NEW RESULTS ON THE SPECTROSCOPY AND DYNAMICS OF FISSION

Volker Metag

CONF-800863--4

MASTER

Max-Planck-Institut für Kernphysik, Heidelberg, West Germany
and
University of Washington, Seattle, USA

Abstract: The present status of Coulomb fission experiments is discussed. Probabilities for fission induced by the purely electromagnetic interaction between heavy ions are compared for the systems $\text{Sm} + \text{U}$, $\text{W} + \text{U}$, $\text{W} + \text{Cm}$ and $\text{W} + \text{Th}$. Experimental results on the moments of inertia, spins, and quadrupole moments of fission isomers are summarized. Data are presented which prove their large deformation and thereby justify their interpretation as shape isomers in the second minimum of a double humped fission barrier.

1. Introduction

Since the last talk on fission in this series of conferences given by Hans Specht 7 years ago a large number of experimental and theoretical investigations have been performed. It is therefore completely impossible to give a comprehensive overview of the development in this field. I will concentrate on some of the highlights and a few selected areas in which the most remarkable progress has been achieved and which I am personally most familiar with.

In the first part of my talk I will discuss some new results on the dynamics of fission, in particular the recent experimental proof that fission can be induced by the purely electromagnetic interaction between two heavy nuclei via the direct excitation of collective modes.

In the second part I will summarize various experimental results on spectroscopic properties of fission isomers which have provided the unambiguous proof of their large deformation being close to that of a spheroid with an axis ratio of 2:1. This discussion of nuclei at extreme deformations will then lead over to the following talks in which nuclei at extremely high spins will be the topic.

2. The present status of Coulomb fission experiments

As soon as very heavy ion beams became available at Berkeley, Dubna and Darmstadt, several groups¹⁻⁴⁾ began to search for fission induced entirely by the strong time varying electric interaction between two colliding heavy ions. The novel feature⁵⁾ of this reaction mechanism is that the Coulomb interaction couples directly to the fission degree of freedom of the target nucleus, i.e., the β -vibrations which are collective vibrations along the symmetry axis of the deformed nucleus. Coulomb fission should therefore be an excellent probe for collective dynamics at high spins and large deformations. All other fission mechanisms studied so far proceed indirectly via compound nucleus intermediate states.

In the early experimental investigations^{1,2,4)} of sub-Coulomb heavy ion induced fission particles scattered off fissile targets were detected in coincidence with the 2 fission fragments. The insufficient charge and mass resolution, however, made it impossible to separate Coulomb fission events from fission induced by the sub-Coulomb transfer of one or more nucleons.

In more recent experiments at GSI⁶⁾ a firm identification of the back-scattered particles has been provided by measuring the conversion electrons from low lying transitions in these ions. The electrons are detected in a solenoid electron spectrometer using the recoil shadow technique. Conversion electrons from the decay of long lived (ns) states are emitted in flight from the back-scattered ions upstream of the target and are transported to the electron detector by the magnetic field of the solenoid. The detector is geometrically shielded from δ -electrons produced directly in the target with megabarn cross sections. The coincident fission fragments are registered in an annular detector which

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

subtends a large fraction of the forward hemisphere. A more detailed description of the set up is given in fig. 1 and in the original literature⁶⁾.

Fig. 1 Experimental arrangement (not to scale) for identifying backscattered reaction products by measuring internal conversion transitions with a solenoid electron spectrometer. Coincident fission fragments are registered in an annular detector which is shielded against elastically scattered projectiles by a Ta foil.

This experimental approach limits the choice of projectiles to well deformed nuclei with low-lying rotational states which decay predominantly by internal conversion. Beams of ^{152}Sm , ^{184}W and ^{232}Th have been used so far. Results for only the first two projectiles will be discussed here.

Electron spectra measured for the $^{184}\text{W} + ^{238}\text{U}$ system in singles and in coincidence with events in the forward fission detector are shown in fig. 2. The singles spectrum as well as the coincidence spectrum at a bombarding energy of 92% of the Coulomb barrier is dominated by the K, L and M conversion lines of the $2^+ \rightarrow 0^+$ transition in ^{184}W . At the highest bombarding energy ($1.03 \times E_C$) the spectrum still has a substantial contribution from the projectile excitation but has become more complex, showing contributions from one and two nucleon transfer reactions. Excitation functions for the inelastic and transfer channels are compared in fig. 3. Fission induced by inelastic scattering is dominant at energies below 95% of the Coulomb barrier.

Fission probabilities integrated over the populated excitation energy range in the fissioning nucleus are derived from the ratio of coincidence to singles events taking the fission fragment detection efficiency into account. A comparison of data for inelastic backscattering of ^{152}Sm and ^{184}W off ^{238}U (fig. 4) indicates a strong dependence on the charge of the projectile as expected for a pure Coulomb interaction. Parameterizing this dependence as Z_p^n a value of $5 < n < 6.5$ is deduced which is characteristic of a multiple step excitation process.

