MEASUREMENT OF CROSS SECTIONS OF HEAVY NUCLEI FISSION INDUCED BY INTERMEDIATE ENERGY PROTONS IN THE ENERGY RANGE 200–1000 MeV

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1. Introduction

The need for the information concerning fission reactions induced in heavy nuclei by intermediate energy projectiles has been obvious for a long time. The interest to this process emerges from both fundamental and applied problems of nuclear physics. In spite of extensive experimental efforts, the fission process of nuclei induced by intermediate energy projectiles remains insufficiently understood in many aspects. The proposed measurements of the energy dependence of total fission cross sections of heavy nuclei induced by intermediate energy protons will add to our understanding of the fission process in terms of nuclear properties of highly excited nuclei, such as a temperature dependence of level density and fission barriers of excited nuclei. For physics applications, the nuclear data are required for new energy production concepts with the help of accelerator driven system (ADS), for nuclear waste transmutation technologies, for accelerator and cosmic device radiation shields. All the above mentioned problems require fission cross section data of high accuracy and reliability. However, the determination of absolute total cross sections for nuclear fission induced by intermediate energy protons is not an easy task because of experimental difficulties. The main problem is to eliminate a background due to different nuclear reactions which may accompany the nuclear fission. Present threshold methods for the detection of a single fission fragment are not capable to provide the necessary discrimination from background reactions with a proper accuracy. Unfortunately, experimental data have been obtained by different methods and at different proton beam energies. Existing available data on the fission cross section are dispersed in the range which exceeds the declared accuracy of measurements and do not allow to establish reliably an energy dependence of the fission cross section on proton energy. A high accuracy of the fission cross section measurements may be only achieved by the use of modern electronic methods of the registration of both fission fragments in coincidence. Only such methods together with high precision monitoring of a proton flux on the studied target can provide the reliable discrimination of the fission process and minimize the possible errors of the cross section measurements. In the present experiment, the method based on the use of gas parallel plate avalanche counters (PPAC) for the registration of complementary fission fragments in coincidence and a telescope of scintillation counters for direct counting of the incident protons on the target have been used. Firstly this method was suggested and elaborated at PNPI for measurements of the fission cross sections [1]. At the present experiment, the PPACs for the detection of fission events together with a target are placed on the proton beam line providing very large solid angle acceptance. It allowed us to provide high precision measurements at the intensity of proton beam equal about 10^5–10^6 p/s that is important for precise monitoring of the proton flux by scintillation counters. This method was checked up in the experiment on measurements of the absolute proton induced fission cross sections of ^{238}U and ^{209}Bi in the energy range from 200 to 1000 MeV, and first preliminary results for several proton energies are presented.

2. Experiment

The experiment was carried out at the 1 GeV proton synchrocyclotron of Petersburg Nuclear Physics Institute (Gatchina). The targets of the aforementioned nuclei were irradiated with protons and for each fission event two resulting fission fragments were detected. The total fission cross sections have been determined by counting the number of fission events and dividing this quantity by the number of incident protons detected by scintillation counters.

2.1. Proton beams

The PNPI synchrocyclotron 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 100 MeV intervals, 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. First of all the processes in the degrader were simulated by a code GEANT-3. Calculations showed that even after energy dumping up to 200 MeV there is a considerable value of intensity of the secondary proton beam at the degrader outlet. It allowed one to obtain the necessary beam intensity at the place of the experimental setup located at the distance about 18 meters from the degrader outlet. On the base of the beam optics calculation the system of beam transportation from the accelerator outlet to the experimental setup has been created. The system consists of two doublets of magnetic quadrupoles and a bending magnet. The first doublet of magnetic quadrupoles was located just after the degrader. Then the secondary proton beam is turned by 18 degrees by the bending magnet. The second doublet of quadrupoles was placed before experimental setup and designed to focus the beam onto the investigated target. Really, the system of the beam transportation and focusing is a magnetic spectrometer with a high momentum resolution $\Delta p/p$ ~ 0.008 (FWHM). The measurements of the beam characteristics have been performed in several test runs and the calculation results have been confirmed. The measurements of the intensity showed that the beam intensities up to 10^7 p/s on the area 2×2 cm^2 could be reached even for 200 MeV proton beam that is more than enough for the 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. The 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. Such counters are also ideal for experiments at accelerators because they have good timing properties (the time resolution for fission fragments is better than 300 ps) and are practically insensitive to neutrons, photons and light charged particles with minimum specific energy losses in medium.

