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Nuclear structure and Indian Clover array

H C JAIN
Tata Institute of Fundamental Research, Mumbai 400 005, India

Abstract. A brief description of the nuclear structure studies performed with the 14-UD pelletron at TIFR has been presented. The experimental facilities developed for these studies are described. Some of the interesting results obtained for mass 70 to 80 nuclei are presented. The development of a recoil mass spectrometer and an Indian clover array for the study of high spin states in nuclei near drip lines is discussed.

Keywords. DCO; Clover; recoil mass spectrometer; n-p interaction.

PACS Nos 23.20.Lv; 21.60.Ev; 21.10.Tg

1. Introduction

It is nearly 10 years since 14-UD pelletron was set up in TIFR, Bombay by National Electrostatic Company, USA. It was the first of its kind and an unique facility in the country. There was naturally an air of excitement in TIFR. The effective and efficient use of this accelerator required the development of new and more powerful experimental facilities compared to those which existed earlier. I was personally interested in the study of nuclear structure in mass-80 region. The reason was the prediction of stable ground state deformation in nuclei with N or $Z = 36, 38$ [1], the low level density and the presence of $g_{9/2}$ orbitals near the Fermi surface which would lead to change in shape and structure of nuclei in this mass region with small changes in neutron and proton numbers. Nuclei in this region were also expected to be γ-soft. In addition, one could also look for signatures of n-p interaction since both neutrons and protons occupied the $g_{9/2}$ orbitals. All these features made nuclear structure studies in mass-80 region quite attractive. However, these studies also presented experimental challenge since the heavy ion reactions to be used for production of nuclei in this region had large number of exit channels with emission of protons, alpha particles and also neutrons. This would require special techniques to separate various reaction channels and also to identify new reaction channels as we move away from the β-stability line towards the proton rich nuclei. The low cross sections for the production of proton rich nuclei also required higher efficiency and high resolution γ detector array. In view of the above, new experimental facilities were established and tested soon after the accelerator beams became available.

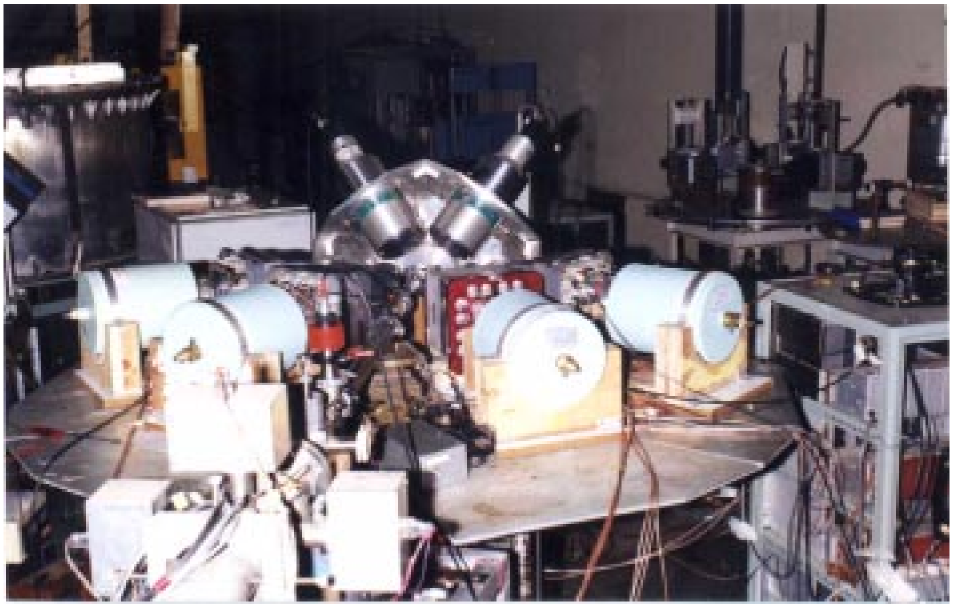

Figure 1. A photograph of the 4 CS-Clover array with a neutron detector array at TIFR.

