Workshop on Fission Fragment Angular Momenta

mardi 21 juin 2022 - vendredi 24 juin 2022

Recueil des résumés

Contents

Welcome and Introduction / 12

Welcome

Auteur: Aurel Bulgac[1]

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Welcome and Introduction / 13

Introduction

Auteur: Jerry Wilhelmy[1]

[1] *Los Alamos National Laboratory*

Experiment / 14

Overview of available spin-related experimental data

Auteur: Jonathan Wilson[1]

[1] *IJC Lab, Orsay*

The understanding of angular momentum generation in the fission process is important not only for a complete description of nuclear fission but also determines the neutron/gamma competition and total number of gamma rays emitted in fission fragment decay. This knowledge impacts the gamma-heating problem in nuclear energy applications and also for understanding the accessibility of excited states in nuclear structure studies of neutron-rich nuclei. Since the early 1970's it has been observed from discrete gamma-ray emission that fission fragments possess an average angular momentum of typically 6-7 hbar [1]. In this presentation an overview will be given of the various measurements of spin-sensitive observables (gamma-ray multiplicities, isomeric yield ratios, average spins at yrast, etc.) that have been performed up until the present time. Of particular interest is how these observables vary as a function of the mass, charge and kinetic energy of the resulting fission fragments and the mass, charge, excitation energy and initial angular momentum of the compound nucleus undergoing fission. Suggestions will be given for how future multi-observable experiments might help advance our current understanding of this interesting problem, including exploration of fragment gamma-ray angular distributions and correlations.

[1] J. B. Wilhelmy, E. Cheifetz, R. C. Jared, S. G. Thompson, H. R. Bowman, and J. O. Rasmussen Phys. Rev. C 5, 2041 (1972)

Fission modelling / 15

Fission fragment rotational modes: Classification, agitaiton, observation

Auteur: Jorgen Randrup[1]

[1] *Lawrence Berkeley Laboratory*

Gamma ray multiplicities and spectra / 16

Correlations between fragment angular momentum and excitation energy

Auteurs: Nathan Ghia[1]; Stefano Marin[1]

[1] *University of Michigan*

We present recent experimental results that indicate the existence of significant correlations between the fragments'angular momenta and excitation energies. Both the experiment we present are based on the Chi-Nu array at the Los Alamos Neutron Science Center but are independent observations of the spin-energy correlations in fission. We find evidence of event-by-event neutron-gamma multiplicity, energy, and angular correlations in 252Cf(sf). We have also determined an increase in quadrupole gamma rays along rotational bands with increasing incident neutron energy in 239Pu(n,f). We briefly described the experimental methods used to determine these correlations and how the data were compared to model calculations. These experimental results indicate an increase in the average angular momentum with fragment intrinsic excitation energies.

Microscopic Calculations / 17

Fission fragment intrinsic spins, their relative orbital angular momentum, and their correlations within a fully microscopic approach

Auteur: Aurel Bulgac[1]

[1] *University of Washington, Seattle*

Fission dynamics from saddle-to-scission, and even beyond, is a non-equilibrium quantum process and its description within a fully quantum many-body framework has been a formidable problem to find its solution in theoretical physics for more than 8 decades now. Within the Time-Dependent Density Functional Theory (TDDFT) extended to superfluid fermion systems, which is a mathematically equivalent formulation of the Schrödinger many-body equation at the one-body level, many questions can now be addressed. It was recently proven within TDDFT framework that the saddle-to-scission dynamics is strongly dissipative, hence the use of nuclear potential energy surface and corresponding collective moments of inertia becomes illegitimate, and only a small number general properties of the nuclear energy density functional are important (nuclear saturation density, surface tension, symmetry energy and to a less extent its density dependence, spin-orbit interaction, pairing, and single-particle level density at the Fermi level, thus only 7 parameters) in order to quite accurately describe the properties of the fission fragments, without any fitting parameters. Apart from that TDDFT reveal that several other assumptions made in many phenomenological approaches are incorrect.

