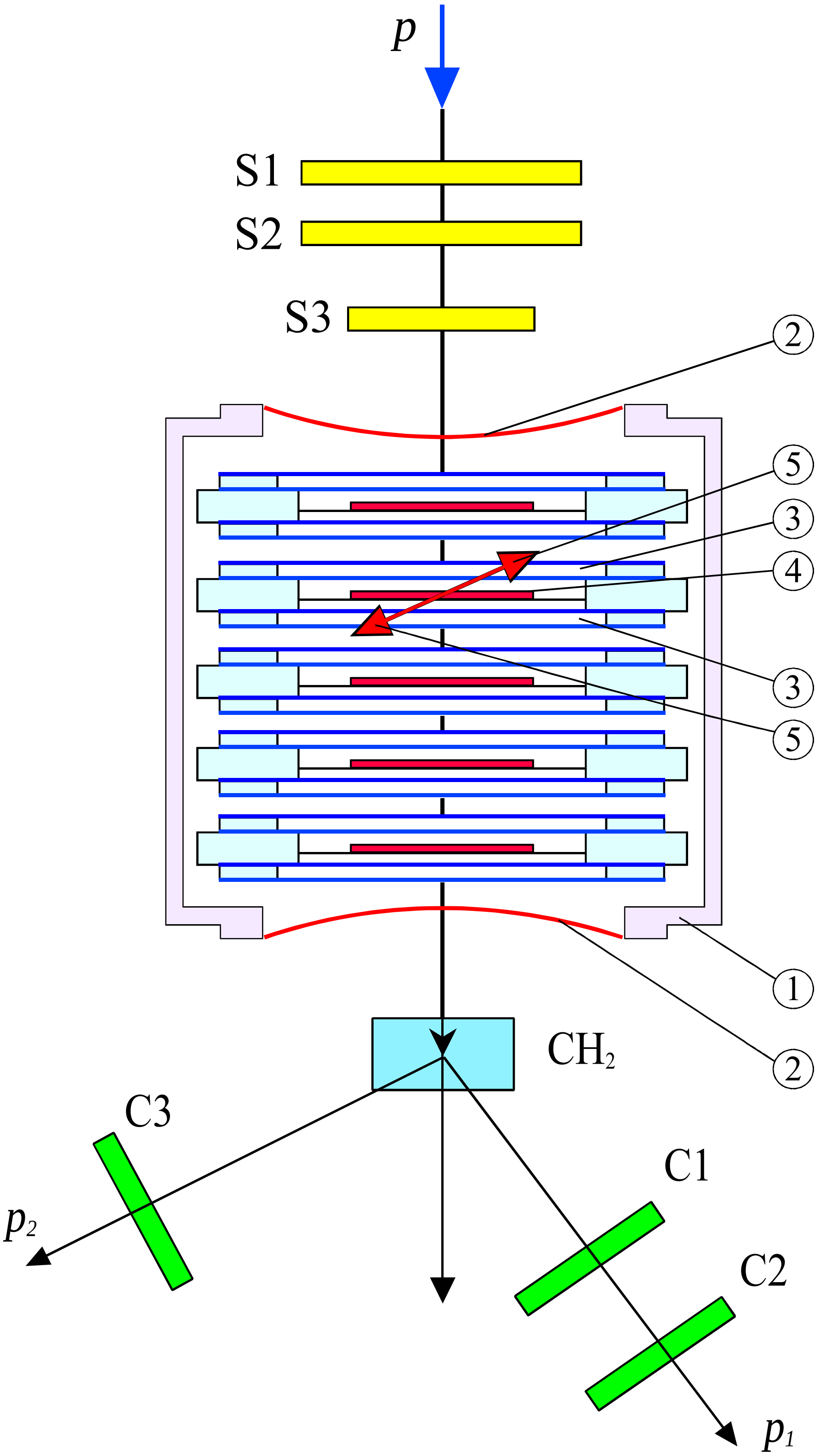

Fig.2. Schematic view of the setup for fission cross section measurements
1. chamber filled by heptane; 2. thin entrance window (Kapton); 3. parallel plate avalanche counters; 4. target on thin supporting foil; 5. registered fission fragments; S1,S2,S3- scintillation counters; C1,C2,C3- scintillation counters for registration pp-elastic scattering.

2.4 Monitoring System

The monitoring system (see Fig.2) consists of the set of scintillation counters. It intends for measurement of the incident proton flux on a working part of the target. The number of incident protons has been determined by direct counting. The monitoring was performed by telescope of three scintillation counters S1, S2 and S3 which was located just before an entrance window of the reaction chamber. All counters together with the assemblages of PPACs have been carefully aligned. However the recorded number of proton hits for each investigated target is somewhat less than the actual number because of the inefficiency of the telescope. The value of the efficiency can be estimated by measuring the ratio of the number of fission events in coincidence with the telescope and the number of fission events registered by PPAC assemblages. This ratio gives the reliable estimation of the monitor efficiency because the registration efficiency of PPAC for fission fragments is 100% and the diameter of the scintillation counter S3 is equal to the diameter of target spot. The value of inefficiency was maximum at 1000 MeV energy proton beam and did not exceed 8%.

Another source of the inefficiency of monitor is connected with a probability of appearance over than one proton in the single bunch which increases with proton intensity. The experimental estimation of the probability has been obtained by measuring the number of events corresponding to appearance at least two protons in two neighboring bunches. This value has been used for correction of monitor counting. This correction value amounts to several percent at the intensity about 10^5 p/s. All measurements have been performed at the intensities about 10^5 - 10^7 p/s.

The total proton flux has been obtained by two methods. First one is based on measurement of the sum of fission events for all targets and second one – on registration *pp* elastic scattering (see Fig.2). Both methods have been calibrated by means of direct proton counting with scintillation telescope at low intensity.

