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Keynote address: One hundred years of nuclear physics – Progress and prospects

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Abstract. Nuclear physics research is growing on several fronts, along energy and intensity frontiers, with exotic projectiles and targets. The nuclear physics facilities under construction and those being planned for the future make the prospects for research in this field very bright.

Keywords. Nuclear structure and reactions; nuclear properties; superheavy nuclei.

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1. Introduction

Nuclear physics research is nearly one hundred years old. Currently, this field of research is progressing [1] broadly in three directions (figure 1): Investigation of nuclei and nuclear matter at high energies and densities; observation of behaviour of nuclei under extreme conditions of temperature, angular momentum and deformation; and production and study of nuclei away from the line of stability. Nuclear physics research began with the investigation of about 300 nuclei. Today, this number has grown many folds, nearly by a factor of ten.

In the area of high-energy nuclear physics, some recent phenomena observed have provided interesting connections to other disciplines in physics, e.g. in the heavy-ion collisions at relativistic energies, it has been observed [2] that the hot dense matter formed in the collision behaved like an ideal fluid with the ratio of shear viscosity to entropy being close to $1/4\pi$. This value is similar to the ones reported in string theory, atomic physics (dealing with ultracold atoms), nuclear physics (deduced from giant dipole resonance widths) and strongly correlated condensed matter systems. It appears that this observation is a general feature of strongly coupled systems and the underlying similarities among different branches of physics.

In this paper, we shall restrict the discussion to the recent exciting developments occurring in the frontier area of 'Nuclei near the limits of stability.'

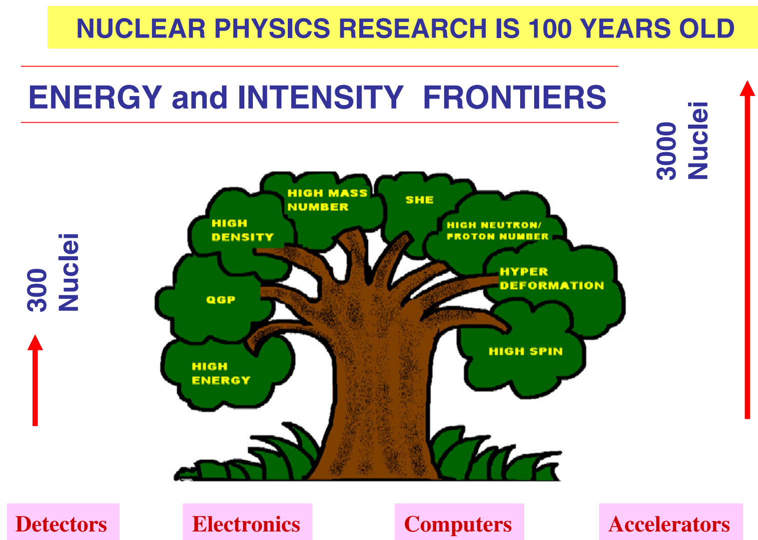


Figure 1. Growth of nuclear physics research along several branches.

