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RESEARCH ON FISSION DYNAMICS AT JYFL USING HENDES — HIGH EFFICIENCY NEUTRON DETECTION SYSTEM *

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In an effort to extend the scope of basic research centred around the new K-130 heavy-ion cyclotron at the Physics Department of the University of Jyväskylä a new experimental device called HENDES has been constructed. It is designed for correlation measurements of fission fragments, neutrons, and light charged particles produced in heavy ion induced reactions in the energy range of about 5 to 10 MeV/A. Collective dynamical parameters of nuclear matter are extracted from the data. New results were obtained from ^{40}Ar + ^{180}Hf reaction at E_{Ar} = 190–250 MeV. Work is in progress to study the influence of neutron excess on the fusion–fission dynamics in different combinations of Ni beams on Sn targets.

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1. Introduction

Completion of the new heavy-ion cyclotron with the K-value of 130 ($E_{\mathrm{beam}}[\mathrm{MeV}] = Kq^2/A$; where q is the charge number and A is the atomic mass number of the accelerated ion) and of the new experimental hall (inaugurated in October 1992) made a strong impact on nuclear research at

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the Department of Physics of the University of Jyväskylä; also known by its Finnish acronym JYFL. Both the extension of the available beam species, their energies and intensities as well as broad involvement of physicists from other European laboratories resulted in several new experimental projects that widened the traditional line of research at JYFL. HENDES, build primarily to obtain direct information on large scale collective nuclear motion in fusion–fission reactions induced by heavy ions, was one of the very first such new projects.

Persistent excess of pre-scission component in neutron and alpha particle spectra, contrary to the statistical model prediction, provides evidence of dynamical hindrance in fission process. It is the main goal of HENDES to investigate these phenomena. Typically, experimental spectra, separated into pre- and post-scission components, are compared with numerical calculations based on a new code with nuclear dissipation effects added to statistical model calculations. Also, since fusion–fission processes are of fundamental interest in the production and study of new exotic isotopes lying far from the stability line, some of the results, experimental techniques and model calculations developed for HENDES are of direct interest to other research groups at JYFL.

2. Description of HENDES

HENDES stands for High Efficiency Neutron Detection System — the main apparatus used during the experiments. As the name implies, neutron detectors are the major component of the set-up. Position Sensitive Neutron Detector (PSND) unit designed at Radium Institute in St. Petersburg especially for this project forms the core of the neutron detection system. HENDES has been designed to accommodate up to 48 PSNDs [1] but, thanks to the position sensitivity of each module, successful experiments have been made with as few as 3 PSNDs [2]. In the subsequent experiments that number was increased to 5 and at present 8 PSNDs are available. Neutron detectors surround a large, 80 cm in diameter, spherical reaction chamber made of titanium ring and two detachable stainless steel hemispheres. The chamber houses target ladder, a set of Fission Fragment detectors, two arrays of Light Charged Particle (LCP) telescopes, and a Micro Channel Plate (MCP) start detector for TOF measurements.

3. Position sensitive neutron detectors

Each PSND consists of a 1 m long, 6 cm in diameter quartz tube filled with about 2.3 l of NE-213 liquid scintillator. At both ends of the quartz tube there is a Photo Multiplier Tube [PMT] coupled directly to the scintillator to minimise light attenuation. The active part of the detector is closed inside a light tight, rectangular titanium box, 10 cm by 10 cm by 1.6 m. From each PMT three parameters are extracted: time signal and both fast and slow component of the light output. These parameters are needed to determine energy (from the time of flight), position (from the time difference between the opposite ends), and neutron–gamma separation (from the pulse shape analysis). As illustrated in Fig. 1, we get good gamma–neutron discrimination in the relevant neutron energy range. Position sensitivity of a PSND varies from 20 cm for 1 MeV neutrons to 10 cm at and above 4 MeV. In the same energy interval the efficiency drops from a threshold is typically set around 0.7 MeV of proton recoil energy.