2. Experimental facilities

Following experimental facilities were developed at the outset: (i) A set of 5 CS-HPGe detectors with a multiplicity filter consisting of 14 NaI(Tl) detectors [2,3]. (ii) A nano second beam pulsing system consisting of a double harmonic beam buncher at the low energy end after the injector magnet and a sweeper at the high energy end after the analysing magnet [4]. (iii) A plunger set up to measure the life times of nuclear excited states in the region of 10^{-9} to 10^{-12} sec [5]. (iv) The line shape analysis programs were developed to be able to measure lifetimes of nuclear excited states in the region of 10^{-14} to 10^{-12} sec [2,3]. (v) 4π-charged particle ball for identification/separation of reaction channels in heavy ion reactions [6,3].

3. Nuclear structure studies in Y, Sr and Zr isotope

The facilities listed above were used to measure gamma-gamma coincidences, angular distribution and DCO ratio to establish new energy levels and their spins in Y, Sr and Zr isotopes [2,3,7–11]. The lifetimes of nuclear excited states in these nuclei were measured using the techniques mentioned above to investigate the microscopic structure of these states and to study the variation in nuclear shape and structure with variation in excitation energy, angular momentum and nucleon numbers. As example, we discuss our results obtained for ^{84}Y, ^{82}Y, ^{84}Sr and ^{84}Zr. Gamma rays in ^{84}Y were identified for the first time through particle-γ coincidences using the 4π-charged particle ball and the high resolution CS-HPGe detectors. Gamma–gamma coincidences were performed to place more than 100

γ transitions in the level scheme of ^{84}Y [2,3]. The spins and the parities of these levels were determined through the angular distribution and DCO ratio measurements. The presence of regularly spaced levels both in the positive and negative parity bands indicated presence of deformation in ^{84}Y. It was also observed that the odd spin levels were asymmetrically placed with respect to the even spin levels indicating signature splitting in the positive parity band. This band also showed signature inversion at $I = 11^+$. The measurement of lifetimes provided information on the shape and also the magnitude of the deformation in this nucleus. The yrast positive parity band showed prolate deformation with $\beta_2 \sim 0.17$ and nearly simultaneous alignment of 2 proton and 2 neutrons with increasing angular frequency. The negative parity band, on the other hand, showed a jump in B(M1) value at $I = 11^-$ indicating alignment of 2 protons at this spin. The negative parity band also showed prolate deformation in ^{84}Y.

Let us see what happens if two neutrons are removed from this nucleus? The level scheme of ^{82}Y was extended to higher spins in our work [7] and the lifetimes of levels measured up to the highest possible spin to study the shape variation in nucleus. It is seen that there is irregular spacing of levels below the 8^+ state indicating single particle configurations but there is sudden appearance of regularly spaced levels above the 8^+ level – thus indicating the onset of deformation. A comparison of the measured Q_t values with the predictions of the total Routhian surface (TRS) calculations showed a good agreement between experiment and theory. Data showed small Q_t values below the 8^+ state indicating spherical configuration. The sudden jump in Q_t value above the 8^+ state confirmed the shape transition and a comparison with the predictions of TRS calculations suggested triaxial deformation for high spin states in the yrast positive parity band of ^{82}Y. What happens when a proton is changed to a neutron or vice-versa in ^{84}Y? ^{84}Sr shows spherical configuration at low spins but develops into a deformed prolate band with $\beta_2 \sim 0.2$ after the alignment of 2 protons and 2 neutrons [8]. The measured lifetimes for the negative parity states indicated high K configuration in this nucleus. Finally, ^{84}Zr showed strong deformation with $\beta_2 \sim 0.24$ even at low spins [10]. Furthermore, this nucleus showed a decrease in Q_t value near the first band crossing involving alignment of 2 protons at $\hbar\omega = 0.48$ MeV and again an increase in Q_t value near the second band crossing involving alignment of 2 neutrons at $\hbar\omega = 0.59$ MeV [10]. The measurements of lifetimes using recoil distance method and line shape analysis method in ^{82}Zr [11] showed that the removal of 2 neutrons from ^{84}Zr leads to an increase in deformation. This is in contrast to the observation in ^{82}Y which shows spherical configuration at low spins. It is quite apparent that the behaviour of all the nuclei discussed above are very different from each other even though they differ in neutron or proton numbers by 1 or 2 only. Thus, nuclei discussed above provide good testing ground for theoretical models in this region.

