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Nuclear reaction studies using the cyclotron at VECC: A Review

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The cyclotron at Variable Energy Cyclotron Centre (VECC), Kolkata has recently completed its 40 years of operation in 2017. During the past four decades, VECC has been able to cross several milestones in exploring the properties of nuclei with the help of low energy light as well as heavy ions accelerated by the cyclotron. In this review, we endeavour to present an overall picture of the intense research activities in various branches of nuclear physics carried out in the past four decades using cyclotron, with special emphasis on the important achievements in each field.

Keywords: Scattering and direct reactions, Nuclear orbiting, Hoyle state, Fission, Nuclear level density and collectivity, Giant dipole resonance, Nuclear flow

1 Introduction

The room temperature cyclotron at Variable Energy Cyclotron Centre (VECC), Kolkata, commissioned in 1977 by the Department of Atomic Energy, Government of India, has completed four decades of continuous operation, except for a few planned maintenance and upgradation shutdowns. The accelerated light and heavy ion beams from the cyclotron have been utilised mainly for researches in nuclear physics, material science, nuclear chemistry, biology and other application areas. In the limited span of this review, we briefly highlight only a few important milestones achieved in nuclear reaction studies using the VECC cyclotron, which include (a) shape evolution of the hot light α-cluster and non α-cluster composite systems, (b) low temperature scaling of the width of hot giant dipole resonance (GDR), (c) precision measurement of the Hoyle state decay width, a crucial ingredient for the understanding of stellar nucleosynthesis, (d) collective enhancement of nuclear level density and nuclear shape phase transition in deformed nuclei, (e) fluidity of the moderately excited nuclear matter and its universality and (f) nuclear shell effect in fission, to mention a few. Some of these measurements were done for the first time at VECC and triggered further research activities in those directions. For a more complete review of the nuclear research using the VECC cyclotron, the reader is referred to the latest review[1]. The layout of VECC accelerator and the associated experimental area is shown in Fig. 1. The accelerator is an 88-inch, azimuthally varying field cyclotron, which delivers energetic light as well as heavier ions (*p*, *d* ~10 - 25 MeV, ^{4}He ~30 - 80 MeV; O, Ne, Ar ~5-12 MeV/nucleon) for experiments. There are three beam lines in the experimental area. The beam line-1 at 0° is used for high current (~1 μA or more) irradiation studies and the beam lines 2 (at 30°: for charged particle studies) and 3 (at 45°: for γ-ray, *n* studies) are used for in-beam nuclear physics experiments.

2 Nuclear Reaction Studies

2.1 Scattering and direct reactions

Light ion beams from the cyclotron have been used extensively for the measurement of scattering and direct reaction angular distributions in order to study the nuclear optical model potentials, inelastic excitation mechanisms as well as to extract spectroscopic information. Recently, direct reactions ^{27}Al (*d, t/^{3}He*)

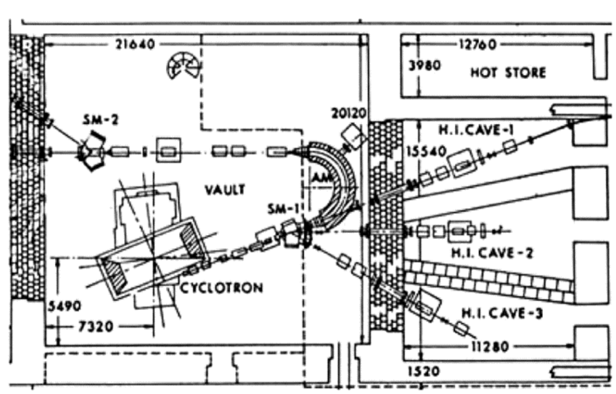

Fig. 1 – Layout of the accelerator and its experimental area.

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^{26}Al/^{26}Mg have been used to study the structures of ^{26}Al and ^{26}Mg, both of which are important from astrophysical point of view (Fig. 2). The T=1 analogue states in the two nuclei (^{26}Al, ^{26}Mg) forming isobaric doublet have also been identified[2].