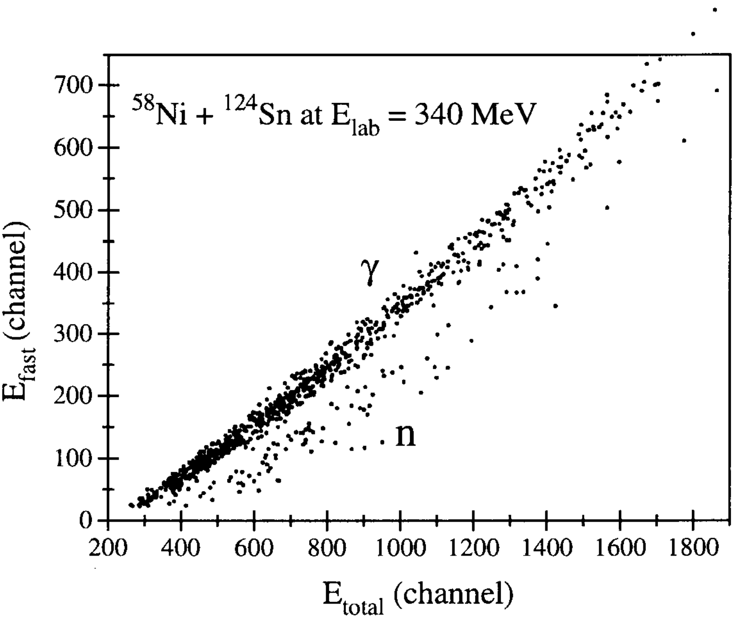

Fig. 1. Neutron–γ separation with PSND using pulse shape analysis

Figure 2 shows a typical time of flight spectrum from the 216 MeV ^{40}Ar bombardment of a ^{180}Hf target registered by a central part of a PSND located some 57 cm from the target. The sharp peak is due to prompt γ-rays and the broad bump is induced by neutrons. The remarkably low background was achieved by good shielding of the beam dump, located 3.5 m from the target, by 20 cm of paraffin (with Boron) and 25 cm of lead. In addition, no collimators are used in the vicinity of HENDES' target area.

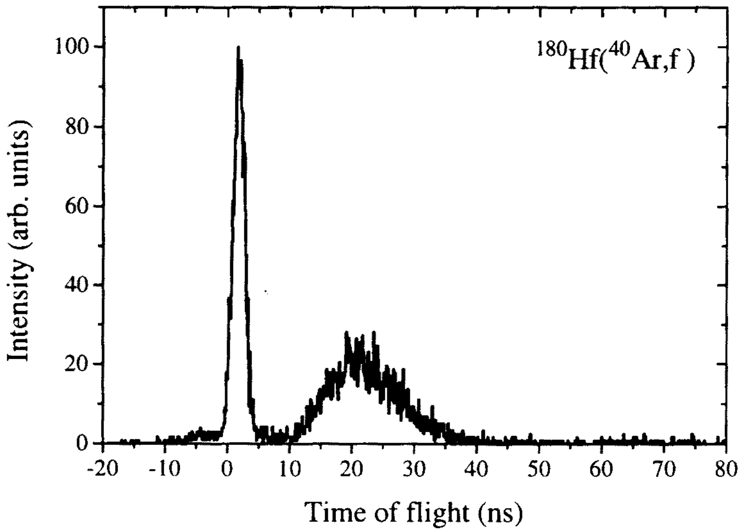

Fig. 2. A typical TOF spectrum obtained with a central section of PSND. The sharp peak corresponds to prompt γ-rays; the broad peak is due to neutrons. Although there is a very clear separation of prompt γ-rays, there is always some γ-ray contamination in the neutron bump, due to (n, γ) reaction on chamber walls *etc.*, that has to be rejected with pulse shape analysis.

4. Fission fragment detectors

Heavy fission fragments are detected with Position Sensitive Avalanche Counters (PSAC). At present, two, large area, transmission type PSACs are installed inside the HENDES chamber. They were originally designed for Dubna's FOBOS spectrometer [3]. Both PSACs have 243 mm diameter of the sensitive area. The polyester entrance foils are 1.2 μm thick. X and Y anode planes of each detector are made of 30 μm thick Cu-Be wire placed at 1 mm interval and separated by analogue delay lines allowing to reach 1mm resolution in both X- and Y-direction. Intrinsic time resolution of the PSAC is somewhat position dependent but, after corrections, can reach down to 200 ps. The detector operates on pentane in a flow-through regime under a pressure of about 6 mbar. All channels are protected against damage in case of discharges in the gas.

5. LCP telescope arrays

To detect LCPs emitted during various phases of fission we use two arrays of ΔE–E telescopes. Each consists of 10 PIN diode detectors,

$10 \times 10 \times 0.380$ mm and a common, position sensitive proportional counter working as ΔE. Position sensitivity (of the order of 1%) of the ΔE is achieved from the resistive anode made of carbon coated fibre. To reduce the need for electronics on the E side, the 10 PINs are grouped into just two sets: even and odd. This allows for a quick on-line verification of position resolution without the use of collimators.

For LCP ranges higher than 0.38 mm of silicon, we have a set of 10 double PINs that is identical to the original configuration except that behind each of the front PIN there is one more added behind producing an E detector with effective thickness of $2 \times 0.38 = 0.76$ mm. To reduce the total capacitance and maintain good energy and timing properties, the double-PIN configuration is divided not into 2 but into 5 groups.

6. Start detector

As the majority of parameters obtained with HENDES rely on TOF technique, a good start signal is of utmost importance. Since the beam pulse structure from the JYFL cyclotron has a width of over 1 ns it can not be used for this purpose. Parallel Plate Avalanche Counters (PPAC) work well as start detectors but they are relatively thick and distort substantially spectra of heavy fission fragments. By so far we have obtained the best results with custom made MCP detectors.

