Characterization of Incomplete Fusion Reaction with AFRODITE and DIAMANT

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Abstract.
This project concerns the nuclear reaction ^{7}Li + ^{176}Yb at 50 MeV which was carried-out using the AFRODITE and DIAMANT facility of detectors at iThemba LABS, Cape town. A ^{7}Li nucleus is considered suitable for the breakup fusion (incomplete fusion) reaction because of its well developed cluster structure of an α-particle and *triton* which are weakly bound in this nucleus. One of the fragments may be captured by the target while the other escapes at the beam velocity. Light charged-particles (alphas, tritons, deuterons and protons) were detected with the DIAMANT (CsI) array in coincidence with gamma-rays detected by the AFRODITE (HPGe) spectrometer. The project involves data processing to produce charged-particle-gated gamma-gamma coincidence matrices which are analysed with the RADWARE software package [1]. The intensity ratios as function of spin for the proton to triton-gated matrices populating ^{178}Hf nucleus were extracted. Insights could be developed into the incomplete fusion reaction mechanisms initiated by the breakup of the incident ^{7}Li projectile.

1. Introduction

In this work we investigate the incomplete fusion (IFC) mechanism following the breakup of ^{7}Li projectiles incident on a target of ^{176}Yb, by looking at the ^{178}Hf isotope populated through (^{6}He, 4n) and (^{4}He, 2n) exit channels. This nucleus is located in the region of deformation near $A = 180$. This region is characterised by collective rotational behaviour which coexists with intrinsic quasiparticle modes of excitation as a means with which to form the yrast line. These quasiparticle states have large K values which arise as a result of the large angular momentum projections (Ω) of the single-particle orbitals on the nuclear symmetry z-axis. Electromagnetic transitions of multipolarity λ between high K states are forbidden if ΔK is greater than the multipolarity, λ of the photon. This causes the excited quasiparticle states to be isomeric in character. Bands built on these metastable states are decoupled from the level scheme below, due to the isomeric nature (i.e. having long lifetimes) of these bandhead states. This makes it difficult to assign these bands to a particular isomer, and indeed to the nucleus itself.

However, studies done by Mullins *et al.* [2, 3], show that there is a distinct correlation between the relative gamma-ray intensities of the product nuclei when selected by alpha/triton-particles detected at forward or middle/backward angles. These relative yields can be a useful tool in the assignment of the unknown transitions to their associated bands and also to the particular nucleus itself. We investigate these correlations in gamma-ray intensity ratios by looking at the various bands of ^{178}Hf nucleus populated through forward gated proton or triton-particles, i.e. taking a ratio of the (^{6}He, 4n) to (^{4}He, 2n) exit channels.

2. EXPERIMENTAL TECHNIQUES

The measurements were carried out with a beam of ^{7}Li ions incident on the target, which was supplied at an energy of 50 MeV by the iThemba LABS separated sector cyclotron . A self-supporting metallic foil (of 4.6 mg/cm^2 thickness) of ^{176}Yb, which is isotopically enriched to 95%, was used as a target. States in ^{178}Hf were populated via two possible exit channels (^{6}He, 4n) and (^{4}He, 2n). The *proton* and α-particle yields came from breakup of the beam, $^{7}\mathrm{Li} \longrightarrow {}^{6}\mathrm{He} + {}^{1}\mathrm{H}$ or $^{7}\mathrm{Li} \longrightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H}$ respectively. This process is called incomplete fusion or "massive transfer" [4, 5] reaction process, and it is believed to occur for collisions detected forward of the grazing angle. During the fusion reaction process, a weakly-bound projectile such as ^{7}Li may break-up into two clusters as mentioned above, and fusion of one of the fragments and the target occurs. This results in an anisotropic distribution of the emitted particles. According to Dracoulis *et al.* [6], the presence of incomplete fusion enhancing the anisotropy in the angular distribution of emitted particles, produces different intensities of γ-transitions when in coincidence with particles detected at backward and forward angles (yield ratios) for the isotopes produced in a heavy-ion reaction.