2.2 Nuclear quasi-molecule and orbiting

Light α-cluster nuclei, (i.e., ^{8}Be, ^{12}C, ^{16}O, ^{20}Ne, etc.) are known to have preformed α-cluster like structure, which influences the compound nuclear formation and leads to the observation of the phenomena like anomalous large angle scattering, resonance like structure in excitation functions and large deformation (di-nucleus formation) of the excited composite. The formation of such di-nuclear quasi- molecular structure in ^{28}Si* was clearly evident in the prominent resonance-like structures in the measured excitation function of ^{24}Mg (^{4}He, ^{12}C) ^{16}O reaction[3]. Such long-lived dinuclear configuration and vis-a-vis orbiting is likely to be washed off at higher excitation. The extent of survival of orbiting at higher excitations was investigated for the reaction ^{20}Ne + ^{12}C in the bombarding energy range[4] of 145 - 200 MeV. Observed excess in energy damped yields of C, B fragments over the corresponding statistical model predictions (solid curve) indicate the survival of orbiting at these energies (Fig. 3). For light α-cluster nuclei, the formation of orbiting di-nuclear complex leads to anomalously large deformation which was studied using light charged particle evaporation from both α- and non α-cluster (^{20}Ne + ^{12}C, ^{27}Al) systems. Anomalously large deformation observed in the former case indicated the formation of orbiting di-nucleus[5]. Further study of the splitting of GDR line shapes[6] clearly demonstrated the prolate shape for the hot ^{32}S* composite, whereas triaxial shape for ^{47}V* at similar excitation (Fig. 4).

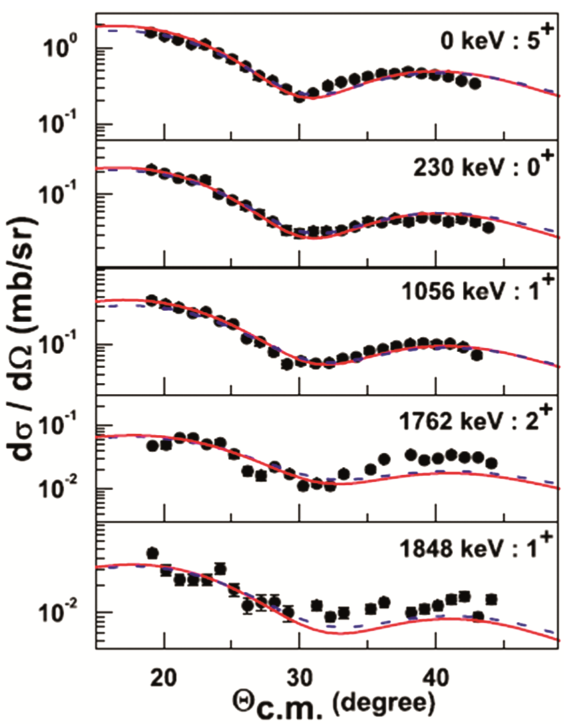

Fig. 2 – ^{27}Al(d, t) ^{26}Al angular distributions for a few states of ^{26}Al[2].

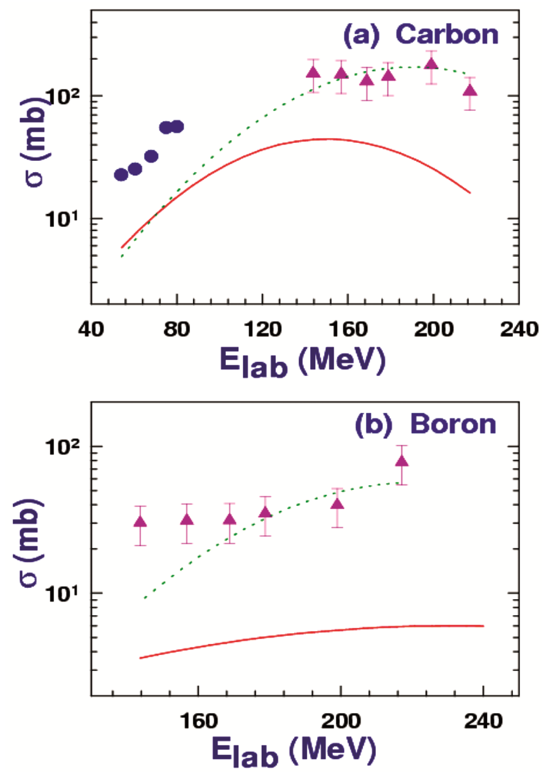

Fig. 3 – Enhanced C, B yields in ^{20}Ne+^{12}C reaction[4]