We have been limited in our efforts to extend our studies to higher spin states or to more proton rich nuclei because of the limited efficiency of our high resolution CS-HPGe detector set up. Therefore, the high resolution γ spectrometer has been upgraded to include 4 CS-Clover detectors over the last 3 years. Each Clover consists of 4 HPGe crystals placed together in the same vacuum chamber. When used in add-back mode, each Clover has an efficiency about 6 times the efficiency of a single crystal for 1.4 MeV gamma rays. In addition to the Clover array, a neutron array has also been constructed to suppress the charged particle channels. A photograph of the Clover array along with a neutron array is shown in figure 1. The Clover set up has a gamma–gamma coincidence efficiency about an order of magnitude larger than the earlier set up. The addition of Clover detectors has enabled us to study the shape variation in ^{72}Se and ^{78,80}Kr up to the highest spin $I = 22^+$. The study of these nuclei was particularly attractive because of the prediction of gamma softness in mass 70 to 80 region. A brief summary of results obtained for these nuclei is presented below.

4. Shape coexistence in ^{72}Se

The competing gaps in f-p-g shell region strongly influence the properties of neutron deficient nuclei with $A \sim 70$ to 80. Theoretical calculations predict a prolate and also an oblate minima in potential energy curves for light Se, Kr and Sr isotopes. Energy of the oblate minima is predicted to be several hundred keV higher than the prolate minimum for $N, Z = 38$ but decreases with neutron number to a few hundred keV below the prolate minimum for systems with $N, Z = 35, 36$. This gives rise to prolate-oblate mean field coexistence. This shows up, for example, in ^{72}Se which exhibits a vibrational behaviour up to 6^+ state and merges into a rotational type band with deformation $\beta_2 \sim 0.3$ at higher spins. In the present work, the shape variation has been studied through a measurement of lifetimes of high spin states in ^{72}Se. Energy levels in ^{72}Se were produced through the heavy ion fusion- evaporation reaction ^{54}Fe(^{24}Mg, $2p2n$)^{72}Se using 104 MeV ^{24}Mg beam from the 14-UD pelletron at TIFR. Lifetimes of high spin states up to the $I = 22^+$ state in the yrast positive parity band and up to the 13^- state in the negative parity band have been measured [12] using line shape analysis method. The experimental and theoretical line shapes obtained for the 1457 keV transition de-exciting the 16^+ level and 1068 keV transition de-exciting the 11^- level in ^{72}Se at $\theta = 45°$ and $75°$, respectively, are shown in figure 2. Q_t values were derived from the measured lifetimes to obtain information on shape coexistence and shape variation with spin in ^{72}Se.

