Spectroscopy of trans-lead nuclei

Debasmita Kanjilal*
Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata-700064, INDIA

Introduction

As our knowledge of the nuclear chart is extended towards the proton drip line, new experiments become increasingly difficult. For many of these heavy nuclei, only the ground state spin and parity are known from their g-factor/magnetic moment measurements, and perhaps a few low lying excited isomeric states are observed so far. The main challenge for producing such nuclei is due to low production cross-section ($\sim$ 10 mb or less) of evaporation residue (ER) in presence of very high fission background. The resulting background of γ-rays emitted from the fission products makes γ-ray spectroscopy of ER products much more difficult, particularly for short-lived high-spin states. Experimental investigation of the high spin states of quite a few trans-lead neutron deficient nuclei ($Z > 82$, $N \leq 126$) have been of interest recently [1–3]. Lots of nuclear phenomena from core excited single particle states to the existence of shears band in these extreme proton rich heavy nuclei were observed[1, 4]. A systematic study of such nuclei will possibly reveal many other interesting features. The high spin states of these nuclei are generally interpreted as single particle configurations arising from the $(1h_{\frac{9}{2}}, 2f_{\frac{7}{2}}, 1i_{\frac{13}{2}})$ protons and $(3p_{\frac{1}{2}}, 2f_{\frac{5}{2}}, 3p_{\frac{3}{2}}, 1i_{\frac{13}{2}})$ neutrons. One of the major interests in the spectroscopic investigation of these nuclei is the role played by the $i_{\frac{13}{2}}$ intruder state in creating isomeric levels which decay through transitions of higher multipolarity, or are hindered by the close proximity of the levels below. The interesting structural features in this trans-lead region, provided motivation to select a few neutron deficient Francium (heaviest alkali metal) isotopes, ^{208,210}Fr, for exploration in the present thesis [5, 6]. For $^{208-210}$Fr nuclei, either very little or contradictory results existed at the time of our experiment.

*Electronic address: `debasmita.kanjilal@saha.ac.in`

Experimental details

The experiment to produce $^{208-210}$Fr was carried out at the Inter-University Accelerator Centre (IUAC), New Delhi. The Fr isotopes were produced by bombarding a 3.5 mg/cm^2 self-supporting Gold (99.95% purity) target with ^{16}O beam at 88, 94 and 100 MeV. The nuclei of interest were produced as evaporation residues (ER) through (^{16}O, $xn\gamma$) reactions. Based on PACE calculations, $\sim$ $60 - 80$ % of the fusion products at these bombarding energies undergo fission, which causes a huge background. The prompt γ-rays produced were detected by the Indian National Gamma Array (INGA), consisting of 18 Compton suppressed Clover detectors placed around the target centre at the INGA-HYRA beam line at IUAC. The data were collected using the CANDLE data acquisition system, and were analysed off-line using the CANDLE, INGASORT and RADWARE softwares.

Results and Discussion

One of the major challenge in the experiment was unambiguous identification of the Fr isotopes. Large gamma detector array having high resolving power, good efficiencies for $\gamma\gamma$ and $\gamma\gamma\gamma$ coincidence events, along with additional measurements of excitation functions from in-beam and off-beam measurements yielding consistent results with PACE code and validation by the characteristic Fr X-rays gating, have been utilized in our attempt to resolve the ambiguity related to $^{208-210}$Fr. By gating on characteristic X-rays, ER nuclei are tagged by the atomic number Z.

The trends of the excitation functions graphs obtained from the yield of the relatively strong gamma peaks, emitted by the $^{208-210}$Fr nuclei, are comparable to that predicted from the PACE calculations. The relative yields of the $^{208-210}$Fr isotopes at different energies were also obtained from the radioactive decay data collected in the beam-off condition. The E_γ vs. time matrix was generated using CANDLE from which, the gamma spectra at different time windows were generated. The half lives of different decay branches ($\alpha-$ and $\beta-$ decay), obtained by fitting the data with a single exponential $n = n_0 \exp(-t/\tau)$, agree with previous results listed in NNDC. From the n_0 parameters obtained from the fit, the relative yields of the Fr isotopes were calculated. The results are found to be consistent with the PACE calculations and also with the excitation function measurements.

After energy calibration and gain matching, the $\gamma\gamma$ matrices, Francium X-ray gated $\gamma\gamma$ matrices, the prompt and various delayed $\gamma\gamma$ matrices and the γ-gated $\gamma\Delta T$ matrices were constructed at three different beam energies for establishing the level scheme and locating the isomeric transitions. To get the information on the spin and parity, DCO mesurements were performed with the data taken at $(90°, 148°)$ and $(90°, 123°)$ angle pairs.

Based on the intensity correlations obtained from the gated spectra, and also from the DCO ratio measurements, the level scheme for ^{208}Fr was established and extended up to $\sim 23\hbar$ and $\sim$ 5.5 MeV excitation energy [5]. About 25 new transitions, over and above those observed in earlier investigation[2], were found. One of the major point of controversy, the half-life of the 194 keV isomeric transition was extracted as 233 $\pm$ 18 ns, which is consistent with the result quoted in Ref. [7]. Also a new isomeric E2 transition was obtained for ^{208}Fr and its half-life was measured as 33 $\pm$ 7 ns. The Weisskopf estimates of the single particle strength of the associated isomeric levels reveal similarity with the previous estimates in the neighbouring nuclei.

High spin states and isomeric levels in ^{210}Fr are investigated for the first time using INGA [6]. Relatively strong transitions in ^{210}Fr were identified by the excitation function measurements and were compared with the predictions based on the statistical model, and validated with Fr X-rays. Starting from the two known transitions observed earlier [8], the level scheme has been established up to $\sim$ 5.3 MeV excitation energy and $J \sim 20\hbar$ for the first time through $\gamma\gamma$, $\gamma\gamma\Delta T$ coincidence, and DCO ratio measurements. A new low-lying isomeric transition at 203 keV was observed with the half-life 41 $\pm$ 2 ns. The measured half-life was compared with the corresponding single-particle estimate, based on the level scheme obtained from the experiment. A new ground-state transition depopulating the levels was also observed for the first time. The lifetimes of two strong transitions were extracted from the data using the DSAM technique.

From the shell model based interpretation of the level scheme of ^{208,210}Fr, it is clear that the majority of the excited states are caused by $1h_{9/2}$ proton excitations, and neutron hole excitations predominantly in $2f_{5/2}$ and $1i_{13/2}$ shells. The level scheme systematics for the odd-odd Francium isotopes $^{206-212}$Fr indicate that their nuclear structures can be qualitatively explained from the shell model, though it is difficult to do a detailed shell model calculations at present.

References

[1] D. J. Hartley et al., PRC **78**, 054319 (2008).
[2] G. D. Dracoulis et al., EPJ A **40**, 127 (2009).
[3] G. D. Dracoulis et al., PRC **79**, 054313 (2009).
[4] A. P. Byrne et al., NPA **448**, 137 (1986).
[5] D. Kanjilal et al., NPA **842**, 1 (2010).
[6] D. Kanjilal et al., PRC **84**, 064321 (2011).
[7] Zs. Podolyák et al. , AIP Conf. Proc. **831**, 114 (2006).
[8] P. Kuusiniemi et al., EPJ A **22**, 429 (2004).