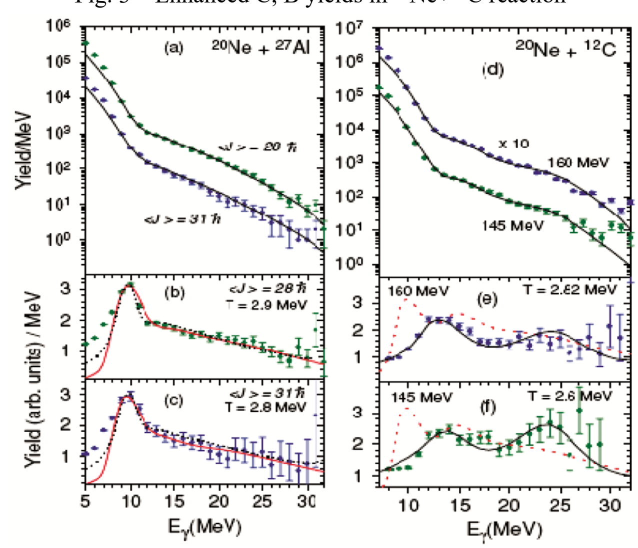

Fig. 4 – Splitting of GDR line shapes for deformed ^{32}S* and ^{47}V* [6].

2.3 Decay of Hoyle state

The Hoyle state (0_2^+; E_x=7.654 MeV) of carbon, which is key to understand stellar nucleosynthesis, is very interesting from nuclear structure point of view. Being a 3α-cluster state, it is assumed to exist in various configurations, (i.e., 3α-linear chain, bent arm / compact triangle, Bose-Einstein (BE) gas and/or its condensate), which may affect its decay rate[7]. As stellar nucleosynthesis crucially depends on it, precision estimate of the Hoyle state decay rate is of utmost importance. So, high precision and high statistics measurements of the Hoyle state decay rate using inelastic scattering of ^{4}He (60 MeV) + ^{12}C have been systematically made at VECC in a series of experiments[7] (Fig. 5). The latest study with highest statistics till date (~160000 Hoyle events) led to the lowest ever upper limit of direct decay at ~0.019% with 95% confidence limit[7].

2.4 Nuclear shell effect in fission

In the study of ^{238}U(α, f) reaction, the measured slope of the average total kinetic energy was found to be a strong function of fragment mass, indicative of the presence of shell and pairing effects[8]. The evolution of nuclear shell effect on fission was studied for ^{232}Th (α, f) reaction by measuring fission fragment (FF) mass distributions over a wide excitation energy range[9] (21-65 MeV). The shape of the FF mass distribution changed from asymmetric to symmetric at excitation energy ~ 40.5 MeV, clearly indicating the washing out of shell effect above that excitation (Fig. 6). The influence of shell effect on fusion-fission dynamics in the Hg-Pb region was studied for ^{210}Po* and ^{213}At*, produced by fusion of ^{4}He + ^{206}Pb, ^{209}Bi, respectively. The measured FF mass distributions in both cases were found to be predominantly symmetric in nature indicating the absence of shell effect, except in the fission of ^{210}Po* at the lowest excitation energy of 30.8 MeV. Here, a slightly asymmetric mass distribution indicated the preference for asymmetric saddle to scission pathway (persistence of shell effect)[10].

2.5 Nuclear level density and collectivity: shape phase transition in nuclei

Knowledge of nuclear level density (NLD) and its dependence on excitation energy, spin, shape etc., is required for precise understanding of a wide variety of nuclear reactions, from evaporation to fission and spallation. For deformed nuclei there is additional collective enhancement of NLD due to the coupling of mainly rotational and single-particle degrees of freedom. Beyond a critical temperature, collectivity dies out leading to the fadeout of collective enhancement in

