Physics and Chemistry of Fission

1973

Volume 1

PROCEEDINGS SERIES

PHYSICS AND CHEMISTRY OF FISSION 1973

PROCEEDINGS OF THE THIRD IAEA SYMPOSIUM
ON THE
PHYSICS AND CHEMISTRY OF FISSION
HELD BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
IN ROCHESTER, NEW YORK, 13-17 AUGUST 1973

In two volumes

VOL. I

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1974

PHYSICS AND CHEMISTRY OF FISSION 1973
IAEA, VIENNA, 1974
STI/PUB/347

FOREWORD

This third international Symposium on the Physics and Chemistry of Fission, held in Rochester, N.Y., from 13 to 17 August 1973, was a worthy successor to the important symposia held in Salzburg (1965) and in Vienna (1969). Although there may not have been in Rochester quite the excitement that prevailed in Vienna (where the beautiful verification of the structured fission barrier provided by the Strutinsky calculations was presented), the present meeting reaped the benefits of this revolutionary discovery. The first direct experimental verifications of the deformed fission isomers have also only recently been achieved.

The present Symposium, somewhat more than previous ones, concentrated on theoretical concepts and calculations concerning the fission process itself, and only on those new experimental results most pertinent to the theoretical development. Contained in these two volumes are the full texts and discussions of the 62 papers presented at the Symposium, and abstracts of those contributions that, because of time limitations, could not be presented.

These Proceedings of course do not represent the *last* word on this obviously complex topic. It is apparent that even the liquid drop features of the fission process have not yet been fully, or even adequately, worked out, the most obvious deficiency still being a reliable treatment of the dynamics, where a better knowledge of the 'viscosity' is obviously needed. The importance of quantum mechanical, single particle effects in the fission process is emphasized in these Proceedings, and a number of advances in microscopic calculations are included.

It is clear, in view of the large participation and the quality of the work presented, that scientists throughout the world find these meetings a valuable international forum for the exchange of information and welcome the Agency's initiative in promoting this continuing series of symposia.

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Chairman: J.R. Huizenga (United States of America)

EXPERIMENTAL FISSION BARRIERS FOR ACTINIDE NUCLEI*

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Abstract

EXPERIMENTAL FISSION BARRIERS FOR ACTINIDE NUCLEI.

Fission probability distributions are measured for a number of isotopes of Th, Pa, U, Np, Pu, Am, Cm and Bk using (d,pf), (t,pf), (^{3}He,df), (p,p'f), (^{3}He,αf) and (t,αf) reactions. The results, together with previous data available from (d,pf) and (n,f) studies, are analysed with a statistical model and estimates are obtained for the heights, E_A and E_B, and curvatures, $\hbar\omega_A$ and $\hbar\omega_B$, of the two peaks of the fission barrier for a wide range of actinide nuclei. The statistical model used for the analysis of odd A and odd-odd nuclei includes competition between fission, neutron emission and gamma-ray de-excitation in the decay of the compound nucleus. The results suggest that fission widths which are greater by about a factor of 4 than those calculated are necessary to reproduce the magnitude of the measured fission probabilities. The results show that E_A is roughly constant throughout this region and E_B decreases with increasing Z. An exception to the approximate constancy of E_A is in Cm where E_A drops by 1.0 MeV from ^{248}Cm to ^{250}Cm. In some cases an odd-even fluctuation of 0.30-0.50 MeV is observed in the experimental E_A values.

1. INTRODUCTION

At the last IAEA conference on the Physics and Chemistry of Fission[1] in 1969 many of the exciting new developments were related to the investigation of the qualitative implications of the effects of deformed nuclear shells on the potential energy surfaces associated with the fission process and the wide variety of experiments that had recently confirmed the major predictions of this new theory. At that conference experimental results were presented on the existence of fission isomers in a wide range of actinide nuclei, intermediate structure resonances in subbarrier

* Work supported by the US Atomic Energy Commission.

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neutron fission, and gross structure resonances in (n,f) and (d,pf) studies. All of these experimental phenomena were found to be consistent with the concept of a two-peaked fission barrier that resulted theoretically from fluctuations in the shell corrections to the single-peaked fission barrier predicted by the liquid drop model.

Since the last conference there has been considerable activity both theoretically and experimentally directed toward trying to quantitatively determine the characteristics of the potential energy surface involved in fission and to try to understand how these complex potential energy surfaces affect some aspects of the fission process. In other papers at this symposium both the current status of potential energy calculations and recent theoretical efforts to qualitatively understand the more difficult problems of fission dynamics will be reviewed [2,3]. In our paper we will present a review of current efforts to try to experimentally determine fission barrier characteristics for actinide elements with particular emphasis on recent direct reaction fission results from Los Alamos. In general, the fission barrier properties that can be most readily compared with theoretical calculations are the energies of the two saddle points and the secondary minimum relative to the ground