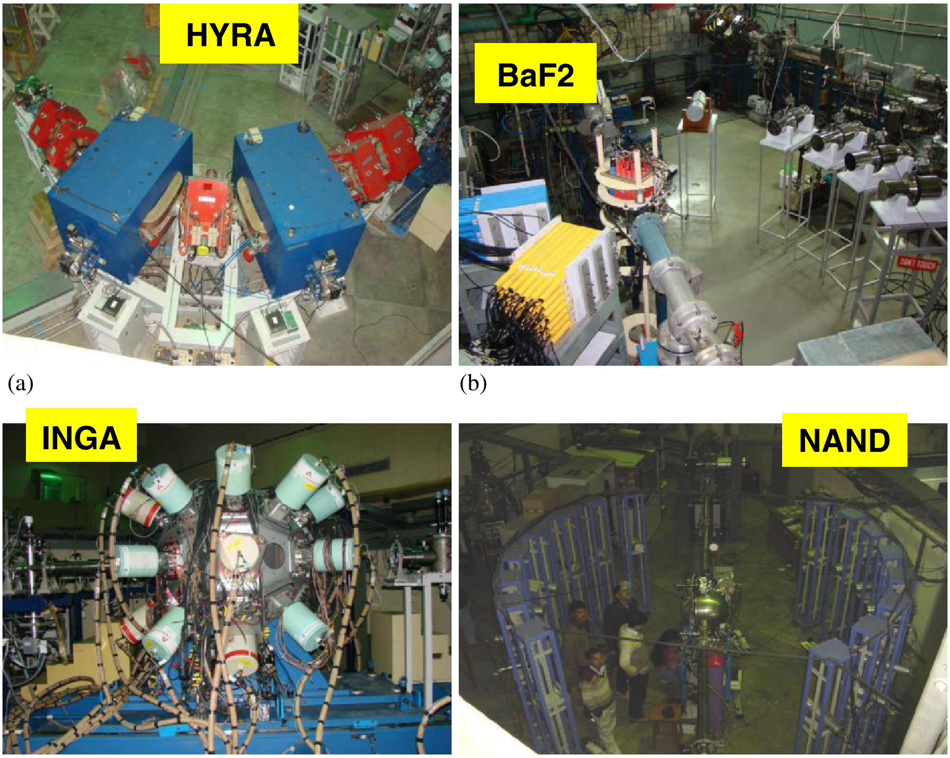
2. Tools for nuclear physics research

To pursue frontiers in nuclear physics, the major tools are accelerators that can deliver beams of varying energies, intensities and species. In the recent years, accelerators have been built not only for stable beams but also for projectiles far removed from the line of stability. Currently, the efforts are on to develop these rare beams with increasing intensity and mass numbers approaching the drip lines. Many investigations have been carried out with these secondary beams. The status of this field of research is reported in the recent conferences, e.g. NN2012 [1]. For the efficient detection of events of interest, it is essential to build large arrays of gamma, charged particle and neutron detectors of different types and recoil separators. In major accelerator facilities, the state-of-the-art detector arrays as mentioned earlier are already in operation. In figure 2, we have shown a collection of some of the versatile detector set-ups that are in use or are being developed in the laboratories in India.

Besides these, state-of-the-art nuclear electronics and high-performance computing are crucial for the success of nuclear physics programmes. It has been a continuing effort, world over, with advancement on all these aspects required for frontline nuclear physics research, e.g. the recent development of digital signal processing for INGA has led to handling of high counting rates facilitating measurement of higher-fold coincidences.

3. Present scenario in nuclear physics research

One of the fascinating areas of research is production of nuclei far away from the line of stability and measurement of their properties such as mass, radius and moments. These then become the testing beds of nuclear theories being developed. Some of the



(a) (b) (c) (d)

Figure 2. A collection of the detector set-ups in Indian accelerator labs. **(a)** HYRA – Heavy Residue Analyzer–recoil separator and the focal plane detector set-up. **(b)** BaF2-based gamma array. **(c)** Indian National Gamma Array (INGA) based on Ge clover detectors. **(d)** National Array of Neutron Detectors (NAND).

salient features of this research has been the observation of new neutron-rich nuclei [3] (^{64}Ti, ^{67}V, ^{69}Cr, ^{72}Mn), unusual structures (structure of ^{98}Cd is similar to that of ^{130}Cd) and decay modes (two-proton and two-neutron decay), new magic numbers (N=16 is a magic number) and vanishing of old magic numbers (N=20 is not magic for Z=11, N=8 is not magic for Z=3,4), halo nuclei (^{11}Li is as large as ^{48}Ca (the r.m.s. values are nearly the same), ^{22}C is as big as ^{90}Zr) and superheavy nuclei (up to Z=118), exotic shape evolution (spherical to deformed).

One of the interesting features in nuclear structure has been the observation of constancy of energies of the first excited states of a range of Sn nuclei with mass numbers A = 104 to 128. The energy values are observed to be lying between 1130 and 1290 keV. Similarly, for the neighbouring Cd and Te nuclei (figure 3), the first excited state energies are observed [4] to be nearly constant over a range of isotopes. However, the values of excitation energy are significantly lower than that for shell-closed Sn nuclei. Another interesting feature of the structure of nuclei has been the one related to relatively heavy nuclei close to N=Z line, in particular, for A between 50 and 80. The energy