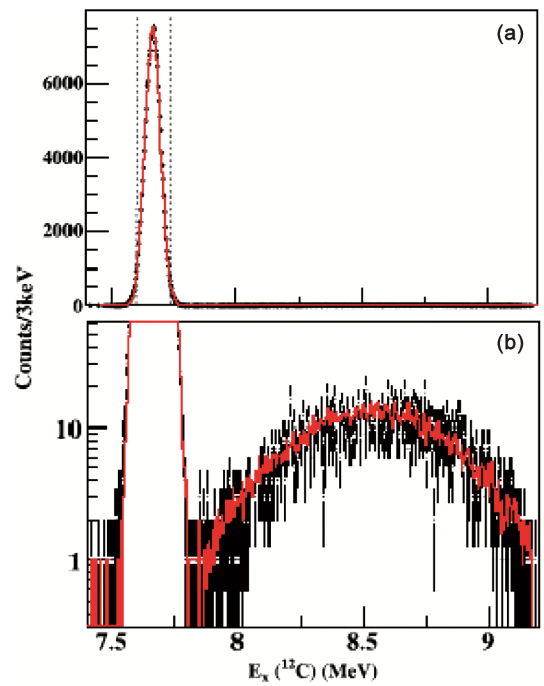

Fig. 5 – Reconstructed (a) hoyle state and (b) the background[7].

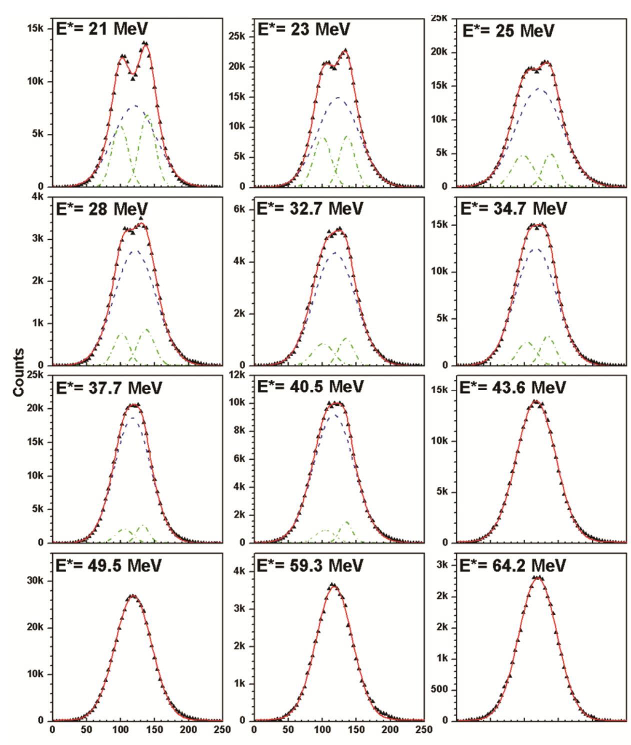

Fig. 6 – Evolution of shell effect in ^{232}Th(α, f) FF mass distribution[9].

NLD and shape phase transition (from deformed to spherical) of the nucleus. Experimental search for this phenomenon, which had not been detected so far, was done at VECC by measuring the neutron evaporation spectra of $^{201}Tl^*$ (near spherical), $^{185}Re^*$, $^{173}Lu^*$ and $^{169}Tm^*$ (all highly deformed) in the excitation energy range E^* ~25-55 MeV[11,12]. A sharp variation (relative increase) of inverse NLD parameter, k (=1/a), around E^* ~27 – 37 MeV was observed for the deformed $^{185}Re^*$, $^{173}Lu^*$ nuclei, which was absent for spherical $^{201}Tl^*$ (Fig. 7). This is a clear and direct signature of fade out of collective enhancement of NLD, observed for the first time by the VECC group[12]. Later, GDR studies at VECC further confirmed the existence of this phenomenon[13].

2.6 GDR width at low temperature

Cyclotron beams have been extensively used for detailed studies on continuum γ-rays in general and GDR decay in particular. Systematic study of the variation of GDR width with temperature (T) has been carried out at VECC. It has been observed that GDR width (Γ_{GDR}) increases steadily with T above a critical value of T (T_c); below T_c, it remains nearly constant in all mass regions (Fig. 8). This near-universality of Γ_{GDR} at low T has been explained in terms of critical temperature included fluctuation model (CTFM)[14]. Due to the presence of non-zero nuclear shape fluctuation due to GDR vibration even at T = 0 MeV, the thermal shape fluctuation will be detectable only when it is larger than the intrinsic value. This happens at T ≥ Tc, below which Γ_{GDR} remains nearly constant.