Fig. 4 also contains recent theoretical predictions^{7,8)} for the experimentally studied systems. Calculations using a pure Coulomb interaction and assuming a linear dependence of the moment of inertia on deformation are in good agreement with the experimental fission probabilities. A predicted interference minimum close to the Coulomb barrier due to a cancellation between the repulsive Coulomb and increasing attractive nuclear force is, however, not observed. Possible reasons for this discrepancy will be discussed by Volker Oberacker in his contribution⁸⁾ to this conference.

Apart from the projectile-charge-dependence the variation of the Coulomb fission cross-section for different target nuclei is of interest since it is expected to depend strongly on details of their collective structure. Fission probabilities for ^{184}W induced Coulomb fission of ^{232}Th , ^{238}U and ^{248}Am are shown in fig. 5. The fission probability for ^{232}Th is about 40% lower than for ^{238}U but increases as a function of bombarding energy with approximately the same slope. Only two points have been measured so far for ^{248}Cm . In order to correlate the observed

Fig. 2 * Electron spectra measured in singles and in coincidence with fission for the $^{184}\text{W} \rightarrow ^{238}\text{U}$ system. The K, L, M lines from the conversion of the $2^+ \rightarrow 0^+$ transition in ^{184}W and transitions in neighbouring isotopes are indicated. The solid curve is a fit to the experimental data taking the known energies and relative intensities of the conversion electron lines into account.

Fig. 3 Excitation function for fission of ^{238}U by inelastic scattering of ^{184}W and various transfer reactions. The bombarding energies E are given as a fraction of the Coulomb barrier E_c defined as $Z_1 Z_2 e^2 / R_{int}$ with $R_{int} = 1.16 (A_1^{1/3} + A_2^{1/3} + 2) \text{ fm}$.

Fig. 4 Fission probability of ^{238}U after inelastic scattering of ^{184}W and ^{152}Sm to backward angles. The solid and dashed lines represent calculations by Oberacker et al.⁹⁾ considering pure Coulomb as well as Coulomb and nuclear interactions.

variation in fission probabilities with collective parameters of the target such as quadrupole moments, β -vibrational frequencies or $B(E2)$ values for vibrational and rotational transitions a more detailed experimental investigation including a broader range of target nuclei is required. In addition, differences in fission barrier heights will have to be taken into account. Information on the spins of the fissioning states may be obtained from measurements of the fission fragment angular distribution which are presently under way.

This is the current experimental status of Coulomb fission. It is apparent that further experimental and also theoretical investigations will be required to reveal the physics involved. Let us now turn to a field in which a very clear picture has emerged within recent years.

Fig. 5 Fission probability of ^{232}Th , ^{238}U , and ^{248}Cm after inelastic scattering of ^{184}W to backward angles. The solid lines are fits to the data points for the U and Th target, respectively.

3. Spectroscopic properties of fission isomers

3.1 THE DOUBLE HUMPED FISSION BARRIER

Fission isomers are metastable states in heavy nuclei which can be populated in a nuclear reaction and--in contrast to other excited nuclear states--decay predominantly by spontaneous fission. To date 36 fission isomeric states are known with halflives ranging from 5 ps to 14 ms, all located in the actinide region. Their halflives and isotopic assignments are given in fig. 6 which shows the "island" of fission isomers in the nuclear chart.

Several years after the first observation of these nuclear species by S. Polikanov and coworkers⁹⁾ at Dubna in 1961 theoretical investigations of the nuclear binding energy as a function of deformation pioneered by V. Strutinsky¹⁰⁾ led to an interpretation of fission isomers as shape isomers located in the

Fig. 6 Part of the nuclear chart giving the halflives of all fission isomers presently known. Two values for the same nucleus indicate spin isomeric states in the second minimum. In some cases their excitation energy relative to the lowest state in the second well have been measured. Information on the spins of the isomers in $^{237,239}\text{Pu}$ is also included.

second minimum of a double humped fission barrier (fig. 7). The double humped structure of the fission barrier results from the superposition of shell corrections to the nuclear binding energy onto the rather flat macroscopic part of the deformation energy described by the liquid drop model.

The oscillating pattern of shell corrections as a function of the deformation reflects variations in the density of single particle levels at the Fermi energy. As schematically illustrated in fig. 7 gaps in the single particle spectra which correspond to strongly bound magic nuclei are not only found for spherical shapes but also for certain deformations. In the simplified harmonic oscillator potential degeneracies of single particle levels always occur when the axis ratio of the spheroid, describing the nuclear shape, approaches the ratio of two small integers^{11,12)}. In particular, for an axis ratio of 2:1 the high symmetry of the nuclear shape leads to large gaps in the single particle spectrum ("deformed shells") resulting in an increased nuclear binding energy as in the case of spherical magic nuclei. According to Strutinsky¹³⁾ the nature of gross shell effects becomes more apparent in a semiclassical quantization of the single particle motion along stationary dynamical orbits in a given potential well. The intensity of the shell structure is then determined by the degree of degeneracy of the family of classical orbits. Experimentally, the magic neutron number for which the largest shell corrections to the nuclear binding energy occur for strongly deformed actinide nuclei has been found to be $N = 146$ from a systematic analysis of fission isomer half-lives¹⁴⁾.