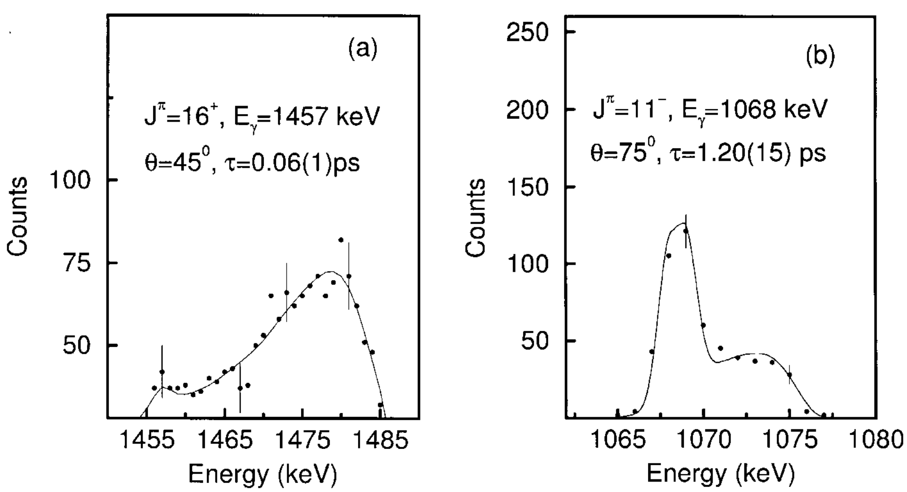

Figure 2. The experimental and theoretical line shapes obtained for the 1457 keV transition de-exciting the 16^+ level and 1068 keV transition de-exciting the 11^- level in ^{72}Se at $\theta = 45°$ and $75°$, respectively.

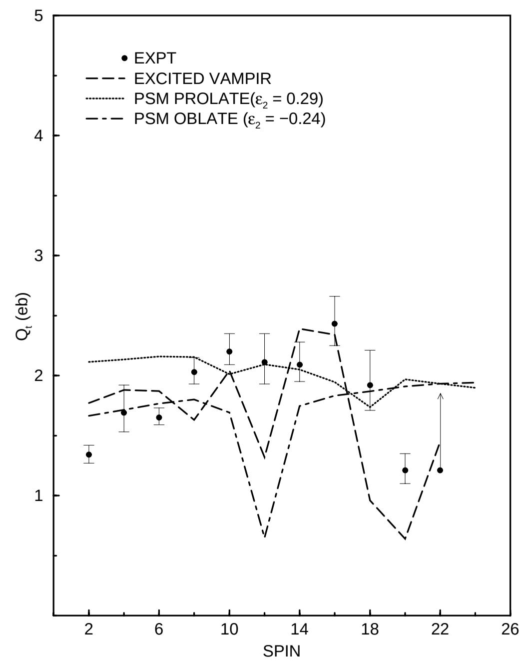

Figure 3. Experimental and theoretical Q_t values for levels in positive parity yrast band in ^{72}Se.

The experimental values are compared with projected shell model (PSM) and EXCITED VAMPIR [13] model calculations in figure 3. The PSM calculations show that the oblate mean field reproduces the observed Q_t values quite well for $I < 6^+$ but the prolate mean field gives good agreement for $I > 6^+$. Thus, the PSM calculations suggest oblate deformation for $I < 6^+$ and prolate deformation for $I > 6^+$ in ^{72}Se. The transition quadrupole moments obtained from the EXCITED VAMPIR model [13] are also plotted in figure 3. These calculations reproduce the qualitative behaviour of Q_t values with increasing spin quite well. There is good agreement with the experimental values for spins up to 6^+ but the calculated values are relatively lower for states with spins 8^+, 12^+, 18^+ and 20^+ states. The decrease in Q_t values for some of the spins has been interpreted as arising due to dynamical variation of quadrupole and hexadecapole deformations. The experimentally observed decrease in Q_t values at higher spins for the negative parity band in ^{72}Se indicates a transition from collective prolate to non-collective shape.

PSM calculations with oblate mean field show good agreement with the observed Q_t values for $I < 6^+$ but the prolate mean field gives good agreement for $I > 6^+$.

5. Band crossings in ^{78}Kr

Kr isotopes have attracted considerable interest because of their unusual properties. For example, the light Kr isotopes like ^{72,74,76}Kr [14,15] show almost simultaneous alignment