Within a series of recent studies, we have extracted the fully separated fission fragment intrinsic spins and their relative orbital angular momentum, before the emission of neutrons or statistical gammas, without resorting to any assumptions or simplification. Moreover, we have also extracted the triple probability distributions of the fission fragments intrinsic spins and their relative orbital momentum for several actinides, in both spontaneous and induced fission and studied the dependence of these properties, including the excitation energies of the emerging fission fragments on the initial energy of the fission compound nucleus. We were able to characterize various relative fission fragments modes (twisting and tilting, bending and wriggling) and their correlations between fission fragments. We showed that twisting mode is extremely active, and that the bending mode surprisingly favor and almost anti-parallel fission fragment intrinsic spin orientation, at odds with other predictions from phenomenological models so far. Among the many unexpected surprises reveled by the real-time microscopic study of fission dynamics we have shown that the primordial light fission fragment carries more excitation energy, and as a result is "hotter,"and that the primordial light

fission fragment carries a larger intrinsic spin before the emission of neutrons and statistical gammas. Estimates of fission fragment spin distributions show an increase of the average spin in both fragments with the energy of the compound, with the heavy fragment spin increasing faster.

Microscopic Calculations / 18

How does the angular momentum of fission fragments depend on their mass? An insight from microscopic theory

Auteurs: Nicholas Schunck[1]; Petar Marevic[2]

[1] *LLNL*

[2] *ENS Saclay*

Recent experiments have provided strong evidence that the angular momentum of fission fragments follows a sawtooth pattern as a function of their mass. Reproducing this behavior without fitting it explicitly requires microscopic models capable of describing the physics of scission without adjustable parameters. Using the Hartree-Fock-Bogoliubov theory and symmetry restoration techniques, we recently reported the first microscopic calculation of angular-momentum distributions for a wide range of fragment masses observed in experiments. For the benchmark case of the neutron-induced fission of 239Pu, we found that the angular momentum of the fragments is largely determined by the nuclear shell structure and deformation, and that the heavy fragments therefore typically carry less angular momentum than their light partners. The obtained distributions can also be used as ingredients to phenomenological models that describe deexcitation of the fragments, thus paving the way toward the modeling of fission based on inputs from microscopic theory. In the particular case of 239Pu(nth,f), the calculated dependence of the angular momenta on fragment mass after the emission of neutrons and statistical photons is linear for the heavy fragments and either constant or weakly linear for the light fragments, consistent with recent experiments.

Isomeric Yield Ratios / 19

Measurements of isomeric yield ratios

Auteur: Stephan Pomp[1]

[1] *University of Uppsala*

Isomeric yield ratios are among the observables to study angular momenta of fission fragments. The most common way to obtain such ratios relies on gamma spectroscopy. Recently, direct mass measurement methods have achieved mass resolving power that makes them relevant for isomeric yield ratio studies. This talk will give an overview of the used experimental techniques, and summarize the status of available isomeric yield ratios from fission.

Isomeric Yield Ratios / 20

Angular momentum distribution of 132Sn from thermal n-induced fission

Auteur: Abdelaziz Chebboubi[1]

[1] *ILL Grenoble*

Usually, fission product angular momentum is studied through prompt γ emission. A complementary technique is to use the isomeric ratio. This observable is of interest because it preserves the initial angular momentum information resulting from the fission process just after the prompt particle emission.
The coupling of the LOHENGRIN recoil spectrometer (located at the Institut Laue- Langevin, France) with an ionization chamber to count incoming fragments and two clovers of four Ge detectors each to detect decay γ-rays permits to measure isomeric ratios of fission products. Recently experimental campaigns achieved at the ILL showed the kinetic energy dependence of isomeric ratios for 132Sn for 235U(nth,f) [1] and 241Pu(nth,f) reactions [2]. A Bayesian assessment of the angular momentum distribution of 132Sn is proposed according to calculations performed with the FIFRELIN code. The similar angular momentum distributions found for both reactions are interpreted with angular momentum generation models.
[1] A. Chebboubi et al., Phys. Lett. B, 775, 190-195 (2017)
[2] J. Nicholson et al., EPJ Web of Conferences 256, 00011 (2021)

Isomeric Yield Ratios / **21**

A new technique for extracting isomeric yield ratios of fission fragments

Auteur: Dorthea Gjestvang[1]