The concept of a double humped fission barrier explains the basic features of fission isomers.

- i) their excitation energy of 2-3 MeV deduced from measured excitation functions.
- ii) their surprising stability at this excitation energy against γ -decay.
- iii) their short half-lives for spontaneous fission which are roughly 20 orders of magnitude smaller than those for spontaneous fission decay of the respective nuclear ground states. From the isomeric state a much smaller barrier has to be penetrated than in the spontaneous fission decay from the nuclear ground state.
- iv) the localization of fission isomers in the actinide region. Only in this

Fig. 7 top: the double humped fission barrier. The fission barrier in the liquid drop model is indicated by a dashed line. middle: shell corrections to the nuclear binding energy as a function of deformation. bottom: single particle states of a harmonic oscillator potential for prolate spheroidal deformations¹²⁾. The particle numbers for closed shells are indicated for a sphere and for a spheroid with a 2:1 axis ratio.

mass region Coulomb repulsion and surface tension nearly cancel each other leading to an exceptionally flat liquid drop model fission barrier of only a few MeV. A superposition of shell corrections which are typically of the same order of magnitude can consequently drastically change the structure of the fission barrier in this mass region while their effect is usually negligible compared to the liquid drop part in the rest of the nuclear chart. This statement holds only, however, for low nuclear spins. In the following talk¹⁵⁾ Frank Stephens will discuss possible evidence that for extremely high nuclear spins the liquid drop potential energy surface becomes again sensitive to the superposition of shell corrections leading to shape isomerism also in other mass regions.

In numerous measurements all aimed at investigating the structure of the fission barrier in the actinide region a large body of experimental data has been accumulated over many years. All results could be consistently analyzed in terms of a double humped fission barrier which established strong support for this hypothesis. Its direct proof, however, has only recently been provided by the measurement of the deformation of fission isomeric states which became feasible after studies of the spectroscopic properties of fission isomers had been initiated.

Three different experimental approaches have been pursued. The first evidence for the very large deformation of fission isomers came from the measurement of their moments of inertia. Hans Specht reported on the experiment of the Munich group¹⁶⁾ in this series of conferences in 1973. By measuring conversion electrons in coincidence with delayed fission they identified, for the first time, a rotational band built on the 4 ns fission isomer in ^{240}Pu . Consistent results were obtained by the Seattle-Copenhagen collaboration¹⁷⁾ on the ^{236}U fission isomer. Both measurements yielded moments of inertia of the fission isomeric states which are more than twice as large as those of the respective nuclear ground states and even exceed the moment of inertia for rigid rotation at ground state deformation. More recent experiments at Heidelberg^{18,19)}, which I will describe in more detail, have revealed rotational band structure and enabled determination of moments of inertia for the isomers in ^{238}U and for the first odd mass case, the 8 μs fission isomer in ^{239}Pu .

The next group of experiments deals with the measurement of the lifetimes of the rotational states from which the quadrupole-moments and thereby the deformation of fission isomers can directly be deduced via the rotational model. As I will show you, these lifetimes can be measured using the newly developed charge plunger technique^{20,21)} without ever observing the extremely weak nuclear transitions directly.

Very recently a completely independent experimental proof for the large deformation of fission isomers has been obtained by Curt Bemis and his coworkers²²⁾ at Oak Ridge. They measured the optical isomer shift of a transition in the Am atom using laser induced nuclear polarization and thereby determined the rms radius of the charge distribution of the ^{240}Am nucleus in its fission isomer state.

3.2 ROTATIONAL EXCITATIONS AND MOMENTS OF INERTIA

Let me first comment on the recent electron spectroscopy experiments at Heidelberg. A different experimental scheme than in earlier investigations of rotational band structure has been used in order to eliminate more effectively the enormous background of δ -electrons which previously prevented the observation of low energy transitions such as $2^+ \rightarrow 0^+$ in even-even nuclei or the even smaller rotational transitions in odd-even nuclei. As illustrated in fig. 8 the delayed feeding of rotational levels by the decay of a spin isomer in the second minimum is utilized instead of their prompt population in the preceding nuclear reaction. Thus, the rotational transitions of interest occur with some time delay given by the lifetime of the spin isomer and can be separated in time from the prompt δ -electrons. As in the Coulomb fission experiments, this separation is more effectively achieved in space by applying the recoil shadow technique. Conversion electrons from the rotational transitions are emitted in flight from the recoiling fission isomers downstream of the target. The electrons are again transported in

the magnetic field of a solenoid to a well-shielded detector where they are registered in delayed coincidence with fragments from the subsequent fission decay of the isomer observed in an annular detector. A more detailed description of the experimental arrangement is given in fig. 9 and in ref. 18.