The detector for recording coincident fission fragments represents an assemblage consisting of two identical PPACs and the target to be studied. The electrodes of PPAC were made of a thin stretched aluminized Mylar foil (300 μg/cm^2) and spaced by 1 mm. The assemblage was placed in the reaction chamber filled by the saturated vapour of heptane in the range of pressure from 8 to 10 Torr. The schematic drawing of the assemblage and related electronics is shown in Fig. 1.

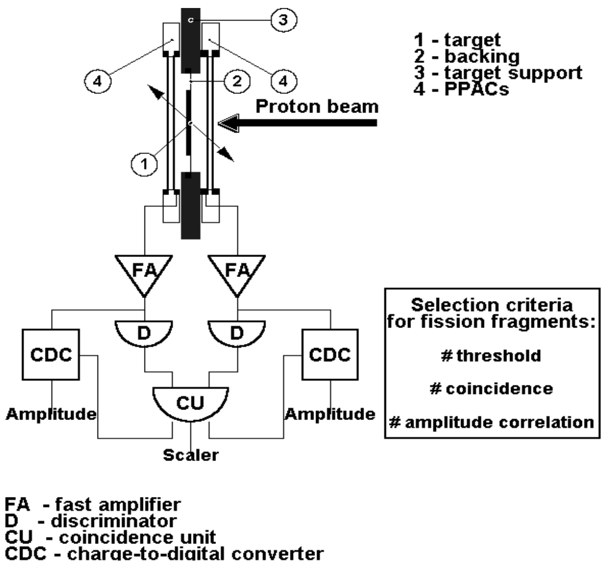

Fig. 1. Schematic drawing of the method of fission fragment registration

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 (about 7 mm) at opposite sides of investigated target, providing a large solid angle acceptance of nearly 10 sr. The signal from each PPAC after amplification by a fast amplifier is sent as input to a standard linear fan-out module that splits it into two identical output signals. One of the output signals is sent to a constant-fraction discriminator (D) and then used as an input for the coincidence unit (CU), whereas another one is delayed and used as an input for a charge-to-digital converter (CDC). The output signal of CU is used as the gate for CDCs.

The pulse height from PPAC depends on the specific energy losses of registered particles and the gas amplification which can be changed by a proper choice of applied anode-cathode potential. Thus, at the fixed threshold of the discriminator the registration efficiency of PPAC can be modified by means of changing the applied high voltage. Fig. 2 shows a dependence of counting rate of PPAC on the anode-cathode potential obtained for the spontaneous fission source ^{252}Cf. One can see two plateaus on the

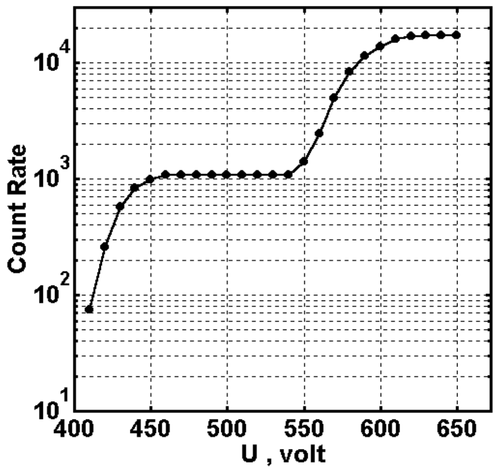

Fig. 2. Registration efficiency of the PPAC for fission fragments of ^{252}Cf versus the anode-cathode potential