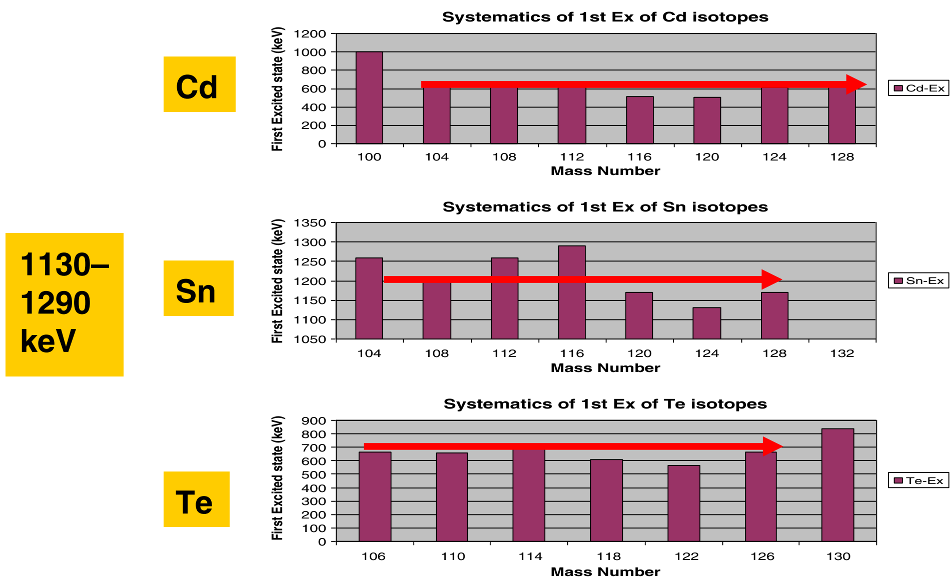


Figure 3. The systematics of the first excited states of Sn, Cd and Te isotopes.

levels of the mirror nuclei (^{54}Ni/^{54}Fe) exhibit an unusual behaviour. The $J=2$ state in ^{54}Fe is surprisingly higher than that of the corresponding $J=2$ state in ^{54}Ni. The other states ($J=4$, 6) follow the expected trend of the energies of ^{54}Fe being lower than that of the corresponding ones in ^{54}Ni. The $J=2$ anomaly problem has been discussed in ref. [5]. From a study of levels in the heavier mirror nuclei – ^{70}Br/^{70}Se, ^{74}Rb/^{74}Kr, ^{78}Y, ^{78}Sr, the role of n/p pairing and the shape influencing the nuclear structure have been brought out [5].

In the area of nuclear reactions, one of the emerging areas has been the surrogate reactions [6] to measure cross-sections for nuclei that are unstable or available in less abundance. This technique has been exploited in particular for measurement of cross-sections of interest to nuclear fuel cycle and accelerator-driven system applications. In one technique called the surrogate ratio method, to measure [7] the cross-section for the reaction ^{233}Pa(n, f), the following procedure is followed. Using weakly bound projectiles such as ^{6}Li (consisting of ^{4}He and ^{2}H clusters) interacting with a target such as ^{232}Th, one can get cross-sections for ^{232}Th(^{6}Li,^{2}H)^{236}U (and fission probability of ^{236}U) and ^{232}Th(^{6}Li, ^{4}He)^{234}Pa (and fission probability of ^{234}Pa) at the same time. The former channel fission probability is the same as that of ^{235}U(n, f). The latter channel fission probability is the same as that of ^{233}Pa(n, f). As we know the cross-section for ^{235}U(n, f), the (n, f) cross-section for the unstable target ^{233}Pa can be deduced. The details are given in refs. [6,7]. This method can be extended to many unstable or radioactive targets [7]. Study of reactions induced by weakly bound projectiles and neutron-rich projectiles and understanding the influence of break-up channels continues to be an area of active research [8]. Establishing the presence of shell effect at the saddle point and the determination of the shape of the fissioning nucleus through heavy-ion fusion and fission reactions is an ongoing programme [9].