Electron spectra obtained in this way for the fission isomers in ^{238}U and ^{239}Pu are shown in figs. 10 and 11. The time correlations between electron and fission events reproduced in the insets are consistent with the known halflives of these isomers showing that the observed electrons originate indeed from transitions preceeding those spontaneous fission decays. In the case of ^{238}U the observed spectrum can be fully accounted for by the L_{III}, M and N conversion electron lines of an E2-transition of 19.6 keV which is close to the energy expected for the lowest rotational transition ($2^+ \rightarrow 0^+$) in an even-even nucleus in the second minimum and implies a moment of inertia of $20/\hbar^2 = 306 \text{ MW}^{-1}$. For ^{239}Pu it is much more difficult to give an unambiguous interpretation of the measured spectrum in view of the rather low statistics and the complexity of the conversion electron spectrum expected for an odd A nucleus. The known energy and intensity relations between L, M and N conversion electron lines, however, restrict the number of possible interpretations. On the basis of a best fit to the data, indicated by a dashed curve, the decay scheme of fig. 12 has been proposed which suggests the existence of 2 cascade and 1 cross over rotational transition.

In this case the fit of the usual rotational energy expansion to the observed transition energies does not only give a moment of inertia of the band of $20/\hbar = 298 \text{ MeV}^{-1}$ but also the spin of the isomer which is found to be $5/2$. Actually, this is the first determination of the spin of a fission isomeric state. Using the additional information on the M1/E2 mixing ratio [$\delta^{-2} = T(M1)/T(E2) \leq 1.4$]

Fig. 8 Schematic illustration of prompt and delayed feeding of rotational states in the second minimum. In either case, the rotational transitions are identified via the detection of conversion electrons preceeding isomeric fission. Delayed feeding allows the application of the recoil shadow method for a more effective suppression of the δ -electron background.

Fig. 9 Experimental arrangement (not to scale) for studying conversion electrons from rotational transitions in the second minimum using the recoil shadow method. The longitudinal baffle and the Pb shielding prevent detection of prompt electrons and γ -rays from the target, while delayed electrons emitted in flight can reach the detector. To improve the detection efficiency, the electrons are accelerated by a voltage of 8 MV applied to the target region. Electrons of less than 1.5 keV are cut off by an additional potential barrier.

Fig. 10 Spectrum and decay curve of electrons measured in delayed coincidence with isomeric fission of ^{238}U . The solid curve represents a fit to the L_{III} , M , and N conversion electron lines of the supposed $2^+ \rightarrow 0^+$ transition. The chance coincidence background (dotted line) and the contribution from Auger electrons (dashed-dotted line) are also indicated.

Fig. 11 Spectrum of electrons measured in delayed coincidence with isomeric fission of ^{239}Pu after correction for random coincidences. The inset shows the decay curve measured for the electrons in the energy range from 3.5 to 31 keV. The dashed curve represents a fit to the data. The position of the K , L , M , and N components of the different transitions are indicated. The curve denoted L -Auger is an estimate for the intensity and spectral distribution of Auger electrons which is included in the fit.

deduced from the electron spectrum and comparing with calculated single particle spectra it has been possible to identify¹⁸⁾ the single particle level occupied by the odd neutron in the fission isomeric state of ^{239}Pu . In the notation using asymptotic quantum numbers of the Nilsson model the dominant part of the wave function is $5/2[633]$.

Other spin determinations for the 2 isomers in ^{237}Pu have been reported in a contribution to this conference by the group in Giessen^{23,24)}. From the relative fission yields of these 2 isomers populated in a photonuclear reaction they deduce spins of $11/2$ and $5/2$ in a statistical model analysis. All other attempts²⁵⁻²⁸⁾ of determining spins from fission fragment angular distributions or g-factor measurements have so far failed to provide statistically significant and reproducible results.

Returning to the discussion of moments of inertia of fission isomers our present knowledge is summarized in table I and fig. 13. The experimental values for fission isomeric and ground states are plotted as a function of the mass number of

Fig. 12 Proposed decay scheme of the 2.6-ns isomer. The intensities of the feeding transitions are corrected for internal conversion assuming multipolarities of E1 (147, 175 keV) and M2 (203 keV). The positive parity of the $5/2$ state is suggested by comparison with theory. No $5-2$ state is predicted close to the Fermi surface.