2.7 Fluidity of finite nuclear matter at moderate temperature

The ratio of shear viscosity (η) to entropy density (s) is the measure of fluidity of matter. For high temperature quark gluon plasma (QGP), η/s (~ 5-10 $\hbar/4\pi k_B$, k_B is the Boltzman constant) is very low and so QGP behaves as perfect fluid. However, η/s for finite nuclear matter at moderate temperature have not been explored in details. Systematic experimental estimation of η, s and η/s for several nuclei (^{31}P, ^{97}Tc, ^{119}Sb, ^{201}Tl) at various excitation energies was done for the first time at VECC. The shear viscosity (η) at different T was extracted from the measured GDR energy and width; the entropy density s was estimated from the back angle neutron evaporation spectrum. The values[15] of η, s and η/s thus obtained are shown in Fig. 9. It is clear from the Fig. 9 that both η, s increases with temperature, whereas η/s shows a decreasing trend. The value of η/s in all cases is within the range of ~2.5-6.5 $\hbar/4\pi k_B$. This observation confirms strong fluidity as universal characteristics of all strongly interacting many-body quantum systems, from moderately hot nuclear matter to quark gluon plasma[15].

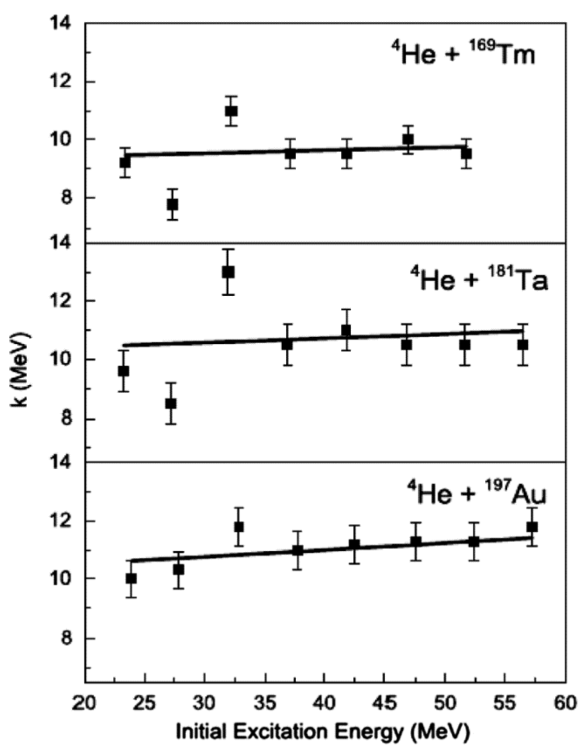

Fig. 7 – Abrupt variation of k for deformed systems[12].

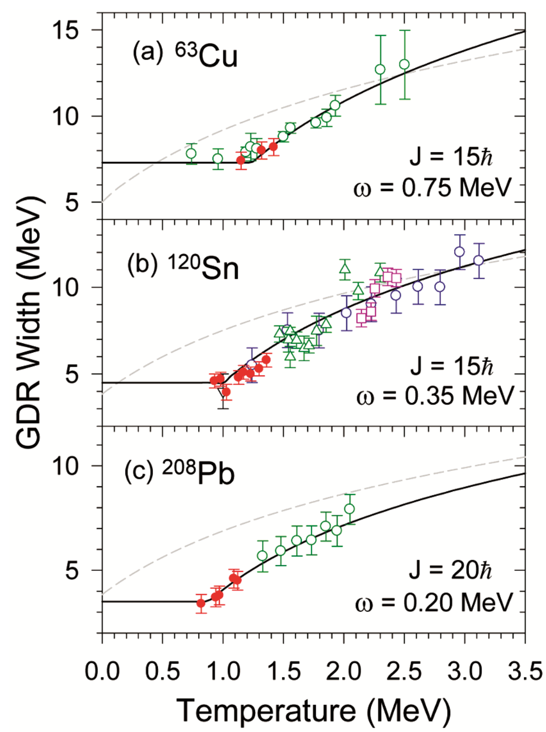

Fig. 8 – Variation of Γ_{GDR} with T in different mass regions[14].

