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A shell model study of the high spin states of ^{88}Y

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Abstract. Experiments were carried out at the Wright Nuclear Structure Laboratory at Yale University using the 21MV ESTU Tandem Van de Graaff accelerator with the purpose of studying ^{88}Y. A beam of ^{18}O impinged at laboratory energies of 60, 65 and 70 MeV on a 600 μg/cm^2 ^{74}Ge target with a thick (10mg/cm^2) ^{197}Au backing. This experiment was performed with the specific aim of accessing medium spin states of the nucleus of interest. A second experiment was undertaken to populate the nucleus of interest in higher spin states by impinging the same ^{18}O beam on a thin 62 μg/cm^2 ^{76}Ge target with a 20 μg/cm^2 carbon backing at a laboratory beam energy of 90 MeV. Gamma rays emitted following the decay of excited states in ^{88}Y and other nuclei populated in the reactions were measured using the YRAST ball detector array, consisting of 10 Compton suppressed HPGe clover detectors. In conjunction with the experimental study presented here, nuclear shell model calculations using a truncated valence space have also been performed in an attempt to describe the single-particle make-up of the states observed. Preliminary results from these experiments and theoretical calculations are presented.

1. Introduction

The nucleus of interest in the current work, ^{88}Y, has 39 protons and 49 neutrons i.e. 1 proton hole outside the Z=40 sub-shell and 1 neutron hole outside the N=50 major-shell closure. This might suggest that the low-lying excitations in this nucleus might be well described by a simple, spherical nuclear shell model with appropriate valence space truncations. However, higher spin states will require an extension of a simple valence space truncation in order to describe their underlying structure. The aim of the current study is to extend the level scheme of ^{88}Y to spins above 20$\hbar$ and perform realistic shell model calculations to test the usefulness of the truncated scheme into this spin regime.

2. Experiment

High spin states of ^{88}Y were populated via the heavy-ion fusion-evaporation reactions ^{74}Ge(^{18}O,p3n)^{88}Y and ^{76}Ge(^{18}O,p5n)^{88}Y. The initial experiment utilised a 600 μg/cm^2 ^{74}Ge target with a thick (10mg/cm^2) gold backing to stop the recoiling nuclei. This allowed for delayed γ-ray decay, such as that from below isomeric states, to be observed. The target in the second experiment was thin enough (^{76}Ge target 62 μg/cm^2 on 20 μg/cm^2 carbon) to allow the recoils to pass through the target, thus necessitating Doppler-shift corrections to be applied to the measured gamma-ray energies in the offline analysis. The measured recoil velocity for the thin target data was v$\sim$0.018c. In order to determine the optimum beam energy for each experiment, `PACE4` [1, 2] calculations were performed. These calculations put the maximum yields for ^{88}Y production at 60MeV for the ^{74}Ge(^{18}O,p3n)^{88}Y (see figure 2(a)) reaction and 90MeV for the ^{76}Ge(^{18}O,p5n)^{88}Y reaction. However, the cross-section results for the ^{74}Ge(^{18}O,p3n)^{88}Y reaction were contrary to a previous excitation function performed on the same reaction which indicated that ^{88}Zr (4n) would be the favoured exit channel [3]. For this reason it was decided that the incident beam energy for ^{74}Ge experiment would be varied to allow a new, relative excitation function to be measured. The `PACE4` program also calculates the partial cross sections for the reaction from which the maximum angular momentum of the compound nucleus, l_{max}, can be obtained (see figure 2(b)).