Table I Rotational parameters of bands in the second well

Nucleus	A [keV]	B[eV]	Ref.
^{236}U	3.36 ± 0.01		[17]
^{238}U	3.27 ± 0.03		[19]
^{239}U	3.36 ± 0.1	4 ± 3	[18]
^{240}Pu	3.343 ± 0.003	$-(0.28 \pm 0.04)$	[16]

actinide nuclei. All moments of inertia of fission isomers consistently exceed those of the respective nuclear ground states by a factor of ≈ 2.3 and correspond to $\sim 75\%$ of the moment of inertia for rigid rotation at the theoretically predicted deformation of the second minimum while for the ground states this fraction amounts only to 40-50% of the rigid body value. Recent cranking model calculations by various authors²⁹⁻³¹⁾ who have used slightly different single particle models are shown for comparison. Although minor differences between calculated and experimental values are still evident the observed overall gross agreement between theory and experiment gives strong support to the hypothesis of shape isomerism.

3.3 ROTATIONAL LIFETIMES AND QUADRUPOLEMOMENTS

Let us now come to the experiments which have provided direct evidence for the large deformation of fission isomers. As mentioned above, in one series of

experiments quadrupole moments of fission isomers have been inferred from measurements of the lifetimes of their rotational excitations. Although improved experimental techniques for studying converted transitions in the second minimum have been developed--as you have seen--it is still not feasible to apply standard nuclear techniques like e.g., the Doppler shift method for measuring the lifetimes of these rotational states.

At Heidelberg we have therefore developed a completely new technique^{20,21)} which exploits some atomic physics effects, and since it is a novel and rather unconventional method let me briefly describe its principle. It is based on the impact of a converted nuclear transition on the atomic shells. The emission of a

conversion electron creates a vacancy e.g., in the L-shell. This vacancy is either filled by X-ray emission or by an Auger effect which occurs with 50% probability in the L-shell of actinide atoms. In the case of such a radiationless transition the vacancy generated by the nuclear decay is transferred to a higher shell and a second vacancy is created by the emission of an Auger electron. Thus, the one vacancy in the L-shell has been replaced by two vacancies in the M-shell. The number of vacancies has been doubled. This process proceeds like an avalanche into the outer shells. The consecutive emission of Auger electrons transforms the atom into a highly charged ion with an average charge of 14^+ in the actinide region. This occurs in a time short compared to the nuclear lifetimes of interest which are of the order of ps and longer. One has, of course, to confine the ions in vacuum such that no recapture of the electrons lost is possible.

How can this process be utilized to measure the lifetimes of nuclear states? Consider a recoil ion excited in a nuclear reaction which leaves the target with an equilibrium charge of 1^+ (fig. 14). After some ps a nuclear transition occurs, a conversion electron is emitted followed by a sequence of Auger electrons. The highly charged recoil

Fig. 13 Moments of inertia of fission isomers and ground states of actinide nuclei in comparison with calculated values²⁹⁻³¹⁾.

Fig. 14 Principle of the "charge plunger" method (L - low charge component, H - high charge component). The long arrows represent conversion electrons and the short arrows Auger electron, respectively.

ions recapture all the electrons lost in the Auger cascade when passing through a thin carbon foil placed at some distance to the target. Low charge recoil ions emerge and their charge distribution behind the carbon foil is again centered at the equilibrium charge. If, on the other hand, the carbon foil is placed close to the target and the nuclear transition occurs after passing the carbon foil no charge resetting will take place and a distribution of highly charged ions will be observed. Thus the charge distribution consists of two completely separate components whose intensities depend on the time of the nuclear decay. By measuring the relative yields of the high and low charge recoil ions as a function of the distance between target and carbon foil the de-excitation of the nuclear state can be determined without ever observing the nuclear transition directly but only its impact on the atomic shells. The obvious analogy to the conventional plunger method in which nuclear lifetimes are deduced from the intensity ratio of Doppler shifted and unshifted γ -rays suggested the name charge plunger technique (CPT).

I will not go into the complications that arise if there is not only one but a sequence of excited states; e.g., in a rotational band. As discussed in the original literature^{20,21,32}) the quadrupole-moment of a band can be extracted from the measured overall de-excitation curve by fitting it with a cascade-calculation which describes the sequence of populating and de-populating transitions within the rotational model.

Deflection in a magnetic field as well as electrostatic separation³³) have been used to measure the charge distribution of fission isomeric recoil ions as schematically illustrated in figs. 15 and 16. In the first approach fission isomeric recoil ions are deflected in a magnetic field onto different positions of a recoil ion collector depending on their charge state.

Their subsequent spontaneous fission decay is registered in track detector foils. If the halflife of the isomeric state is long compared to the ≈ 200 ns flight time to the detector there is a one-to-one correspondence between the fission track and charge distributions.