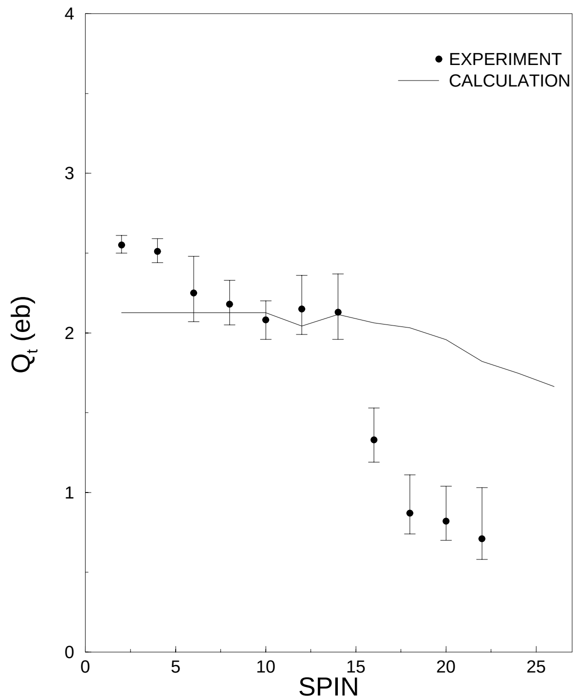

Figure 4. Experimental and theoretical Q_t for levels in positive parity yrast band in ^{78}Kr. Configuration dependent shell model calculations [19] suggest oblate deformation at low spins and a triaxial shape at higher spins $(I > 12^+)$.

of two quasi protons and two quasi neutrons. The alignment and the shape variation in these nuclei have been understood through projected shell model (PSM) calculations in the present work by assuming large prolate deformation with $\beta_2 \sim$ 0.35 [16]. On the other hand, ^{78}Kr has two well separated band crossings at frequencies $\hbar\omega = 0.56$ MeV and $\hbar\omega = 0.88$ MeV. Earlier studies including HFB calculations suggested a prolate deformation and a proton character for the first band crossing. This also predicted large deformation at high spins in ^{78}Kr. However, the first band crossing was found to arise due to two neutron alignment from a measurement of nuclear g factors [17]. Moreover, the second band crossing could not be obtained from CSM or PSM under the assumption of prolate deformation in ^{78}Kr. The lifetimes and Q_t values for high spin states up to 24$^+$ were, therefore, measured in the present work [18] in order to understand the shape and its variation with spin in ^{78}Kr. Levels in ^{78}Kr were populated through the reaction ^{58}Ni(^{27}Al, $\alpha 3p$)^{78}Kr using 115 MeV ^{27}Al beam and an enriched ^{58}Ni target with thickness $\sim$600 μg/cm^2 with a gold backing with thickness of $\sim$ 10 mg/cm^2. Levels with spins up to 16$^+$ were more strongly populated in ^{19}F+^{63}Cu reaction using natural Cu target with Ta backing. One CS-Clover and 4 CS-HPGe detectors were used for the Al + Ni reaction, whereas 3 CS clovers with 1 CS-HPGe detector were used for the ^{19}F + ^{63}Cu reaction. Q_t values obtained as a function of spin up to $I = 24^+$ state are plotted in figure 4. The measurements show a decrease in Q_t at high spins. The PSM calculations with the assumption of oblate deformation reproduce the observed variation with spin but fail to produce the magnitude of decrease after second band crossing. The CSM calculations with oblate deformation ($\beta_2 = 0.38$ and $\gamma = -60°$) predict neutron alignment at the first band crossing in agreement with experiment and the second band crossing frequency is also correctly predicted. The configuration dependent shell model calculation [19] also indicated an initial oblate deformation for the yrast band but shows a change to triaxiality for $I > 12^+$. TRS calculations give oblate, prolate and also triaxial minima at lower spins. The corresponding Q_t values are all close to experimental values (see figure 4). However, there are two minima at higher spins – a triaxial and a non-collective oblate. The experimental Q_t values lie somewhere halfway between the values obtained for these two minima. Thus, the present work showed for the first time an oblate shape for ^{78}Kr at low spins and a triaxial shape at higher spins.