The measurements were performed with the AFRODITE spectrometer in conjunction with a compact array of charged-particle detectors, DIAMANT. The AFRODITE spectrometer is an array consisting of two sets of High Purity Germanium (HPGe)detectors, which are the clover (for high energy gamma-rays) and Low Energy Photon Spectrometer (LEPS) detectors [7]. In this experiment 8 clover detectors were used, with 4 placed at 90°and the rest at 135°with respect to the beam. The DIAMANT is a 4π array of light charged-particle (CsI) scintillation detectors coupled to photo-diodes [8]. It was developed to be used as an ancillary detector used inside large gamma-ray spectrometers to identify the light charged particles emitted in heavy-ion induced reactions. It was placed around the target position at the center of the AFRODITE γ-ray array. This was the arrangement that was used to collect time correlated particle-γ-γ coincidences when the ^{176}Yb target foil was bombarded with ^{7}Li ions.

In order to reduce the amount of scattered beam incident on the particle detectors, the detectors were shielded with $\sim$46 mg/cm^2 aluminium absorber foils. A ^{152}Eu source was used for the energy and efficiency calibration of the HPGe detectors.

3. DATA ANALYSIS

Time-correlated particle-γ -γ coincidence data were sorted off-line into particle-gated E_γ -E_γ matrices with same time conditions. The full-background subtracted projection spectra in coincidence with a (a) proton and (b) triton particle (Fig. 1), show γ-rays from the ground state band (GSB) of ^{178}Hf, the γ-rays are clearly visible up to spin 12^{+}. The level scheme for ^{178}Hf extracted from the triton gated spectrum is given in Fig. 2 [2]. There are no new states established in this work.

The main analysis was carried out with two matrices; one matrix proton-gated i.e. (^{6}He, 4n) exit channel and the other triton-gated i.e. (^{4}He, 2n) exit channel, both at forward angles covering angles up to a maximum of $\sim$60°with respect to the beam axis. The proton gated matrix contained $\sim 3.7 \times 10^{6}$ counts and the triton gated matrix had $\sim 6.5 \times 10^{6}$ counts. Ratios of γ-γ coincidence intensities of the form $(\mathrm{proton/triton})_{\mathtt{forward}}\gamma - \gamma$ were generated, and were

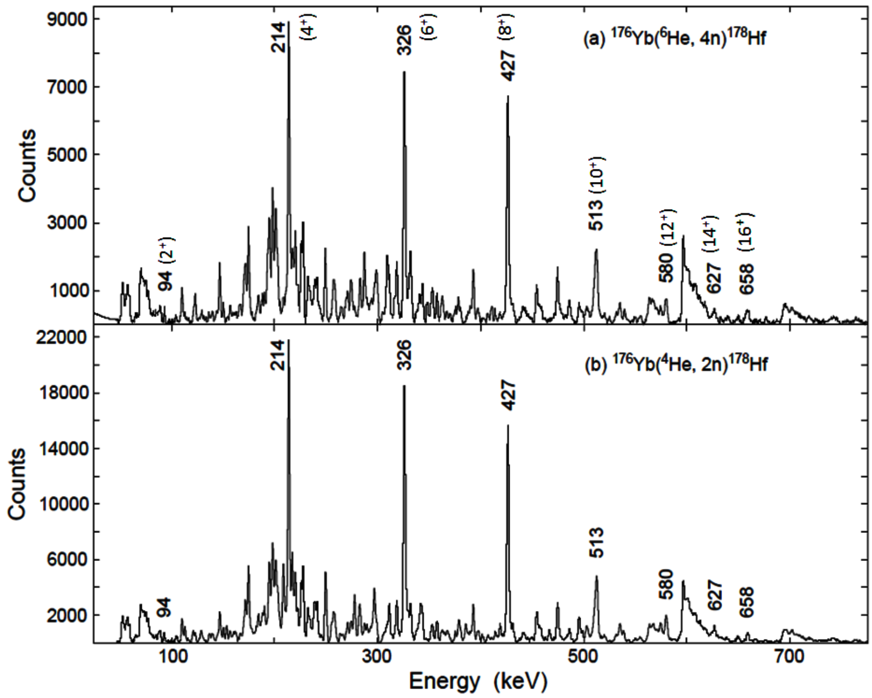

Figure 1. Total background-subtracted projection spectra of the ^{7}Li + ^{176}Yb reaction from a 2-dimensional symmetric $\gamma-\gamma$ matrix, with (a) proton tagged spectrum and (b) triton tagged spectrum.