For short lived (ns) isomers in even-even nuclei which would fission in flight an electrostatic field has been used to separate the low and high charge recoil ions over small distances corresponding to flight times of some ns. By applying high voltage to the target and carbon foil the highly charged recoil ions are reflected back towards the target while low charge recoil ions reach the detector arrangement where their fission decay either in flight or after being stopped on a catcher foil is again registered with track detector foils.

Charge distributions of ^{239}Pu fission isomers measured by magnetic deflection are shown for various distances of the carbon foil to the target in fig. 17. Several consecutive converted transitions which occur in the de-excitation of the rotational band lead to charge states up to 40^+ . With increasing distance from the target i.e., longer flight times the fraction of highly charged ions decreases. Their intensity is proportional to the number of rotational states still excited at the time the recoil ions reach the charge resetting foil. For times ≥ 100 ps, the yield of recoil ions is concentrated in a peak at the equilibrium charge whose

Fig. 15 Experimental arrangement for measuring the charge distribution of long-lived ($T_{1/2} \gg 200$ ns) fission isomeric recoil ions by deflection in a magnetic field. The flight paths for different charge states are indicated.

Fig. 16 Experimental arrangement for separating low and high charge recoil ions with short fission isomeric half-lives ($T_{1/2} > 5$ ns) in an electrostatic field. In the experiment the distance between the carbon foil holder and the detector funnel is 3 mm. For clarity it is not drawn to scale to illustrate the flight paths of highly charged recoil ions.

intensity is a measure for the number of recoil ions in the lowest state of the second minimum.

Fig. 18 shows in the upper part the fraction of highly charged fission isomeric recoil ions of ^{239}Pu measured by magnetic deflection and in the lower part the percentage of low charge ions from the ^{238}U isomer measured by electrostatic separation, both plotted as a function of the distance between target and carbon foil. Using the known recoil velocities the distance scales have been converted into decay times. The decreasing fraction of high charge and increasing fraction of low charge ions reflect the de-excitation of the rotational bands based on the respective fission isomeric states. Information on rotational constants, spins, and $M1/E2$ mixing ratios provided by electron spectroscopy experiments^{18,19)} have been incorporated in fits of cascade calculations to the experimental data. Quadrupole moments of $(36 \pm 4)b$ and $(29 \pm 3)b$ are deduced for the fission isomeric states of ^{239}Pu and ^{238}U , respectively. A more recent measurement³²⁾ on $^{236}\text{m}\text{U}$, again using electrostatic separation, gives a quadrupole moment of $(32 \pm 5)b$.

While all these quadrupole moments have been inferred from collective transition strengths the quadrupole moment of the static charge distribution of the ^{240}Am fission isomer has been determined by C. Bemis et al.²²⁾ by measuring the optical

Fig. 17 Charge distributions of ^{239}Pu fission isomers measured by magnetic deflection at different distances of the charge resetting foil to the target. The dashed curves indicate the decomposition into the contributions from several consecutive converted transitions.

isomer shift of the $10p_{7/2} \rightarrow 8s_{7/2}$ transition in the Am atom.

Their experimental arrangement is sketched in fig. 19. Fission isomeric recoil ions from the $^{238}\text{U}(^7\text{Li},5\alpha)$ reaction are slowed down in the gas between two position sensitive gas detectors which measure the spontaneous fission decay. The Am atoms are irradiated with the beam of a continuous wave dye laser whose frequency is scanned in the vicinity of the Am $8s_{7/2} \rightarrow 10p_{7/2}$ transition. Because of the random orientation of the nuclear spins the fission fragment angular distribution is isotropic. In case of an optical resonance, however, the pumping with the circularly polarized laser light induces an alignment of the nuclear spin I along the direction of the laser beam, leading to an anisotropy in the fission fragment angular distribution for $I > 1/2$. From an oriented nuclear system with $k = I = 1M \pm 1$ (orientation of the spin parallel to the symmetry axis of the deformed nucleus) the spontaneous fission decay preferentially occurs along the laser beam axis, resulting in a decrease of the coincident fission event yield as shown in fig. 20. This is the signature for the resonance condition. A shift of 2.6 Å relative to the $10p_{7/2} - 8s_{7/2}$ transition in ^{241}Am is observed from which a difference between the rms radii of the ground state and fission isomeric state in ^{240}Am of $\delta \langle r^2 \rangle = (5.1 \pm 0.2) \text{ fm}^2$ and a quadrupole moment of $(32.7 \pm 2.0)b$ are deduced.

All presently known quadrupole moments of fission isomers are listed in table II and are plotted in fig. 21 as a function of the mass number of actinide nuclei. An earlier measurement on the ^{236}Pu fission isomer³⁴⁾ using a less accurate technique not discussed here has been included for completeness. The results are compared to the measured quadrupole moments of actinide nuclei in their ground states and to calculations of different groups^{29,30)} based on the Strutinsky-procedure.

