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Summary: 75 years of nuclear fission – present status and perspectives

S KAILAS[1,2]

[1]Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
[2]University of Mumbai, Department of Atomic Energy Centre for Excellence in Basics Sciences, Mumbai 400 098, India
E-mail: kailas@barc.gov.in

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The nuclear fission phenomenon continues to be an enigma, even after 75 years of its discovery. Amongst others, the four key players (figure 1) who were responsible for the discovery of nuclear fission were Hahn, Meitner, Strassmann and Frisch. They published three epoch-making papers in the year 1939, announcing the discovery of nuclear fission.

Within a short period, a comprehensive theory of nuclear fission was provided by Bohr and Wheeler explaining many features of the newly discovered phenomenon. Even today it remains one of the best reviews in terms of our understanding of nuclear fission. Soon this field of research made rapid progress. Probes like neutrons, light and heavy ions were employed to investigate nuclear fission. The measurements included fission angular distribution and excitation functions, mass and kinetic energy distributions of fission fragments, pre-fission particles, etc. Several new features of this phenomenon – existence of fission isomers and double-humped fission barriers, presence of shell effect and its washing out at higher excitation energies were found from these investigations. The detailed experiments, followed by theoretical analysis provided information about the fissioning nucleus – the fission barrier, the deformation at the saddle point, the level densities at equilibrium and saddle deformations. With concurrent developments in experimental facilities and techniques, data are now available for fission cross-sections and mass distributions with high precision over a range of mass numbers, covering both stable and unstable heavy nuclides. Sophisticated theories which include nuclear structure and dynamics of nuclear fission have been developed over the years. In figure 2, we have summarized the landmark findings and the progress made in nuclear fission research in the last 75 years.

To commemorate the 75 years of the discovery of nuclear fission and to take stock of the progress we have made in this exciting field of research, a meeting was organized by Bhabha Atomic Research Centre (BARC) during May 8–10, 2014. The meeting was inaugurated by R K Sinha, Chairman, Indian Atomic Energy Commission. The senior

Figure 1. The key players in the discovery of nuclear fission.

scientists S S Kapoor and V S Ramamoorthy who have played leading roles in the Indian nuclear fission programme also spoke during the inaugural session. In this brief summary report, we have tried to capture the highlights of this meeting. The broad theories developed to describe the measurable quantities in fission are summarized in figure 3.

The key drivers of nuclear fission research are: Structure, dynamics and dissipation. The various phenomena associated with nuclear fission are influenced by these three aspects. Many contributions in this meeting had brought out the above key features of nuclear fission. For convenience, we have grouped the papers presented in the following categories: General reviews, reaction dynamics, cluster decay and superheavy nuclei,

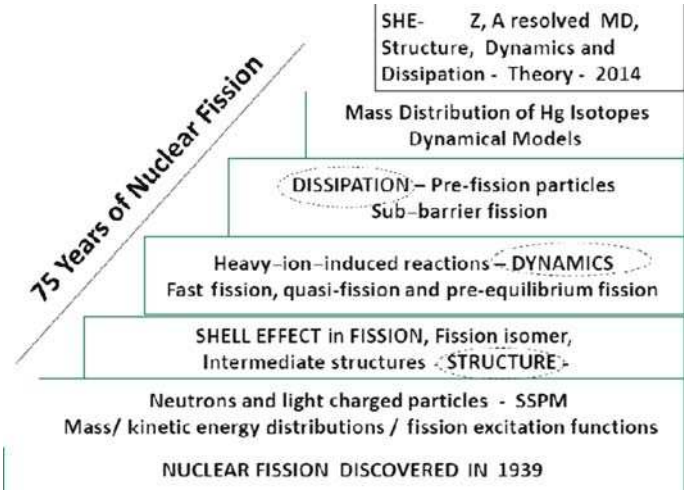

Figure 2. The landmark findings in the 75 years of nuclear fission research. SSPM – saddle point statistical model; MD – mass distribution.