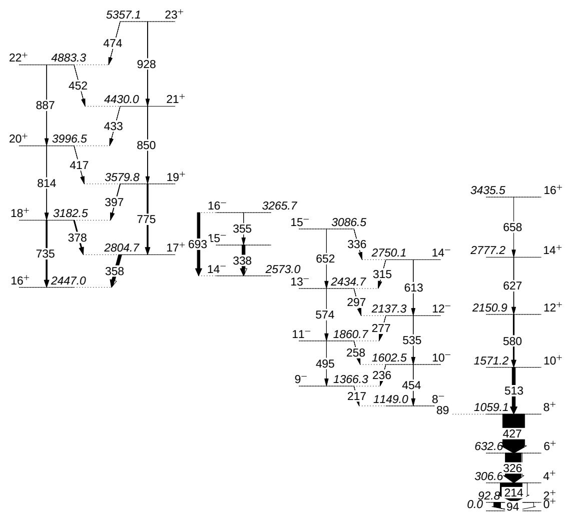

Figure 2. A partial level scheme of ^{178}Hf [2] extracted from the spectrum in Fig. 1(b), produced through ^{176}Yb(^{4}He,2n)^{178}Hf exit channel of this experiment.

plotted as a function of spin for each of the various bands GSB, $K^\pi = 8^-$, $K^\pi = 14^-$ and $K^\pi = 16^+$ band of the ^{178}Hf isotope, Fig. 3. From the plot, all bands i.e. GSB, $K^\pi = 8^-$, $K^\pi = 14^-$ and $K^\pi = 16^+$ show no change in the proton-triton intensity ratio with increase in angular momentum. The yield ratios are spin independent. However, when bands are compared, there are observable differences. The GSB and $K^\pi = 8^-$ bands show relatively low yield ratios compared to $K^\pi = 14^-$ and $K^\pi = 16^+$ bands. The $K^\pi = 16^+$ band has a further higher yield ratio compared to the $K^\pi = 14^-$ band. The rise in the (proton/triton) intensity ratio at higher spins can be attributed to the differences in mass of the fused fragments, with ^{6}He being 50% more massive than ^{4}He. The less mass-asymmetric the beam/target combination for a given compound nucleus, the higher the maximum angular momentum that can be induced into the system. At high spin, ^{176}Yb show a relatively high cross-section for incomplete fusion with ^{6}He as compared to ^{4}He (the alpha particle).

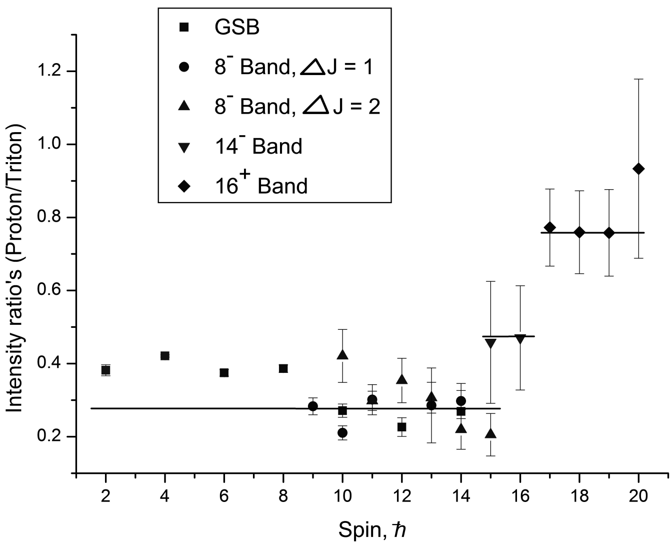

Figure 3. Intensity ratios of the proton to triton-gated gamma-ray yields as a function of spin for $K^\pi = 0^+$ (Ground-State Band), $K^\pi = 8^-$, $K^\pi = 14^-$ and $K^\pi = 16^+$ bands in ^{178}Hf. The lines are drawn to guide the eye.

4. Conclusions

The experimental signatures of incomplete fusion reactions are the observation of strongly forward-peaked charged particles, with a ^{7}Li beam; protons, deuterons, tritons and alphas with much higher energies than observed in conventional fusion-evaporation reactions. These charged particles have been used for a very efficient channel selection. It has been possible to extract the level scheme exclusive to a particular channel for the production of the ^{178}Hf. The relative cross section for various reaction channels could therefore be extracted. There are variations observed between the proton/triton at forward angles and the angular momentum of the residual nucleus, with the different bands showing no change in the yield ratios (proton-triton), but when bands are compared, there are differences. This work has therefore produced data which gives insight to the reaction mechanisms for incomplete fusion processes.

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