The measured quadrupole moments of fission isomers systematically exceed the quadrupole moments of the ground states by about a factor 3. They are the largest quadrupole moments measured so far in nuclei. If one describes the shape of the nucleus by a spheroid an axis ratio of about 2:1 is deduced from the measured quadrupole moments compared to 1.3:1 for the ground states. This provides the

Fig. 18 Fraction of high charge and low charge fission isomeric recoil ions from the reactions $^{238}\text{U}(\alpha, 3n)^{239m}\text{Pu}$ and $^{238}\text{U}(d, p)^{238m}\text{U}$, respectively, plotted as a function of the decay time. The time scale has been obtained from the measured distances between target and charge resetting foil using the known recoil velocities. The data points have been corrected for long lived components due to delayed feeding of rotational states in the decay of spin isomers. The solid curves represent fits of cascade calculations to the experimental data.

Fig. 19 Schematic diagram of the arrangement for the LINUP experiment, showing the cyclotron and laser beams and the position sensitive fission fragment detectors.

Fig. 20 Normalized fission fragment coincidence yield as a function of laser wavelength. The decrease in yield at 6407.7 Å indicates anisotropic fission decay due to nuclear orientation via resonant optical pumping. The solid line is shown to guide the eye.

Fig. 21 Quadrupole moments of fission isomers and ground states of actinide nuclei in comparison with calculated values^{29,30}).

Table II: Quadrupole moments and deformations of fission isomers and nuclear ground states

Nucleus	Isomer			Ground states ^g	
	Q (b)	c/a	Q _{calc} (b)	Q (b)	c/a
²³⁶ U	32 ± 5 ^h	1.9 ± 0.1 ^h	33.1 ^b	10.81 ± 0.11	1.29 ± 0.02
²³⁸ U	29 ± 3 ^a	1.8 ± 0.1 ^a	33.3 ^b	10.84 ± 0.07	1.29 ± 0.02
²³⁶ Pu	37 ± 8 ^{14c}	2.0 ± 0.3 ^c	34.8 ^b , 36.7 ^d	(11.27 ± 0.15)	1.31 ± 0.02
²³⁹ Pu	36 ± 4 ^e	2.0 ± 0.1 ^e		(11.3 ± 0.5)	1.31 ± 0.05
²⁴⁰ Am	32.7 ± 2 ^f	2.0 ± 0.1 ^f			

^aRef. [33]

^cRef. [34]

^eRef. [30]

^gRef. [35]

^bRef. [29]

^dRef. [30]

^fRef. [22]

^hRef. [32]

quantitative proof for our understanding of fission isomers as shape isomers and for the existence of a second minimum in the fission potential. It is remarkable that the measured deformation is very close to the 2:1 axis ratio for which the strongest shell corrections to the nuclear binding energy were expected on the basis of the theoretical arguments discussed above.

4. Summary

Coulomb fission induced by the purely electromagnetic interaction between two heavy ions has been established. Further experiments such as a systematic study of the target dependence of the cross section as well as studies of the fission fragment angular distribution are required to reveal details of this fission mechanism. In a series of electron spectroscopy experiments rotational excitations of fission isomers have been identified in 4 actinide nuclei. All measured moments of inertia are consistently larger than the respective moments at ground state deformation. The first investigation of an odd-even nucleus allowed the determination of the spin of a fission isomer and the identification of its single particle state. From measurements of rotational transition strengths and the observation of the optical isomer shift the quadrupole moments of 5 fission isomers have been determined, providing direct experimental proof for their large deformation and interpretation as shape isomers. The measured deformations are close to the 2:1 major to minor axis ratio theoretically predicted for deformed magic nuclei in the actinide region.

Acknowledgment

I am indebted to C.E. Bemis and V. Oberacker for comments and their permission to include some of their results in this talk and to R. Vandenbosch for reading the manuscript. It is a pleasure to acknowledge the fruitful collaboration with the fission group at Heidelberg and GSI, Darmstadt, in particular D. Habs, H. Backe, and H.J. Specht, who have been the major contributors to the physics programme which I had the opportunity to present here.