dependence. One of them spans above 450 V and corresponds to the total (100%) recording efficiency of fission fragments while another starts from 615 V and corresponds to the total recording efficiency for both fission fragments and α-particles. Thus, the possibility to discriminate light particles with low specific energy losses and the good timing properties of PPACs [2] 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 a single PPAC show some contribution of the background events with the low amplitude. These events are the products of other nuclear reactions mainly produced by protons in the electrodes of PPACs, backing and different media on the path of the beam. If the coincidence condition is turned on, this component is strongly suppressed. It can be seen in Fig. 3 where the two-dimensional plot of amplitudes for coincidence events from uranium target is presented. 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 proton beam line. This is very important in order to increase the statistics of the measurements. In our experiment we placed four similar assemblages with the investigated targets in the reaction chamber. A schematic view of the experimental setup together with the set of scintillation counters is given in Fig. 4. In this case the experimental trigger is defined by a logical OR among all the outputs of coincidence units (CUs). Every time when a trigger signal is produced, a LAM (look at me) signal is also produced and sent to the data acquisition (DAQ) computer. In response to the LAM signal, the DAQ system reads out the contents of CDCs, TDC, input register and all scalers.

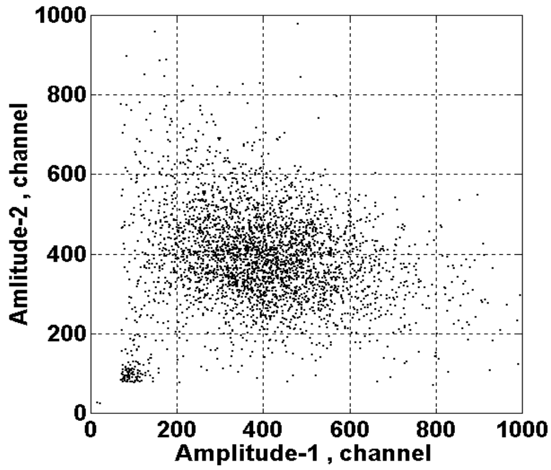

Fig. 3. Scatter plot of fission events for the uranium target

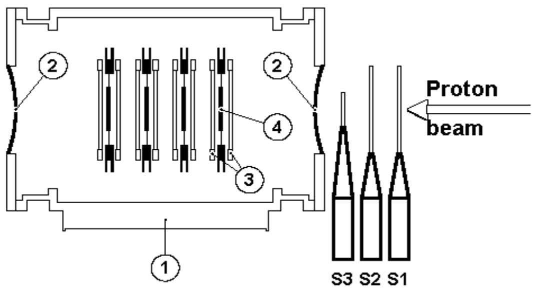

Fig. 4. Schematic diagram of the installation for fission cross sections measurements

2.3. Targets

The investigated target represents the thin layer of fissioning material laid by the method of vacuum evaporation on thin backing foil (50–80 μg/cm^2) made of alumina-Al_2O_3. The diameter of backing foils is equal to 50 mm while the diameter of the target spot in the centre of backing is 40 mm. The thickness of Bi target (630 ± 25 μg/cm^2) and also all backings were measured by the α-particles transmission method. The thickness of uranium target (155 ± 8 μg/cm^2) was measured by the α-activity analysis.

2.4. Monitoring system

The monitoring system consists of a 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 of each one. The monitoring was performed by a telescope of three scintillation counters S1, S2 and S3 located just before an entrance window of the reaction chamber (Fig. 4), all the counters together with the assemblages of PPACs being carefully aligned. The thin scintillation counter was used for measurements of the vertical and horizontal profiles of the proton beams in the target plane. These measurements were performed every time after changing the energy of the proton beam. However, the recorded number of protons hits for each investigated target is somewhat less than the actual number, because of the inefficiency of the telescope. The efficiency value 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 one of PPAC assemblage. 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 the target spot. This value was being continuously measured during the experimental run and recorded number of protons has been corrected for the efficiency. The value of inefficiency was maximum at 1000 MeV energy proton beam and did not exceed 8%.

The other source of the monitor inefficiency is connected to the time structure of the proton beam. The accelerator operating with a repetition of 50 Hz delivers up the proton beam (duty factor is about 0.5) which represents the sequence of the bunches of 12 ns width, the time interval between them being equal to 76 ns. In this case there is a probability of appearance of more than one proton in the single bunch which increases with proton intensity. The experimental estimation of this probability has been obtained by measuring the number of events corresponding to appearance of at least two protons in two neighbouring bunches. This value has been used for the correction of monitor counting. This correction value amounts to several percents at the intensity about 0.5×10^5 p/s.