[1] *University of Oslo*

An observable that is strongly coupled to a fission fragment's angular momentum is its isomeric yield ratio (IYR), defined by the amount of fragment decays that passes though a metastable state. Though this observable is limited to fragments with such isomeric states, the IYR is known to be sensitive to small changes in the fragment's angular momentum distribution. Isomeric yield ratios have therefore been measured over the last four decades, where various techniques allow the IYR extraction of isomers with different half-lives, see eg. Refs.[1-3].
A new technique for extracting IYRs of fission fragments has been developed. With this technique, isomers with half-lives on the order of 10−7 seconds become accessible. We show values for the IYRs of 134Te produced in the 238U(n,f), 232Th(n,f), and 252Cf(sf) reactions. Furthermore, this technique allows for the control of the number of neutrons emitted from the system as well as the minimum spin of the partner fragment, which adds new information to our understanding of angular momentum generation in nuclear fission.
References:
[1] H. Naik, et al., Nuclear Physics A 587, 273 (1995).
[2] T. Datta, et al., Phys. Rev. C 28 (1983).
[3] A. Mattera, et al., Eur. Phys. J. A 54, 33 (2018).

Shape dynamics models / **22**

Rotational angular momenta of fission fragments studied by antisymmetried molecular dynamics

Auteur: Satoshi Chiba[1]

[1] *Tokyo Institute of Technology*

Jingde Chen, Chikako Ishizuka, Satoshi Chiba
Angular momentum of fission fragments (FFs) is an important physics quantity which governs the statistical decay of excited FFs through conservation law formulated as the Hauser-Feshbach theory, which leads to the independent fission products. Indeed, spins of the fission fragments are "measured"by applying the Hauser-Feshbach theory to interpret various observables, such as photon

spectra or isomer ratios, obtained after the statistical decay. Despite its importance, direct observation nor theoretical estimation of spins of the FFs is not an easy task, and much uncertainty still exist. Origin of the spins of FFs itself is uncertain. Historically, spins of the FFs are discussed in relation to rotation of the fission fragments, and possibility of several rotational modes have been suggested, namely, bending, wiggling, tilting and twisting modes. The first 2 of this list refer to rotation of FFs perpendicular to the fission axis, while the last 2 refer to rotation in parallel or antiparallel to the fission axis. In this talk, we will explain results of calculation of the rotational angular momentum of FFs, their relative orientation and their orientation with respect to the fission axis. These quantities were obtained by the antisymmetrized molecular dynamics, which takes account of the mean-field effects and stochastic nucleon-nucleon collision, the latter giving branching of the wave function and gives "distributions" of any quantities we can calculate. Our results, which can be fitted nicely by the conventional Fermi-gas spin distribution function, were compared with those calculated by Bulgac et al. with a legitimate method based on time-dependent density functional theory and angular momentum projection. Interesting similarities and differences were observed.

Shape dynamics models / 23

Fission fragment angular momenta generated during overdamped motion

Auteurs: Sven Aberg[1]; Thomas Dossing[2]

[1] *Lund University*

[2] *Niels Bohr Institute*

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The angular momentum of fission fragments is calculated for thermal neutron induced fission of 236U. The basis is the scission shapes and internal excitation energies calculated previously by the Metropolis random walk realization of overdamped motion [1]. At scission, the statistical excitation, described by level densities of the emerging fragments, generate the angular momentum. It is argued that the distribution of angular momentum is basically two-dimensional, with the fragments carrying zero or very small angular momenta in their direction of motion.
First, we perform an evaluation based on the Fermi gas description with excitation energies from measured neutron multiplicities. We then include shell structure and utilize level densities calculated combinatorically versus excitation energy and angular momentum [2]. Calculated average angular momenta are compared to recent data [3], and overall, a good agreement is found. The observed saw-tooth behavior of the average angular momentum as function of mass number is discussed in connection to the similar behavior of the average neutron multiplicity. Our calculations underestimate the amplitudes of both saw-tooth curves. The magnitudes of the angular momenta of light and heavy fragments are weakly correlated, in accordance with data.