Road to Super Heavy Nuclei

Z=107	Bohrium	54Cr + 209Bi
Z=108	Hassium	58Fe + 208Pb
Z=109	Meitnerium	58Fe + 209Bi
Z=110	Darmstadtium	62Ni + 208Pb
Z=111	Roentgenium	64Ni + 209Bi
Z=112	Copernicium	70Zn + 208Pb (7 s)
Z=113		70Zn + 209Bi
Z=114	Flerovium	48Ca + 244Pu (2 s)
Z=116	Livermorium	48Ca + 245,248Cm(60 ms)
Z=117		48Ca + 249Bk
Z=118		48Ca + 249 Cf
Z=119 ongoing		50Ti + 249Bk
Z= 120 ongoing		50Ti + 249 Cf

Figure 4. The quest for superheavy nuclei.

Another exciting area of intense investigation has been in the area of superheavy nuclei. With increasing mass number, the nuclei are expected to decay by fission. However, due to the nuclear shell effect, the prospects of superheavy nuclei are bright [10]. As per theoretical prediction, some of the nuclei with Z=120–126 (N=184) are expected to be more stable than the neighbouring and lighter nuclei. World over, there have been painstaking experimental efforts to produce these heavy nuclei using neutron-rich projectiles such as ^{48}Ca, ^{50}Ti interacting with radioactive targets such as Bk, Cm. While an element with Z=118 has been populated, experiments are underway to produce heavier nuclei approaching Z=120. In figure 4, we have summarized the status of the quest for superheavy nuclei.

While it is well known that the nuclear force is dominated by the two-nucleon interaction, the role of three-nucleon interaction cannot be ignored. In recent years, there has been renewed interest to obtain information about the three-nucleon interaction from the analysis of nuclear structure of light nuclei [11] and nuclear reactions induced by protons in particular [12]. The importance of three-nucleon and tensor interactions in the description of nuclei approaching the drip lines has been brought out in the recent studies [3].

4. Conclusion

The expanding nuclear landscape continues to be interesting and exciting. Scaling intensity and energy frontiers continue to be recurring themes in nuclear physics research. In addition to the existing facilities, amongst other facilities, the upcoming Facility for Antiproton and Ion Research (FAIR), will be important to all branches of nuclear physics, low-, intermediate- and high-energy regimes. The dedicated facilities for rare ion beams coming up at MSU and GANIL will boost the research in the area of nuclei near the limits. While the experimental efforts continue to be intense, more push needs to be given on the theoretical front to make rapid progress in nuclear physics research. It is becoming increasingly clear that three-nucleon interaction has to be included in the description of the nuclei away from the line of stability [3]. The future of this field is bright as in addition to addressing outstanding questions in nuclear physics, it is also expected to provide answers to outstanding questions in astro and high-energy physics.

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References

[1] 11th International Conference on Nucleus–Nucleus Collisions (NN2012), *J. Phys.: Conf. Ser.* **420** (2013)
[2] N D Dang, XIX International School on Nuclear Physics, Neutron Physics and Applications, *J. Phys.: Conf. Ser.* **366**, 012035 (2012)
[3] O B Tarasov *et al*, *Phys. Rev. C* **87**, 054612 (2013)
J Nolen, *Physics* **6**, 59 (2013)
[4] S Kailas, unpublished
[5] M Bentley, *Nucl. Phys. News* **22**(**1**), 13 (2012)
[6] J E Escher, J T Burke, F S Dietrich, N D Scielzo, I J Thompson and W Younes, *Rev. Mod. Phys.* **84**, 353 (2012)
[7] B K Nayak *et al*, *Phys. Rev. C* **78**, 061602 (2008)
V V Desai *et al*, *Phys. Rev. C* **87**, 034604 (2013)
[8] V V Parkar *et al*, *Phys. Rev. C* **87**, 34602 (2013)
S Santra *et al*, *Phys. Rev. C* **85**, 014612 (2012)
H Kumawat *et al*, *Phys. Rev. C* **86**, 024607 (2012)
A Shrivastava *et al*, *Phys. Letts. B* **718**, 931 (2013)
[9] V Singh *et al*, *Phys. Rev. C* **87**, 64601 (2013)
K S Golda *et al*, *Nucl. Phys. A* **913**, 157 (2013)
K Mahata and S Kailas, to be published
[10] Yu Ts Oganessian *et al*, *Phys. Rev. C* **87**, 034605 (2013)
[11] B R Barrett, P Navratil and J P Vary, *Nucl. Phys. News* **21**(**2**), 5 (2011)
[12] S Rafi *et al*, *Phys. Rev. C* **87**, 014003 (2013)