3. Preliminary results

The experimentally measured fission cross sections are proportional to the ratio of fission events and the number of incident protons. The number of fission events (after subtraction of the background events using aforementioned criteria of selection) has been corrected for the solid angle acceptance. To determine the geometrical acceptance of the target-PPACs system, a Monte Carlo calculation was performed. This calculation included a proton beam spot size, an effect of any collimators between the target and PPACs, an anisotropy of fission fragments in the lab. system caused by a longitudinal component of the momentum of the fissionning nuclei and the energy losses of fission fragments in the target, backing and PPAC electrode. The last factor is essential only for fragments emitted at small angles relatively to the target plane. The number of protons has been also corrected for two kinds of inefficiency discussed in the previous section. First preliminary results of measuring fission cross sections of ^{238}U and ^{209}Bi by protons at the energy range from 200 MeV to 1000 MeV are presented in Figs. 5, 6. The existing proton-induced fission cross sections

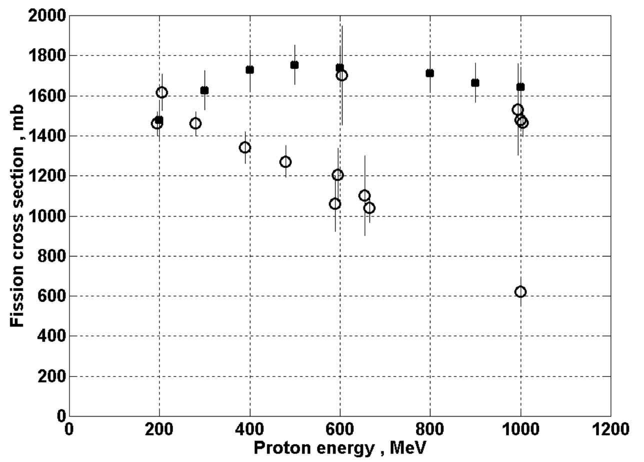

Fig. 5. Proton-induced fission cross section for ^{238}U as a function of the incident proton energy. The results of this work (full squares)

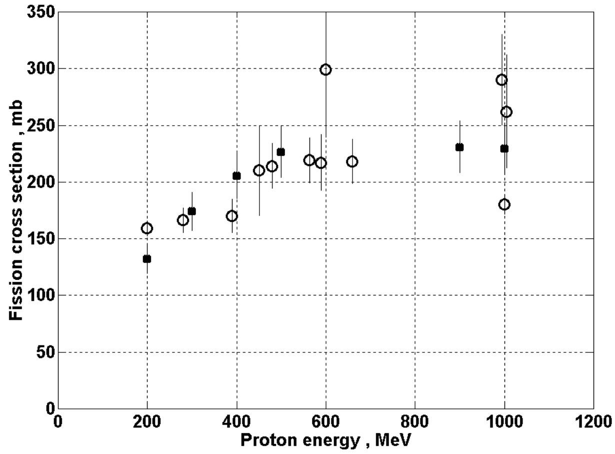

Fig. 6. Proton-induced fission cross sections for ^{209}Bi as a function of the incident proton energy. The notations are the same as in Fig. 5

data for ^{238}U and ^{209}Bi are also shown. As one can see in Fig. 5, our results for uranium disagree completely in the energy range from 300 MeV to 900 MeV with the earlier obtained data. Our data on the fission cross sections demonstrate slight decreasing with increasing energy from 400 MeV to 1000 MeV. At the same time, our data goes up with increasing energy from 200 MeV to 400 MeV.

Our findings for ^{209}Bi are somewhat different from the most data obtained in other experiments and show the rise of the fission cross section with increasing energy from 200 MeV to 500 MeV. Our data at energies above 500 MeV have quite similar values (in the error limits), demonstrating, in all probability, a plateau in the energy dependence of the fission cross sections at the energies up to 1000 MeV.

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