References

- 1) P. Colombani, P.A. Butler, I.Y. Lee, D. Cline, R.M. Diamond, F.S. Stephens, and F.S. Ward, Phys. Lett. B65 (1976), 39.
- 2) P.A. Butler, I.Y. Lee, J.O. Newton, Y. El-Masri, M.M. Aleonard, P. Colombani, R.M. Diamond, F.S. Stephens, R.W. Loughheed, and E.K. Hulet, Phys. Lett. B68 (1977), 122.
- 3) Yu P. Gangrsky, B.N. Markov, Nguyen Cong Khanh, Yu. Ts. Oganessian, Pham Zuy Khien, P7-7022 (1973) Dubna.
- 4) D. Habs, V. Metag, J. Schukraft, H.J. Specht, C.O. Wene, and K.D. Hildenbrand, Z. Phys. A283 (1977), 261.
- 5) E. Guth and L. Willets, Phys. Rev. Lett. 16 (1966), 30; and L. Willets, E. Guth, and J.S. Tenn, Phys. Rev. 156 (1967), 1349.
- 6) H. Backe, F. Weik, P.A. Butler, V. Metag, J.B. Wilhelmy, D. Habs, G. Himmele, and H.J. Specht, Phys. Rev. Lett. 43 (1979), 1077.
- 7) H. Kruse, W.T. Pinkston, W. Greiner and V. Oberacker, Phys. Rev. C
- 8) V. Oberacker, W.T. Pinkston, H. Kruse, and W. Geiner, contribution to this conference, and V. Oberacker (Oak Ridge) private communication.
- 9) S.M. Polikanov, V.A. Druin, V.A. Karnaukhov, V.L. Mikheev, A.A. Pleve, N.K. Skobelov, V.G. Subbottin, G.M. Terakopyan, and V.A. Fomichev, Sov. Phys. JETP 15 (1962), 1016.
- 10) V.M. Strutinsky, Nucl. Phys. A95 (1967), 420; Nucl. Phys. A122 (1968), 1.
- 11) A. Bohr and B. Mottelson, Nuclear Structure, Benjamin, New York (1974), Vol. II, p. 602 ff.
- 12) P. Möller and J.R. Nix, IAEA Third Symp. Phys. and Chem. of Fission, Rochester (1973), Vol. I, p. 103.
- 13) V.M. Strutinsky, A.G. Manger, S.R. Ottengenden, and T. Døssing, Z. Phys. A283 (1977), 269.
- 14) V. Metag, Nukleonika 20 (1975), 789.
- 15) F. Stephens, invited paper, this conference.

- 16) H.J. Specht, Proc. Int. Conf. Nucl. Phys., Munich (1973), Vol. II, p. 312; and H.J. Specht, J. Weber, E. Konecny, and D. Heunemann, Phys. Lett. B41 (1972), 43.
- 17) J. Borggreen, J. Pedersen, G. Sletten, R. Heffner, and E. Swanson, Nucl. Phys. A279 (1977), 189.
- 18) H. Backe, L. Richter, D. Habs, V. Metag, J. Pedersen, P. Singer, and H.J. Specht, Phys. Rev. Lett. 42 (1979), 490.
- 19) V. Metag, Symp. Phys. and Chem. of Fission, Jülich (1979), paper SM-241/B3.
- 20) D. Habs, V. Metag, H.J. Specht, and G. Ulfert, Phys. Rev. Lett. 38 (1977), 387.
- 21) G. Ulfert, D. Habs, V. Metag, and H.J. Specht, Nucl. Instr. Meth. 148 (1978), 369.
- 22) C.E. Bemis, Jr, J.R. Beene, J.P. Young, and S.D. Kramer, Phys. Rev. Lett. 43 (1979), 1854.
- 23) W. Günther, K. Huber, U. Kneissl, H. Krieger, H.J. Maier, H. Ries, H. Ströher, and W. Wilke, contribution to this conference.
- 24) W. Günther, K. Huber, U. Kneissl, H. Krieger, and H.J. Maier, Phys. Rev. C19 (1979), 433.
- 25) R. Kalish, B. Kerskind, J. Pedersen, D. Shackleton, and L. Strabo, Phys. Rev. Lett. 32 (1974), 1009.
- 26) D. Habs, B. Herskind, V. Metag, J. Pedersen, G. Sletten, and H.J. Specht, Max-Planck-Institut für Kernphysik, annual report (1975), p. 57.
- 27) D. Habs, V. Metag, P. Paul, G. Schatz, and H.J. Specht, Max-Planck-Institut für Kernphysik, annual report (1976), p. 51.
- 28) D. Habs, S. Hanna, V. Metag, J. Pedersen, G. Sletten, and H.J. Specht, Max-Planck-Institut für Kernphysik, annual report (1977), p. 48.
- 29) K. Pomorski and A. Sobiczewski, Acta Physica Polonica B9 (1978), 61.
- 30) M. Brack, T. Ledergerber, H.C. Pauli, and A.S. Jensen, Nucl. Phys. A234 (1974), 185.
- 31) I. Hamamoto, Phys. Lett. B56 (1975), 431.
- 32) V. Metag, D. Habs, and H.J. Specht, Phys. Rep. C, to be published.
- 33) G. Ulfert, V. Metag, D. Habs, and H.J. Specht, Phys. Rev. Lett. 42 (1979), 1596.
- 34) V. Metag and G. Sletten, Nucl. Phys. A282 (1977), 77.
- 35) J.L.C. Ford, P.H. Stelson, C.E. Bemis, F.K. McGowan, R.L. Robinson, W.T. Milner, Phys. Rev. Lett. 27 (1971), 1232.