Photofission experiments at the γ-ray line of Alba

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We propose an experimental program based on the use of fission induced by quasi-monoenergetic γ-rays delivered by the Alba Compton backscattering line to investigate some specific properties of the structure and dynamics of the atomic nucleus. In particular, this facility offers the possibility to address the temperature dependence of pairing and shell effects as they manifest in the nascent fission fragments in their path from saddle to scission. The quasi-monoernergetic γ-rays also provide ideal conditions to investigate multi-phonon excitations through the fission channel as well as the dynamics of fission at high excitation energies driven by nuclear dissipation. In addition, basic nuclear data to characterise nuclear waste repositories or against fissile material proliferation can be obtained.

1 Introduction

Fission constitutes the most clear example of a large-scale collective motion in nuclear matter where both, the nuclear structure and the dynamics of the atomic nucleus manifest. This is the reason why fission is considered as a unique laboratory to investigate the atomic nucleus. However, the probes used to characterise the structure and the dynamics of the nucleus through fission are very often influenced by the reaction mechanism used to induce fission. In this sense, photons represent the cleanest approach since the excitation energy produced in the reaction corresponds to the initial energy of the photon, only a very small amount of angular momentum is induced and the composition of the target nucleus is not modified. However, the use of photon induced fission has been limited by the fact that the most commonly used photon facilities are based on bremsstrahlung. These facilities provide a continuum spectrum of photons with a maximum energy, limiting the interest of this reaction mechanism.

The possibility to produce quasi-monoenergetic γ-rays in a Compton backscattering facility opens new opportunities to investigate fission under very clean

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and well defined conditions. In addition, the large energy range that can be covered using lasers with different wavelengths, offer the possibility to investigate phenomena that manifest at different energy domains. For example it is well known that pairing and shell effects disappear with the excitation energy of the nucleus. However, multi-phonon excitations as well as the role of nuclear viscosity are expected to manifest mainly at higher excitation energies.

In this paper we summarised the physics case that can be addressed using photo-fission induced at the γ line of Alba. In addition, we also discuss the experimental techniques and detection systems required for such a research program.

2 Physics case

2.1 Pair breaking and even-odd structure in fission fragment yields

The enhanced production of even elements and the appearance of asymmetric splittings are typical examples of structural effects in low-energy fission. The observed even-odd structure in the final fission residues is related to the survival probability against pair breaking from the superfluid configuration at saddle down to the scission point. These measurements are relevant to characterise the viscosity of cold nuclear matter and then the coupling between collective motion and intrinsic single-particle degrees of freedom [1].

The first systematic overview on even-odd structure in a continuous region of fissioning nuclei was obtained only a few years ago by studying electromagnetic-induced fission from excitation energies around 11 MeV, using secondary beams [2]. This experiment showed that even-Z fissioning systems lead to an enhanced production of even fission residues with an increase of the local even-odd effect for asymmetric charge splits. At the same time, odd-Z fissioning systems lead to a positive even-odd effect for the light fission residue and a negative even-odd effect for the heavy fission partners. These results could be interpreted with theoretical considerations based on the statistical model. The local even-odd effect of the odd-Z fissioning systems and an essential part of the variation pf the even-odd effect of the even-Z fissioning nuclei have been attributed to the larger single-particle phase space available for the unpaired nucleons in the heavier fragment. Once this effect was considered, the enhanced production of fission fragments with even neutron or even proton number was quantitatively explained by the number of excited states with a completely paired configuration of the proton or the neutron subsystem at the scission point [3]. I was shown that the subsystem of one kind of nucleons (e.g. protons) may remain in the ground-state configuration with a certain probability, while the energy is stored in quasi-particle excitations of the other kind of nucleons (e.g. neutrons), even if the excitation energy exceeds the pairing gap.

However, very little is known about the excitation-energy dependence of proton even-odd effects in fission-fragment yields. Some results were obtained few years ago using fission induced by bremsstrahlung radiation and reconstructing the fission yields with gamma-spectroscopic methods [4]. Theoretical predictions and some measurements indicate that the transition from a superfluid phase to a Fermi liquid takes place at excitation energies around 10 MeV [5].