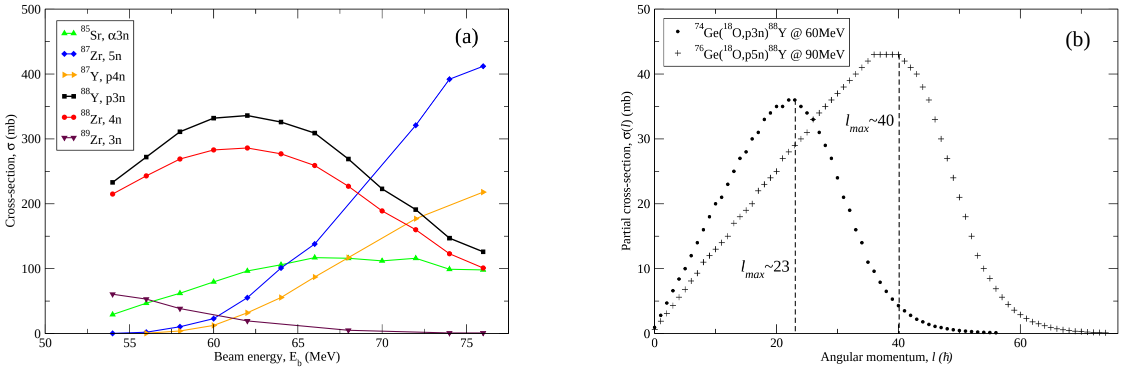

Figure 1: `PACE4` [1, 2] calculations (a) Cross-section calculations for ^{74}Ge(^{18}O,p3n)^{88}Y (b)Partial cross-sections for ^{74}Ge(^{18}O,p3n)^{88}Y and ^{76}Ge(^{18}O,p5n)^{88}Y

The beam was generated by the 300 kV high resolution negative ion injector coupled to the 21 MV ESTU (Extended Stretched Trans-Uranium) tandem Van de Graaff accelerator at the Wright Nuclear Structure Laboratory (WNSL) at Yale University [4, 5]. The beam impinged on the target via steering and focusing magnets, and unreacted beam particles were deposited in a beam dump downstream of the target position. The YRAST ball (Yale Rochester Array for SpecTroscopy) [6] was used to study the resulting γ-ray emission from the above reactions. The array consists of 10 Compton suppressed HPGe clover detectors [7] each at a distance of 202 mm from the central target position, arranged with 6 detectors at 90° and 4 detectors at 42.5° to the beam axis, 2 of these forward and 2 backward of the target position. This configuration allows for angular correlations to be made as well as linear polarisation measurements to aid in the assignment of the spins and parities of newly observed levels.

The data acquisition for the experiment required mutually coincident, independent compton suppressed events in at least three of the 10 clover detectors within a 500 ns time window. This ensured cleaner spectra with most events originating from a cascade of at least three γ-rays. This trigger was also chosen as, due to the high cross section for these reactions, 1- and 2-fold triggers allowed too many events through to the data acquisition, causing an overflow and increasing the dead time of the system.

The data was sorted offline using the `CSCAN` [8] sort code developed at the WNSL.

3. Analysis

Due to the large cross-section of a number of nuclei created in the chosen reaction, the resulting spectra are complex with many peaks from different nuclei close by or overlapping each other. These spectra can be cleaned up significantly by the application of a series of coincidence requirement conditions which can be applied in either the offline sorting or by selection of gamma-ray energy coincidence conditions within the `RADWARE` analysis suite [9].

3.1. Timing conditions

Time conditions were placed on energy spectra to reduce contributions from decays occuring from and below isomeric states. The TDC (CAEN V775) used had a full time range 1.2 μs which corresponds to ~290 ps/ch. This time range allows gating across isomers in a number of nuclei populated during the experiment, providing an illustration of the range of time coincidences which could be measured in the current work.

Previous studies [3] on ^{88}Y using similar reactions provided information on the low-lying near yrast level sequence in this nucleus. This meant that γ-γ matrices and γ-γ-γ cubes could be gated on to allow for identification of previously unobserved γ-ray transitions.

3.2. Matrices and cubes

Symmetrised gamma-ray energy coincidence matrices and cubes were sorted and interrogated using the `RADWARE` suite of programmes to identify new coincidence relationships between transitions associated with decays from previously unidentified transitions in ^{88}Y.

3.3. Directional Correlation of Oriented states

The multipolarity of a γ-ray transition gives additional experimental evidence on the internal nuclear structure by allowing assignments of spins to nuclear states. The multipolarity of such transitions can be probed by investigating the angular correlations between coincident gamma-rays. One method for determining multipolarities is the Directional Correlation of Oriented states method (DCO) in which the angular correlation is taken between two coincident γ-rays. A γ-γ coincidence matrix is constructed such that the axes correspond to different angle groups of detectors in the array. An energy gate is set in software on a transition with known multipolarity. The intensity of the projected γ-rays (from this gate) allows transitions with different multipolarities to be discriminated.