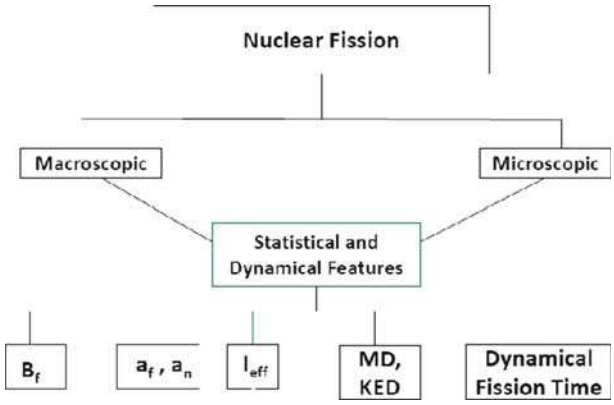

Figure 3. The broad theories developed to describe the measurables in nuclear fission research.

nuclear structure, dissipation, nuclear spectroscopy of heavy nuclei and fission fragments, reactor-related, facilities and instrumentation.

1. General reviews

The nuclear fission work of the Trombay (BARC) Group was summarized by Choudhury and Goswami. The BARC group has one of the largest number of scientists working in the broad area of nuclear fission covering nuclear physics, nuclear chemistry, nuclear data, reactor physics and shielding. The experimental probes used were the research reactors at BARC and the charged particle accelerators operational in the country. Several international collaboration programmes have been pursued as part of this research. The highlights of this research included the pre-equilibrium fission – the theory was proposed by the BARC group and the first experimental finding of this phenomenon was also attributed to the same group. Back who has made pioneering contributions to non-compound nuclear fission phenomenon in particular, captured in his talk the progress made in nuclear fission in general.

2. Reaction dynamics

The role of K-degree of freedom, the scission point model as an alternative to saddle-point model and the dynamical vs. statistical aspects of fission were discussed by John. The identification of non-compound fission component using mass–angle correlation and mass distribution measurements were discussed by Thomas, Ghosh and Tripathi. Hirose discussed the separation of compound and non-compound fission components through symmetric and asymmetric mass distribution measurements for Si, S + U systems at low energies. Schroeder dealt with the fission of medium mass nuclei at high energies and the connection between the dynamic processes, equation-of-state and thermodynamics of nuclei.

3. Cluster decay and superheavy nuclei

Poenaru proposed the analytical superasymmetric fission model to describe cluster radioactivity. He also pointed out that for some of the superheavy elements (SHE), cluster decay dominated over the α decay. The spontaneous fission of SHE (like $A = 292, 290$, $Z = 120$) was the topic of discussion by Gherghescu. Nasirov discussed the new method of cluster decay-collinear cluster tripartition (CCT) in the context of ternary fission with fragments having similar masses, observed in spontaneous ternary decay of ^{252}Cf and ternary fission of $^{235}\mathrm{U} + \mathrm{n}$. The work related to light charged particles accompanying binary fission and CCT (ternary fission) was elaborated by Balasubramanian. The dynamical cluster model and its success in explaining the cluster decay of heavy and superheavy nuclei were dealt with by Sharma. Santosh discussed the α decay of SHE such as $Z = 115$, 117, 118 and 119. The stability and properties of SHE were the topics of Staszczak's presentation.

4. Nuclear structure

Nuclear structure and dynamics influence the various aspects of fission phenomenon. The mass distribution measurements received a boost in recent years with interesting results from the β-delayed fission of Hg isotopes. Truesdale discussed this in detail, with special reference to the recent results for neutron-deficient Pt isotopes. The fission of nuclei after transfer was the focus of Laguillon's paper. He presented the mass distribution data for a number of nuclei in the Th–U region. The investigation of the role of shell effects at the saddle through systematic measurements of fission excitation functions and pre-fission neutron multiplicity measurements, both for light- and heavy-ion probes were the topics of Mahata's presentation.

5. Dissipation

While Mazumdar took up the discussion on GDR γs as a probe for measuring dissipation in fission, Ramachandran considered the pre-fission neutron and charged particle to determine the dissipation effects in fission. Pal presented calculations using the dissipative dynamical model (Kramer's approach) to describe the pre-fission neutron multiplicity data. Behera reported the recent neutron multiplicity measurements for the systems ^{12}C, ^{16}O, $^{19}\mathrm{F} + {}^{194,196,198}$Pt with the motivation to explore the influence of $N = 126$ on these observables. Vardaci discussed in detail the comprehensive set of pre-fission charged particle measurements for medium mass nuclei with a view to understand the statistical and the dynamical aspects of fission.