The gamma facility at Alba offers the possibility to carefully investigate the evolution of the even-odd structure in the final yields of fission residues as a function of the excitation energy. Such an experiment would required at least the full charge identification of the fission residues. This is a real challenge since such a measurement has only been done at Lohengrin at ILL [6] combining magnetic and energy loss analysis. Other possibilities are based on the full digitation of the signals induced by both fission fragments in an ionisation chamber. The final alternative is the use of gamma-spectroscopic techniques.

2.2 Temperature dependence of shell effects

The different components appearing in the yields and in the kinetic-energy distributions of the fragments produced in low-energy fission are attributed to shell effects [7]. At low energies, all nuclei with mass numbers from 230 to about 256 predominantly split into a heavier and a lighter fragment while symmetric splits are strongly suppressed. Over this whole range, the gross behaviour of the fission process is governed by the constant position of the heavy component around mass number 138 [8]. Three different fission components have been identified to explain the measured yields and kinetic-energy distributions, two asymmetric ones, the Standard I and the Standard II and one symmetric, the Superlong. The Standard I mode is characterised by a spherical heavy fragment around mass number 134 and a deformed light fragment. Standard II is characterised by a deformed heavy fragment near mass number 145 and a slightly deformed or spherical light fragment. Finally, in the Superlong component both fragments are strongly deformed. This latter component becomes more important in fission at higher excitation energies.

Important progress was obtained few years ago from an experiment where the charge distributions and kinetic-energy distributions of fission fragments produced in the electromagnetic-induced fission of more than 70 different fissile secondary beams were investigated [2]. However, very few experiments provide information on the excitation energy dependence of the different fission modes associated to shell effects. Once more, the gamma ray facility at Alba could be used for a detailed investigation of the washing out of shell effects with excitation energy by measuring the mass or charge distributions of fission residues at different gamma energies. In contrast to the previous physics case, here we do not require and excellent mass or charge resolution.

2.3 Multi-phonon excitations

In heavy nuclei, giant resonances decay by neutron emission since charged particle emission is suppressed by the Coulomb barrier. In the case of fissile nuclei, fission decay competes with (multiple) neutron emission according to the corresponding partial decay width's, Γ_f and Γ_{xn}. Since fission probabilities increase with excitation energy, multi-phonon giant resonances should appear "enhanced" in the fission channel in comparison to single-phonon states. This effect makes multi-phonon studies in electromagnetic fission particularly attractive.

Evidences for multi-phonon giant resonances in electromagnetic fission of ^{238}U have only been presented recently [9]. In this case, electromagnetic dissociation of nuclei in peripheral heavy ion collisions at relativistic energies through single- and multi-phonon excitations has been used. Although this technique allows to investigate secondary radioactive beams, the main experimental limitation arises in reconstructing the primary excitation energy of the fissioning nucleus. Since the fission fragments are highly excited and emit a multiplicity of particles and γ rays, a complete and precise calorimetry would be required. In this work the problem is overcome by exploiting the known linear relationship between primary excitation energy and the prompt neutron multiplicity accompanying the fission process.

The experiments proposed at Alba can be considered as an ideal case since the primary excitation energy of the fissioning nucleus can be established with an accuracy better than 10%. In addition the high intensity of γ rays allow to reach very low cross section processes. Here the limitation comes from the fact that only stable nuclei can be investigated, namely ^{238}U.

From an experimental point of view such an investigation just requires the measurement of the total fission cross section as function of the incident energy of the γ rays in an energy range up to some 60 or 70 MeV.

The success of the statistical model of Bohr and Wheeler [10] to describe the fission process was questioned by Kramers [11] soon after. According to this later work, fission should be considered as a diffusion process above the nuclear energy-potential in the deformation coordinate. Such a process can be described by the corresponding Fokker-Planck or Langevin equation where the diffusion process is not only governed by the nuclear potential but also by a dissipation coefficient. This coefficient represents the coupling between the intrinsic and collective degrees of freedom populated in fission.

In the pioneer work of Kramers, only the stationary solution of the Fokker-Planck equation describing fission dynamics was proposed. The complete time-dependent solution of the Fokker-Planck equation was not introduced till the eighties by Grangé and collaborators [12]. In this new work, the authors shown that the fission flux across the barrier needs time to reach its asymptotic value defined by the stationary solution of the Fokker-Planck equation proposed by Kramers. The main consequence of this work is that the hindrance of the statistical fission width is not only due to stationary but also to transient effects. In fact, during this transient time until the stationary regime of the fission width is reached, other de-excitation channels are favoured. Consequently the nuclear system cools down reducing again the fission probability respect to these other channels.