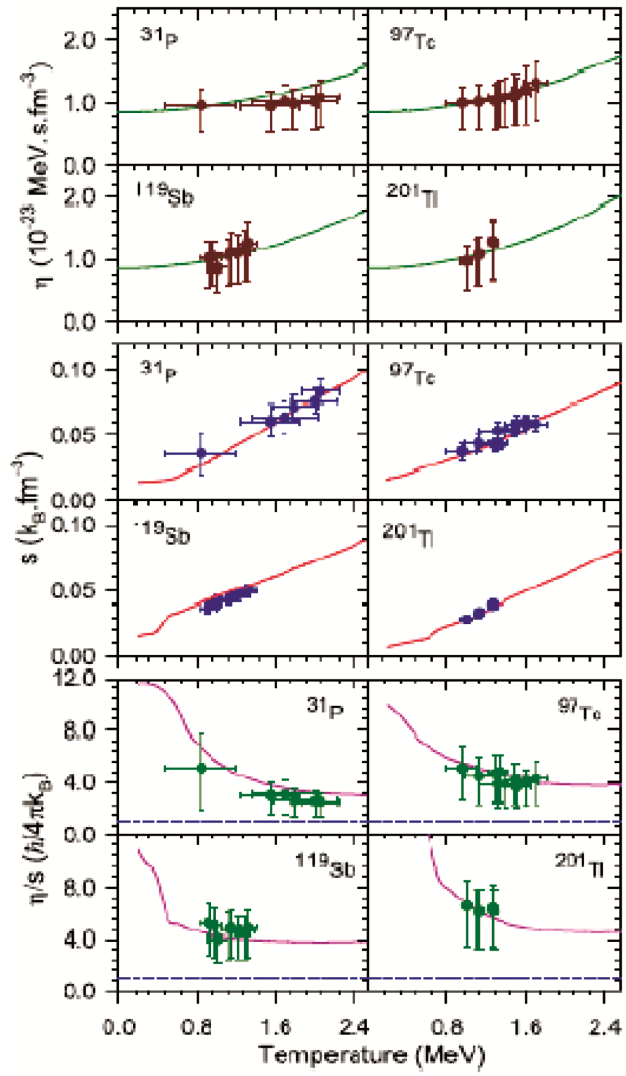

Fig. 9 – Variation of η, s and η/s with temperature[15].

3 Summary and Conclusions

It is clear from the brief presentation above that VECC cyclotron beams were key to successful execution of many pioneering research activities in several frontier areas of nuclear physics. Here, we restricted ourselves to highlighting only a few most important research activities in the area of nuclear reactions, such as the studies on the nature of shape evolution of hot rotating nuclei as well as orbiting di-nuclear complexes, systematics of hot isovector GDR width at low temperature, high precision measurement of hoyle state decay rates, the enhancement and fadeout of NLD and its link with nuclear shape phase transition in deformed nuclei, establishment of the universality of *η/s* in all strongly correlated fluids from moderately excited nuclear matter to highly excited quark gluon plasma, evolution of the role of nuclear shell effect with excitation energy in fission process. Besides, many other equally important and extensive works on different branches of nuclear reaction[1] had to be left out and readers are referred to for a more complete review.

VECC cyclotron has also been used extensively for research on other branches of nuclear physics and related application areas. To mention very briefly, in the field of nuclear structure, pioneering works have been done on alternating parity band structures and their connections with octupole deformation, the evolution and onset of deformation in nuclei with change in neutron number, etc., to mention a few. Systematic studies on the effect of atomic (electronic) environment on the nuclear beta decay (electron capture) rate, which is of fundamental as well as astrophysical interest, have also been carried out at VECC. The interested readers may look for more details in literature[1].

To conclude, it is evident that VECC has achieved its objective to become a major international accelerator centre in terms of quality and quantity of research output. With the renovation of the present accelerator and addition of new accelerators in future, the centre will continue to cater to the need of the core research programmes and produce highest quality outputs in the coming decades.

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