Our current version of MCP start detector has a titanium frame, and a 3 cm in diameter entrance foil made of gold-plated mylar. A double harp 45 degree electrostatic mirror deflecting electrons towards a micro channel plate is made of gold plated tungsten wire, 15 μm in diameter. The same wire and a similar harp grid is placed on both sides of the entrance foil. This symmetric configuration prevents electrostatic bending of the foil that is kept at a negative potential of 2 kV with respect to the grid to accelerate secondary electrons towards the mirror and further towards the MCP disk. The anode signal is amplified by a factor of 1000 in the build-in preamplifier with intrinsic noise below 4 mV and pulse rise time of 0.8 ns. In our experience this configuration allows us to operate MCP in high particle flux without saturation. A typical distance of MCP entrance foil from the target is 3 cm thus covering about 1 steradian of solid angle. A typical in-beam time resolution is better than 100 ps.

7. First results

As the test reaction for the new device ^{180}Hf(^{40}Ar, fission) at $E_{\mathrm{lab}} = 216$ MeV was chosen. Using just 3 PSND units and small MCP detectors to register fission fragment data, new information on neutron pre- and post-scission multiplicity was obtained together with average temperature parameters of neutron spectra as well as total kinetic energy and fragment mass distributions [2]. Subsequently, the measurements were repeated to extend the range of ^{40}Ar energy from 190 to 250 MeV. Also, in an off-beam run the magnitude of cross-talk effects between neighbouring PSNDs was investigated [4].

8. Current research program at HENDES

All research proposals involving K130 cyclotron at JYFL are subject to peer review by the Program Advisory Committee (PAC). At present, 3 different proposals have been approved and are being realized: *(i)* isospin dependence of nuclear collective dynamics in fusion–fission reactions, *(ii)* comparative study of actinides fission induced by light particles and heavy ions, *(iii)* study of ternary fission of ^{242}Pu compound nucleus and Pu fission isomers. In addition, there are two other nuclear reaction experiments that involve only part of HENDES' components.

9. Isospin dependence of nuclear collective dynamics in fusion–fission reactions

Strong influence of Coulomb forces on fusion–fission dynamics makes comparison of results obtained in various reactions very difficult. By restricting the study to different isotopes of the same beam/target combinations the contribution of Coulomb forces becomes fixed. At the same time the range of isospin available to the compound nucleus can remain quite large and the changes in fission barrier and in light particle binding energies can vary dramatically. For instance, using Ni on Sn combination, as in our case, with masses of stable Ni isotopes ranging from 58 to 64 and for Sn from 112 to 124 with a realistic prospect of using in the future the radioactive ^{132}Sn, one can reach compound systems with isospin between $T = 7$ (^{170}Pt) and $T = 20$ (^{196}Pt). For these extreme cases fission barrier changes by a factor of two and light particle binding energy sweeps from the proton drip line to the neutron reach side of the chart of the nuclei. Since our experimental methods allow to extract life time and temperature information at different stages of fission, we are aiming to obtain new and valuable data on nuclear dynamics of heated nuclei with high angular momenta.

At this point (August 1996) the measurements for 340 MeV ^{58}Ni on ^{112,118,124}Sn have been completed and data analysis is in progress. Further measurements are being scheduled for the fall.

10. Comparative study of actinides fission induced by light particles and heavy ions

In this project, differences between characteristics of fragment mass distribution in fission induced by light and heavy ions at similar excitation energies is studied. As the most suitable way to reduce excitation energy of the fissioning system (HI, alpha f) reactions are planned to be used. In principle, such reactions should reduce the excitation energy down to or even below the Coulomb barrier. The first experiment in this series using 128 MeV ^{16}O beam on ^{244}Cm is scheduled for December 1996.

11. Study of ternary fission of ^{242}Pu compound nucleus and Pu fission isomers

Our preliminary value of the yield of alpha particles in ternary fission of ^{242}Pu at excitation energy of 18.6 MeV, $M_a = (1.52 \pm 0.11) \times 10^{-3}$, is in agreement with other measurements. This result was obtained from bombardment of 100 μg/cm^2 ^{238}U target with 24 MeV ^{4}He. As the next step we are planing to increase the detection efficiency of the set-up and employ micro pulsing of the beam to extract $^{241\mathrm{mf}}$Pu and $^{239\mathrm{mf}}$Pu fission isomer yields, their half lives and, possibly, branching ratio for ternary fission from isomeric state. Once Li beams become available at JYFL we are planing to go on to study the ^{242}Am fission isomer using pulsed ^{7}Li beam on ^{235}U target.

12. Conclusions and acknowledgements

The first in-beam experiment using HENDES was performed on September 12, 1994 — less than two years ago. Since then, after 1000 hours of operation of which 471 hours was used during the past 6 months, a substantial amount of data was collected and several important improvements and expansions of the set-up took place. It was possible only through a very fruitful collaboration between the participating laboratories and with the help of the funding agencies. The contributions by the Academy of Finland and by the University of Jyvaskyla are especially acknowledged. We would also wish to thank JYFL cyclotron team for their constant effort in improving beam quality and all the staff of the Laboratory for maintaining excellent working atmosphere.

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