Gamma ray multiplicities and spectra / 24

Measurements of γ-ray multiplicity correlated with fission fragments mass and kinetic energy

Auteur: Valentin Piau[1]

[1] *CEA Cadarache*

Alf Göök, Andreas Oberstedt, Stephan Oberstedt, Olivier Litaize, Abdelaziz Chebboubi
The nuclei generated at scission are left in highly excited states, and will dissipate their excitation energy and angular momentum through the emission of neutrons, photons and conversion electrons. In this context, the study of prompt γ-ray emission is an interesting tool to assess the angular momenta of the fragments after neutron emission. In particular, measurements of the mass-dependent prompt γ-rays multiplicity M¯γ(A) (i.e. the average number of photons emitted by the highly excited fission fragments) are of primary interest.
However, such measurements are challenging, as both fragments are simultaneously emitting γ-rays, shortly after scission. Two methods were developed decades ago to tackle this issue: the collimator method [1,2] and the "weighting method"[3,4], also referred as Doppler-shift method. This second method was recently applied to the VESPA setup (VErsatile γ SPectrometer Array) to extract the prompt γ multiplicities for the spontaneous fission of 252Cf, as a function of fission fragments mass and total kinetic energy [5]. In this talk, the experimental procedure used in this recent experiment will be presented. The results obtained will be discussed, and will be compared to other multiplicity measurements performed in the past for various fissionning systems, and results from recent calculations with the FIFRELIN [6] code.

References :
1. S.A.E Johansson, Nucl. Phys. 60, 378 (1964)
2. P. Armbruster, H. Labus and K. Reichelt, Z. Naturforsch. A 26, 512 (1971)
3. H. Maier-Leibnitz, H.W. Schmitt and P. Armbruster, in Proceedings of the Symposium on the Physics and Chemistry of Fission, Salzburg, IAEA, Vol. II, p. 143 (1965)
4. F. Pleasonton, R.L. Ferguson and H.W. Schmitt, Phys. Rev. C 6, 1023 (1972)
5. M. Travar, V. Piau, A. Göök et al., Phys. Lett. B 817, 136293 (2021)
6. O. Litaize, O. Serot and L. Berge, Eur. Phys. J. A 51, 177 (2015)

Gamma ray multiplicities and spectra / 25

Measurement of prompt fission gamma-ray spectrum of 235U(nth,f)

Auteur: Katsuhisa Nishio[1]

[1] *Advanced Science Research Center, JAEA, Tokai*

Prompt γ-rays from fission fragments have information on the mechanism of the spins of a fragment, and is important to investigate the mechanism of spin population in fission. We have measured the γ-ray spectrum in 235U(nth,f) using thermal neutron beam supplied from the High-Flux Reactor of ILL, Grenoble, France. By significantly improving the detection efficiency and gaining accumulated events with a factor ~105 in comparison to available low-energy neutron-induced data, the γ-ray spectrum up to 20 MeV was measured for the first time. The result shows a hump structure at 15 MeV. In comparison to a statistical model calculation, nuclides as a potential source of such high-energy γ-rays will be discussed.
Reference
[1] H. Makii et al., Phys. Rev. C 100, 044610 (2019).

Fission modelling / 26

Model dependence of spin removal in fission fragments

Auteur: Ionel Stetcu[1]

[1] *Los Alamos National Laboratory*

Prompt fission gamma-ray observables depend on the angular momenta of fission fragments (FFs). However, as neutron emission is much faster than gamma emission, extraction of FF spin properties can be subject to uncertainties due to the corrections for neutron emission. For example, in FREYA and CGMF, two simulation codes modeling the prompt neutron and gamma emissions from FFs, the neutron removal of angular momentum is considerably different, even though they obtain similar results for a large number of prompt neutron and gamma ray properties. In CGMF, the removal of angular momentum by neutron emission has a wide distribution, in contrast with FREYA where very little spin is removed by neutrons. In addition, significant angular momentum is removed by the statistical gamma-rays in the current implementation of CGMF. In this talk, I will concentrate on discussing the model dependence on the spin distribution, and how microscopic calculations can guide the phenomenological models.