6. Nuclear spectroscopy of heavy nuclei and fission fragments

The Indian National Gamma Array (INGA) has been used in a number of investigations on nuclear spectroscopy. Palit, while summarizing some of the highlights of this programme

in general, focussed on mass 130 region in particular. Saha Sarkar discussed the spectroscopy of neutron-rich tin isotopes like ^{136,138,140}Sn and emphasized the importance of three-body forces and pairing interaction. The spectroscopy of heavy fissionable nuclei ($A = 244$–256) and SHE ($Z = 114$, $N = 184$) was the central theme of Tandel's paper. Jain pointed out the importance of isospin in fission in the context of mass distribution data for the system ^{238}U (^{18}O, f). He also pointed out that the fission widths are sensitive to isospin. Danu highlighted the detailed mass distribution measurements for the ^{238}U (^{18}O, f) system which exhibited structures related to shell closure. The ILL facility has been used for pursuing neutron-induced fission of ^{235}U and ^{241}Pu in particular. De France summarized the salient features of this programme with special reference to the spectroscopy of fission fragments in the mass range $A = 85$–160.

7. Reactor related

The ongoing successful three-stage Indian nuclear power programme was covered in three talks: Vohra (pressurized heavy water reactors – 1st stage); Chellapandi (fast breeder reactors – 2nd stage); Vijayan (thorium-based reactors – 3rd stage). The indigenous development of nuclear instrumentation needed for this programme was the focus of Das's talk. Huber pointed out the interesting application of neutrino measurement to monitor the U/Pu ratio in the core of an operating power reactor. Hemalatha discussed the strategies for the transmutation of long-lived nuclear waste in general and long-lived fission products in particular. The highlights of the neutron TOF set-up based nuclear data measurement programme were covered by Wright. Nayak elaborated on the use of surrogate reactions for the measurement of (n, f) cross-sections for the nuclei of interest to Th–U fuel cycle.

8. Facilities and instrumentation

Viesti summarized the development of new techniques in the area of detection of special nuclear materials. The features and progress of the upcoming national facility for unstable and rare ion beams (ANURIB) at Variable Energy Cyclotron Centre, India was elaborated by Bandyopadhyay. Jhingan discussed the capability in developing state-of-the-art detector set-ups for nuclear fission measurements with special reference to the ongoing programme at the Inter University Accelerator Centre. Balabanski discussed the photonuclear reaction facility at ELI-NP. The use of lasers in nuclear physics programme through the measurement of ground-state properties of short-lived nuclei away from the line of stability was the central theme of Billowes's talk. Thoennessen discussed in detail the upcoming FRIB at MSU, USA and pointed out that nearly 20% of the 3000 nuclei away from the line of stability have been produced through the nuclear fission route.

9. Prospects

Based on the progress achieved and the plans being made in the field of nuclear fission, one could point out some research areas which hold promise for future: (1) Evolution of

mass distribution and transition from symmetric to asymmetric as a function of mass of the fissioning nuclei, (2) fission of neutron rich/poor nuclei and the role of nuclear structure and dynamics, (3) sources for pre-fission neutrons and the dynamics associated with the emission of neutrons in fission, (4) investigation of shell effect at the saddle point, (5) use of surrogate method for neutron-induced fission cross-section in particular, (6) application of nuclear isospin in nuclear fission studies, (7) SHE – formation and decay studies, (8) dissipation in fission – complete data set required, (9) comprehensive theory which should include structure, dynamics and dissipation to describe nuclear fission observables. Nuclear physics with and of nuclei away from the line of stability holds great promise for future and nuclear fission studies in this context will be exciting and challenging.

There was a session devoted to reminiscences of senior scientists from India who contributed to the growth of nuclear fission research. Amongst others, Kapoor, Mehta, Gupta, Iyer, Nadkarni and Manohar spoke on this occasion. The organizers of the topical meeting on nuclear fission to celebrate 75 years of nuclear fission deserve appreciation from the participants for making this conference a memorable one. The participants complemented in particular, Datar, Biswas and Mahata who shouldered the major responsibility in organizing the meeting successfully.