3. Preliminary Results

The number of fission events (having subtracted the background events using– threshold, coincidence and amplitude correlation as criteria of selection) has been corrected for a solid angle acceptance. To determine the geometrical acceptance of the target-PPACs system, Monte Carlo calculation was performed. This calculation takes into account the proton beam spot size, an effect of any collimators between the target and PPACs, anisotropy of fission fragments in the lab. system caused by a longitudinal component of the momentum of the fissioning nuclei and the energy losses of fission fragments in target, backing and electrode of PPAC. Our preliminary results for proton-induced fission cross sections for ^{238}U, ^{235}U, ^{209}Bi and ^{nat}Pb at energy range from 200 MeV to 1000 MeV are presented in Fig. 3-6. The previously existing proton-induced fission cross sections data for these nuclei taken from a review[2] are also shown. As one can see in Fig. 3 our results for uranium disagree with the most of early obtained data. The energy dependence of fission cross sections after slight increasing demonstrates some plateau in the energy range from 400 to 1000 MeV. Approximately the same energy dependence for ^{235}U can be seen in Fig.4 although the values of fission cross sections are slightly less than for ^{238}U. Our findings for ^{209}Bi in Fig.5 are somewhat different from the most data obtained in other experiments and show increasing of fission cross section with increasing energy from 200 MeV to 400 MeV. Our data at energies above 400 MeV have quite similar values (in the error limits), demonstrating, in all probability, a plateau in the energy dependence of fission cross sections in this energy range. The same behavior of energy dependence of fission cross sections is observed for ^{nat}Pb (Fig.6).

However, in contrast to data for ^{209}Bi, the increase of fission cross sections at energies from 200 to 500 MeV is steeper than for ^{209}Bi.

4. Summary

The method of experimental study for proton induced fission cross sections in the 200-1000 MeV energy region and preliminary results for ^{nat}Pb, ^{209}Bi, ^{235}U and ^{238}U are reported. The efficiency, accuracy and reliability of the method for obtaining the energy dependence of fission cross sections is shown. The method will be used for further measurements for ^{232}Th, ^{233}U, ^{237}Np and ^{239}Pu target nuclei.

References

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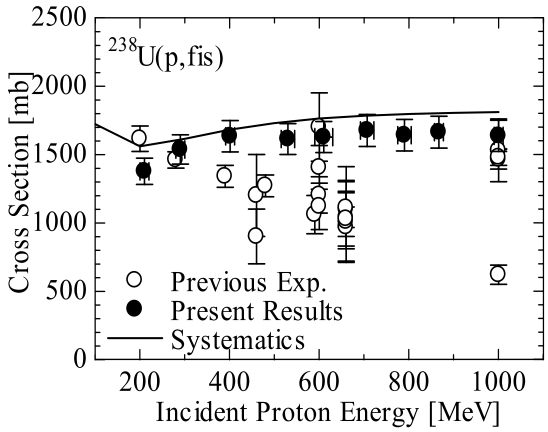

Fig.3. Energy dependence of fission cross section for ^{238}U

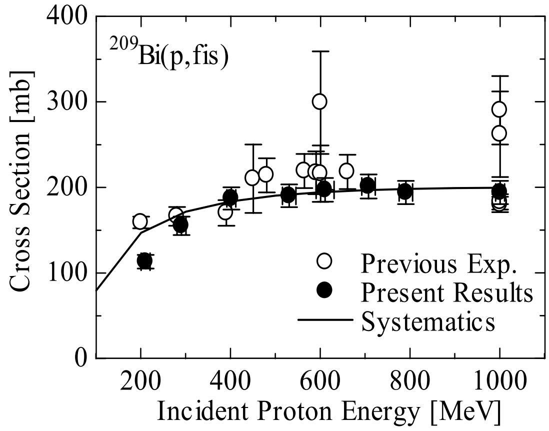

Fig.5. Energy dependence of fission cross section for ^{209}Bi

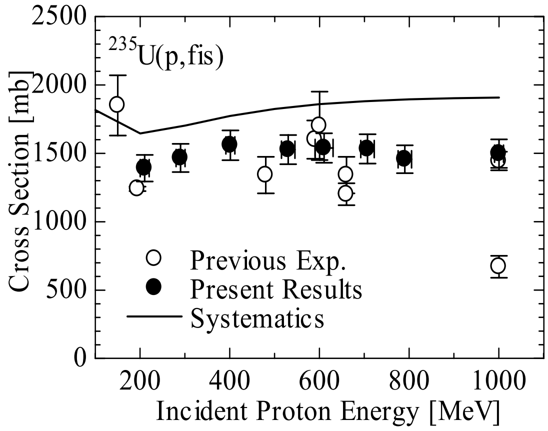

Fig.4. Energy dependence of fission cross section for ^{235}U

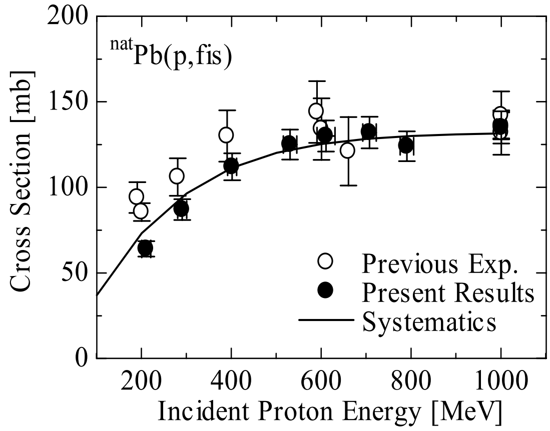

Fig.6. Energy dependence of fission cross section for ^{nat}Pb