Fission modelling / 27

Angular Momentum in FREYA: A Status update

Auteur: Ramona Vogt[1]

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The fission simulation model FREYA is well suited for studying the role of angular momentum in fission because it obeys all conservation laws, including linear and angular momentum conservation at each step of the process. This status update explains how the angular momentum treatment in FREYA is based on the nucleon-exchange mechanism which agitates collective rotational modes in which the two fragment spins are highly correlated (but nevertheless the resulting fragment spins are largely uncorrelated). Furthermore, we briefly describe recent refinements in the treatment of the photon radiation cascades from the excited product nuclei. Several angular-momentum related observables are discussed, including various correlated observables [1]. For example, there is a marked correlation between the spin magnitude of the fission fragments and the photon multiplicity. We also consider the dynamical anisotropy caused by the rotation of an evaporating fragment and study especially the distribution of the projected neutron-neutron opening angles, showing that while it is dominated by the effect of the evaporation recoils, it is possible to extract the signal of the dynamical anisotropy by means of a Fourier decomposition. Finally, it is shown that a sawtooth-like behavior in the mass dependence of the average fragment spin naturally emerges when shell and deformation effects are included in the moments of inertia of the fragments at scission [2].

[1] R. Vogt and J. Randrup, Phys. Rev. C 103, 014610 (2021).
[2] J. Randrup and R. Vogt, Phys. Rev. Lett. 127, 062502 (2021).

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Fission modelling / 28

Status of the FIFRELIN code. Focus on angular momenta in fission

Auteur: Olivier Litaize[1]

[1] *CEA Cadarache*

Authors:
Olivier Litaize, Achment Chalil, Abdelaziz Chebboubi, Valentin Piau, Mathias Sabathé, Olivier Serot, Pierre Tamagno

Angular momenta in fission can be discussed at different time steps of the process for different systems: incoming particle, target nucleus, compound nucleus at saddle, at scission for both nascent fission fragments, fission fragments before neutron emission, after neutron emission, before gamma/electron emission⋯

In the FIFRELIN code, up to now, we consider fission fragments (FFs) after full acceleration (before neutron emission). Fission fragments spins (JL and JH) are sampled through a statistical model following Bethe's original work: P(J)=(2J+1)/2σ2exp(−(J+1/2)/2σ2) where σ is the so-called spin cut-off parameter. Those two spins are correlated through the relative orbital angular momentum (L): JCN⟶=JL⟶+JH⟶+L⃗ where JCN⟶ is the total angular momentum of the fissioning system. There is no direct correlation between both FF spins because the orbital angular momentum related to both FFs is not accounted for in FIFRELIN code at the time being. They are sampled after introducing two free parameters (for rescaling the spin cut-off parameter for light and heavy fragment groups) in order to reproduce fission observables related to prompt neutrons and photons. However, this description can give rise to inconsistencies between the values of the nuclear level scheme, that is constructed from a combination between level density models and experimental low lying levels, and the spin values after scission. Finally, because the goal is to reproduce fission observables, a few model ingredients are strongly correlated and could hide some physical effects in angular momentum generation: pre-neutron data-dependent primary entry zone in (E, J, π), level densites, neutron transmission coefficients, photon strengths functions, electron conversion coefficients. All these 'key points'and potential 'shadow zones'will be discussed in the present work.

Summary and close / 29

Workshop Summary

Auteur: Lee Sobotka[1]

[1] *Washington Uniuversity, St. Louis*

Microscopic Calculations / 30

Reorientation in newly formed fission fragments

Auteur: George Berstch[None]

The strong quadrupolar component of the Coulomb field between newly formed fission fragments can aect the internal energy of the fragments and their angular momentum. Previous estimates of these effects gave contradictory conclusions about their magnitude. Here we calculate them by solving the time-dependent Hamiltonian equation for the daughter 100Zr produced in the fission reaction n + 235U ! 136Te + 100Zr. The Hamiltonian was constructed from the projected angular momentum eigenstates of an aligned deformed mean-field configuration. For typical initial conditions, the average angular momentum of the lighter fragment increases by 1.5 - 3 units.