The work of Grangé and collaborators was triggered by the experimental observation of an anomalous enhanced pre-scission neutron multiplicities in fission induced in heavy-ion collisions [13]. The large pre-scission neutron multiplicities were interpreted as a signature of the delay of fission at high excitation energies. Meanwhile, other evidences for the hindrance of fission induced by dissipation and transient effects were obtained from the analysis of gamma-rays emitted during the de-excitation of the GDR [14] or directly measuring the fission time using crystal blocking techniques [15].

Recently a novel technique based on the use of fission induced in peripheral heavy-ion reactions at relativistic energies has been proposed [16,17]. The advantage of this reaction mechanism is that the excited fissioning nucleus is produced with well defined initial conditions that can be easily described using the Serber model [18]. In addition, these reactions lead to almost undeformed nuclei covering a large range in excitation energy. In these works, the fission cross sections, the charge distribution [17] or the isotopic distribution [16] of fission residues have been used as signatures of the fission dynamics.

The γ line at Alba offers the possibility to investigate photo-fission at high energies. The advantage of this reaction mechanism is the low amount of angular momentum induced in the collision, simplifying the description of the initial conditions of the fissioning nucleus.

Different observables can be used to investigate this process. The simplest would be the evolution of the total fission cross section with the energy of the incoming γ ray. A More complete detection set up would require the measurement of the charge of the final fission fragments and the possibility to detect neutrons.

2.5 Basic nuclear data

Photo-fission is considered as an optimum non-destructive probe for the survey of fissile material through the detection of beta-delayed neutrons emitted by the fission fragments. This technique is valid to detect small quantities of any fissile nuclei in any kind of container since both gammas and neutrons are deeply penetrating radiations. This method can be applied to determine the amount of radioactive material in the containers used for nuclear waste disposal or to control the proliferation of nuclear material by installing detection systems based in this principle in ports or airports terminals.

To detect the fissile material one just need to detect the delayed-neutron emission. However, the identification of that material requires a precise knowledge of all fission residues produced in photo-fission reactions and to characterised the delayed-neutron emission. Nowadays, very few data on photo-fission can be found in the data bases. A detailed experimental program should be performed to obtained all the data required for these applications. Once more the γ ray facility at Alba offers unique possibilities for these applied investigations.

3 Experimental requirements

The physics cases presented in the previous sections required the use of several observables characterising the fission process. In particular, total fission cross sections, mass or charge distributions of fission residues and β-delayed neutron emission constitute some examples.

3.1 Total fission cross section

Total fission cross sections are needed to investigate multi-phonon excitations or the dynamics of fission at high-excitation energy. The simplest technique for these measurements is based on the use of parallel plate avalanche counters PPACs [**?**].

3.2 Charge/mass distribution of fission residues

Mass distributions of fission fragments can be obtained with a resolution around 1% using time-of-flight techniques with PPACs or silicon detectors [**?**]. Charge distributions can also be measured with ionisation chambers with a resolution of a few per cent []. Measurements with this resolution could be used to investigate the excitation energy dependence of shell effects in the yields distributions of fission residues.

The investigation of even-odd effects requires a higher resolution in the determination of the mass or charge of the fission residues. Nowadays seems not evident to reach resolutions well bellow 1%. A possible solution could be based on a complete pulse shape analysis from the digitalisation of the full signals induced by the fission fragments on an ionisation chamber.

3.3 Neutron emission

Neutron detectors could also be required to measure the neutrons emitted during the fission process or the β-delay neutrons emitted in the radioactive decay of the fission residues.

4 Conclusion

Fission induced by quasi-monoenergetic γ rays offer several possibilities for experiments were the excitation energy dependence of structural effects that manifest in fission like pairing or shell effects can be investigated. However, the most promising experiments are related to the search of evidences for multi-phonon excitations or to the characterisation of the fission dynamics at high excitation energy. In addition, basic nuclear data that could be used in some applications related to the detection of fissile material could be accurately measured. The experimental techniques used in most of these experiments are well known and only the precise determination of the mass and charge of the fission fragments seems to be a real challenge.

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