6. Shape of ^{80}Kr at high spin

The shape and structure of ^{80}Kr at high spins has also been studied through a measurement of lifetimes of excited states using lineshape analysis method. Data were obtained with 3 CS-Clover and 1 CS-HPGe detector along with the NaI(Tl) multiplicity filter [20]. High spin states in ^{80}Kr were populated through the heavy ion fusion evaporation reaction ^{65}Cu(^{19}F, $2p2n$) reaction. The Q_t values extracted from the measured lifetimes show a decreasing tendency (see figure 5) after the band crossing indicating a change in the shape of ^{80}Kr at high spins. The TRS calculations predict a change from near oblate to near prolate shape

7. Future projections

We have been upgrading our facilities with a view to take up more challenging problems. A neutron detector array consisting of 6 neutron detectors has been in operation [21].

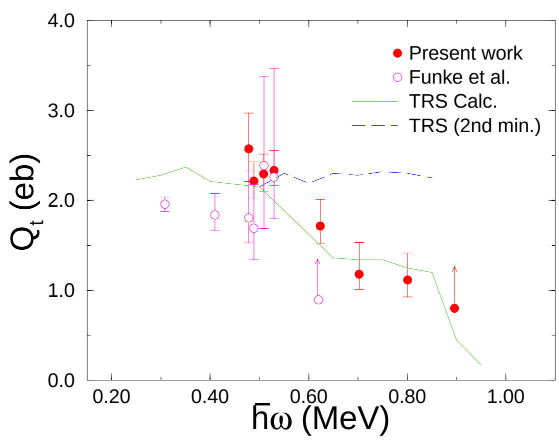

Figure 5. Experimental and theoretical Q_t for the levels in positive parity yrast band in ^{80}Kr. Solid line represents the results of TRS calculations.

Figure 6. A photograph of the recoil mass spectrometer set up at TIFR.

Each neutron detector has a Bicron cell with $5''$ dia. $\times 6''$ thickness and containing BC501 liquid scintillator. This array covers nearly 2π solid angle and enables the separation of neutron channels from pure charged particle channels. In addition, we are working on the following instruments:

7.1 *Recoil mass spectrometer*

A recoil mass spectrometer has been fabricated, assembled and also tested. A schematic diagram of the recoil mass spectrometer assembly is shown in figure 6. Recently, the recoil products produced in the reaction ^{58}Ni(^{12}C; xp, ya, zn) using 60 MeV ^{12}C beam were detected in a solid state strip detector placed at the focal plane of the RMS. Efforts are now underway to experimentally characterize the set up i.e. to measure quantitatively the mass resolution. This instrument can be used in conjunction with the high resolution segmented Clover detectors to study exotic nuclei near proton drip line.

7.2 *National Clover array*

An array with 4 CS-Clover detectors is already in operation at TIFR. Data have been obtained with this set up to study the phenomenon of ‘magnetic rotation’ in Ce isotopes. There have been discussions between TIFR, SINP, IUC-DAEF and NSC during the last several months to pool the resources of all the laboratories to build up a National facility i.e. an Indian Clover array. TIFR has proposed an array with 24 Clover detectors. Some of the design features of the proposed array are listed below:

(i) The total photopeak efficiency for this array will be 5.5% at 1.33 MeV.
(ii) The stand for the array will have provision for putting 6 detectors at 90°, 6 at 65°, 6 at 40° and 6 at 23° with respect to the beam direction. This geometry enables us to perform angular distribution and DCO ratio measurements with good sensitivity.
(iii) The detectors at 90° allow polarization measurements with good sensitivity.
(iv) There is nearly 9″ diameter space available around the target position to accommodate a charged particle ball for particle-γ coincidences.
(v) One half of the clover array can be replaced by the neutron array.
(vi) A plunger set-up can be placed at the center of the Clover array.
(vii) Automatic liquid N_2 filling device has been designed.
(viii) A mechanical loading arm has also been planned for mounting or de-mounting of detectors from the detector stand.

Presently, there are 4 CS-Clover detectors in TIFR, Bombay, 10 CS-Clover detectors in SINP and IUC-DAEF, Calcutta and one Clover with NSC, New Delhi. We are using conventional NIM electronics for 4 CS-Clover detectors. It is estimated that there is enough electronics in the country to start using up to 9 CS-Clover detectors. There is a proposal to immediately set up jointly a 9 CS-Clover array. Such an array will increase the coincidence efficiency by nearly two orders of magnitude compared to what we have been using until not too long ago. However, it is proposed to acquire new electronics for the entire array which uses one multi-layered card for one set of clover. Eurysis Mesurs, France have been developing such electronics for sometime now. There is also possibility of acquiring cards used for gammasphere electronics.