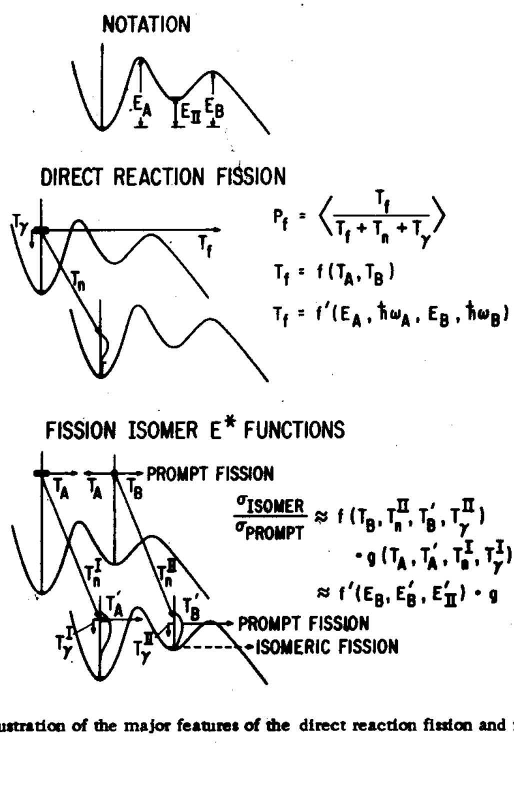

FIG.1. Schematic illustration of the major features of the direct reaction fission and fission isomer population processes.

state. We will concentrate on these properties although in some cases the experiments also yield information on barrier curvatures.

Figure 1 illustrates schematically the two types of experiment which have been used to obtain most of the current information on fission barrier heights. In a direct reaction fission experiment a direct reaction (or neutron capture reaction) is used to produce a residual nucleus at a particular excitation energy and the branching ratio for decay by fission relative to neutron or gamma deexcitation (or the fission cross-section) is measured. This type of experiment gives information primarily on the height and curvature of the highest peak in the fission barrier. However, in some cases resonances are observed which can be associated with vibrations near the top of the second well and a detailed analysis of the experimental results gives information on both peaks. The results and analysis for even-even fissioning nuclei where these resonance structures are observed will be presented in another paper [4]. Figure 1 also illustrates schematically the population of a shape isomeric state in the second well following the evaporation of a neutron. In most cases of experimental interest the isomeric states are populated following the subsequent evaporation of two or three neutrons but qualitatively the data analysis is the same [5]. In practice, fission isomer excitation functions have been analyzed using E_A values from other sources and the experimental data is used to determine E_B and E_{II}. Thus, in the

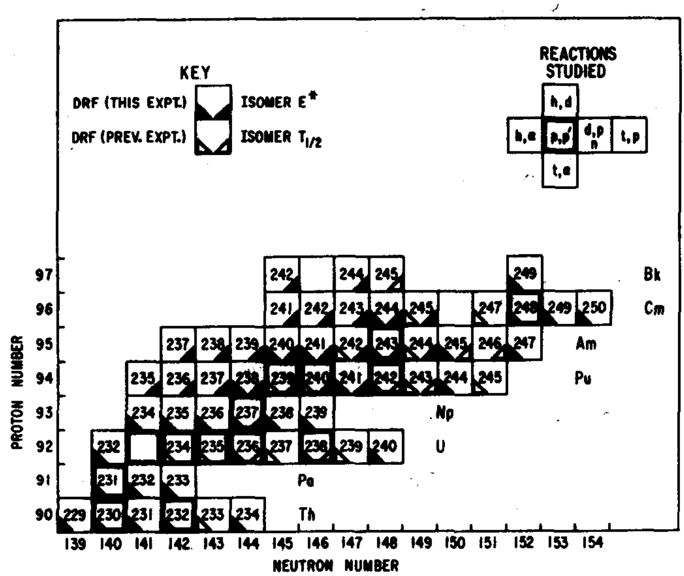

FIG.2. Actinide nuclei for which data are currently available from direct reaction fission or (n,f) cross-section measurements, DRF, and fission isomer excitation functions and half-lives. Heavily outlined boxes indicate nuclei that were used as targets in the present DRF studies.

heavy actinides where $E_A > E_B$, the direct-reaction fission and the fission isomer excitation function measurements are complementary. In addition, intermediate structure resonances from subbarrier neutron fission experiments can in some cases be used to estimate E_{II} [5,6]. Finally, the halflives for fission decay from the ground and isomeric states give information on the curvatures and/or average mass parameters and these aspects will be discussed in other contributions at this conference.

The actinide nuclei which have been studied either by direct-reaction fission or fission isomer techniques are indicated in Figure 2. It is seen that the current direct-reaction fission results plus earlier (d,pf) [7] and (n,f) [8] results provide a rather extensive survey of the actinide region. For several plutonium, americium and curium isotopes complementary information is available from both types of experiment.