The development of facilities mentioned above should enable us to systematically study problems like magnetic rotation, super-deformation, hyper-deformation and shape variation at high excitation energy, high angular momentum in nuclei close to drip lines in different regions of the periodic table.

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References

[1] W Nazarewicz, J Dudek, R Bengtsson, T Bengtsson and I Rangarsson, *Nucl. Phys.* **A435** (1985) 397
[2] S Chattopadhyay, H C Jain, J A Sheikh, Y K Agarwal and M L Jhingan, *Phys. Rev.* (*Rapid Comm.*) **C47**, R1 (1993)
[3] S Chattopadhyay, H C Jain, S D Paul, J A Sheikh and M L Jhingan, *Phys. Rev.* **C49**, 116 (1994)
[4] H C Jain, U T Raheja, P J Bhalerao, V M Datar and M Y Vaze, *DAE Symposium on Nuclear Physics* **B34**, 383 (1991)

[5] H C Jain, S Chattopadhyay, Y K Agarwal, M L Jhingan, S K Mitra, H V Panchal and A Roy, *Pramana – J. Phys.* **37**, 269 (1991)
[6] H C Jain, S D Paul, S Chattopadhyay and M L Jhingan, *DAE Symposium on Nuclear Physics* **B35**, 422 (1992)
[7] S D Paul, H C Jain, S Chattopadhyay, M L Jhingan and J A Sheikh, *Phys. Rev.* **C51**, 2959 (1995)
[8] S Chattopadhyay, H C Jain and M L Jhingan, *Phys. Rev.* **C50**, 93 (1994)
[9] S Chattopadhyay and H C Jain, *Phys. Rev.* **C51**, 3532 (1995)
[10] S Chattopadhyay, H C Jain and J A Sheikh, *Phys. Rev.* **C53**, 1001 (1996)
[11] S D Paul, H C Jain and J A Sheikh, *Phys. Rev.* **C55**, 1563 (1997)
[12] R Palit, H C Jain, P K Joshi, J A Sheikh and Y Sun, *Phys. Rev.* **C63**, 024313 (2001)
[13] A Petrovici, K W Schmid, F Grummer and A Faessler, *Nucl. Phys.* **A504**, 277 (1989)
[14] S L Tabor, P D Cottle, J W Holcomb, T D Johnson, P C Womble, S G Buccino and F E Durham, *Phys. Rev.* **C41**, 2658 (1990)
[15] J Heese, D J Blumenthal, A A Chisti, P Chowdhury, B Crowell, P J Ennis, C J Lister and Ch Winter, *Phys. Rev.* **C41**, R921 (1991)
[16] R Palit, J A Sheikh, Y Sun and H C Jain, (accepted in *Nucl. Phys.*)
[17] J Billows, F Cristancho, H Grawe, C J Grss, J Heese, A W Mountford and M Weiszflog, *Phys. Rev.* **C47**, R917 (1993)
[18] P K Joshi, H C Jain, R Palit and S Nagraj (to be published)
[19] H Sun, J Doring, G D Johns, R A Kaye, G Z Solomon, S L Tabor, M Devlin, D R LaFosse, F Lerma, D G Sarantites, C Baktash, D Rudolph, C-H Yu, I Y Lee, A O Macchiavelli, I Birriel, J X Saladin, D F Winchell, V Q Wood and I Rangarsson, *Phys Rev.* **C59**, 655 (1999)
[20] G Mukherjee, H C Jain, R Palit, P K Joshi, S D Paul and S Nagraj (submitted to *Phys. Rev.*)
[21] R Palit, P K Joshi, S Nagraj, H V Panchal and H C Jain, *Pramana – J. Phys.* **52**, 401 (1999)