In the current direct-reaction fission studies a variety of reactions including (d,p), (t,p), (^{3}He,d), (p,p'), (^{3}He,α) and (t,α) have been used so that a large number of fissioning nuclei could be investigated starting from the limited number of available target species. Of particular interest is the (^{3}He,df) reaction which allows the investigation of many odd-Z nuclei starting from the relatively plentiful even Z targets. In general, it was found that cross-sections for exciting nuclei to energies near the top of the fission barrier were quite adequate for (d,p), (t,p) and (^{3}He,d) reactions but the other reactions tried were of limited usefulness.

In the remainder of this paper we will present: 1) some of the general features of the experimental setup and results, 2) a discussion of techniques used to analyze the data for odd-A and odd-odd residual nuclei and 3) a survey of the experimental information currently available on the barrier heights E_A and E_B for actinide elements. A discussion of resonance phenomena and the analysis of data from even-even fissioning nuclei will be given in Paper IAEA-SM-174/27 (see Ref.[4].

2. EXPERIMENTAL RESULTS

The setup used in the direct-reaction fission studies is illustrated schematically in Fig. 3. The outgoing

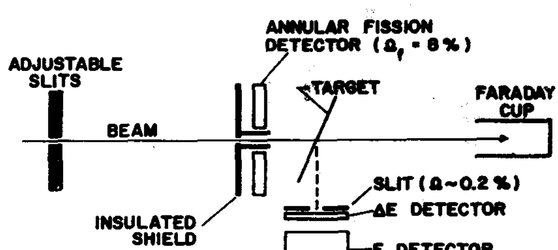

FIG.3. Schematic diagram of the experimental setup for the direct reaction fission experiments.

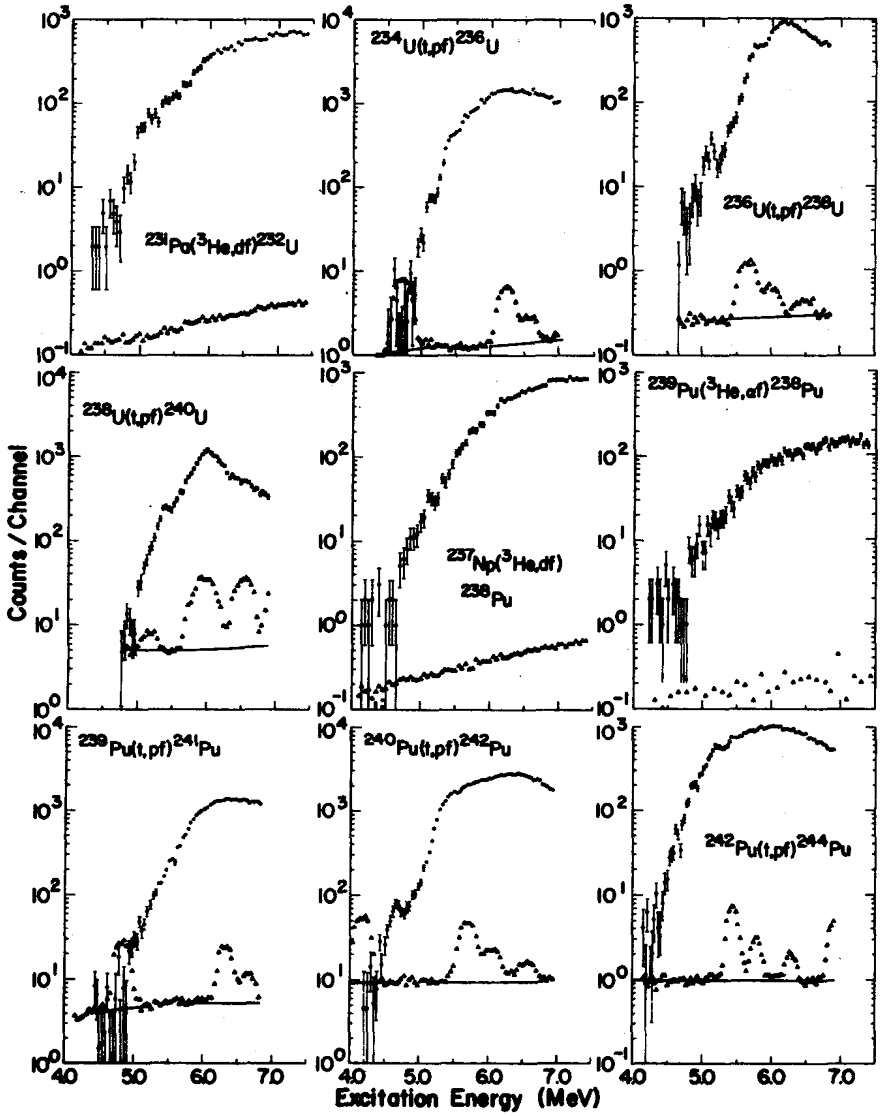

FIG.4. Measured coincidence (circles) and singles (triangles) spectra for a variety of reactions. Solid lines indicate interpolated singles cross-sections for the target element. Singles spectra have been normalized to the level of the accidental contributions in the coincidence spectrum.