3.4. Linear polarisation of γ-rays

DCO measurements allow for assignment of spins to nuclear transitions but give no information on the electric or magnetic nature of the transitions. To determine this, one can measure the linear polarisation of scattered γ-rays. This method utilises a clover detector as a Compton polarimeter [10] and the fact that the direction of scattered γ-rays is dependent on the nature of the transition [11, 12]. Matrices of scattered γ-rays perpendicular to the beam axis vs all γ-rays and scattered γ-rays parallel to the beam axis vs all γ-rays are constructed. The 'all' axis allows for an energy gate to be placed to clean up contaminants on the projected axes. The peaks in the projected axes are fit and a polarisation asymmetry can be obtained. This sign of the asymmetry indicates the nature of the transition.

4. Results

The experiment ran for two weeks from 02/08/2010 to 14/08/2010 with the four experimental settings accumulating between 1.8 and 2.9 billion events with a total ~10 billion triples events

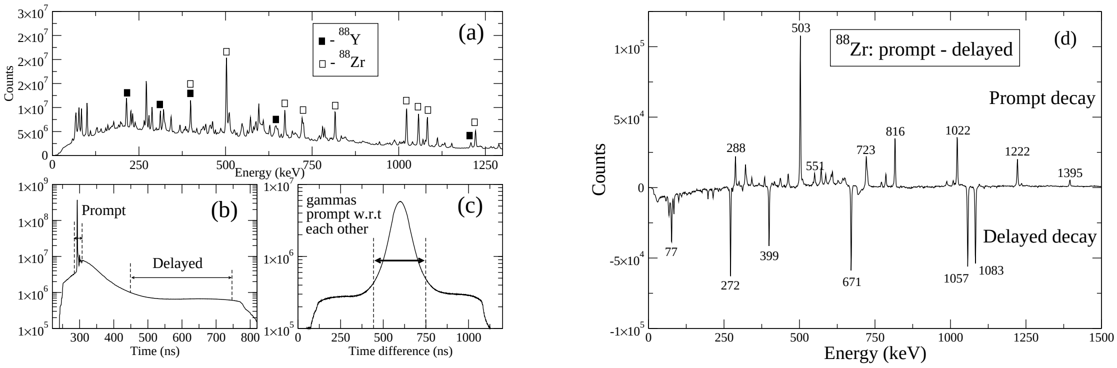

Figure 2: (a) Total projection of γ-γ matrix from the ^{74}Ge(^{18}O,p3n)^{88}Y @ 60 MeV. (b) Sum of TDCs. Time gates for the prompt and delayed time regions are shown. (c) Time difference spectrum between two prompt γ-rays, showing the coincidence window requirement used in the present work. (d) Prompt minus delayed γ-rays from ^{88}Zr gated across the 8^+ $t_{1/2}$=1.7 μs isomer [13](see text).

recorded. The results presented below in the current work are from data using the thick target. Analysis of the thin target data (aimed at the population of higher-spin states) is ongoing.

Figure 2(a) shows the total projection (ungated) of the ^{74}Ge(^{18}O,p3n)^{88}Y at 60MeV. Highlighted are ^{88}Y (filled squares) and ^{88}Zr (empty squares). Figures 2(b) and 2(c) show the TDC and time-difference spectra respectively.

The 8^+ isomeric state in ^{88}Zr [13] provides an ideal testing ground for the software timing conditions. Software gates are set on the TDCs to produce prompt and delayed energy spectra which are then background subtracted. The delayed energy spectra is then subtracted from the prompt spectra to give figure 2(d). The effectiveness of the timing conditions can clearly be seen as all the decays occuring below an isomeric 8^+ state appear as negative peaks and all the positive peaks correspond to a decay occuring above it.

Figure 3 shows the preliminary level scheme for ^{88}Y generated from the present work. Gamma-ray coincidence measurements provide the evidence needed to place previously unreported transitions in the level scheme of ^{88}Y, at gamma-ray energies 307, 327, 432, 543, 552, 576, 597, 703, 778, 813, 967, 1608 and 1991 keV.

The spectra shown in figure 4 (a) and (b) show the difference between a single gated matrix and a double gated cube. By adding the second gate the likelihood of contaminants appearing in the resultant projection is dramatically reduced. This makes identification of weak γ-ray transitions possible. The double gated spectrum in (b) has fewer transitions from the nucleus of interest than (a), this is solely due to the choice of gate (1208 keV transition is only coincident with the main cascade). Figures 4 (c) and (d) represent the same gates as (a) and (b) but placed on the thin target (^{76}Ge @ 90 MeV) data. There are fewer contaminant transitions in the thin target data as all γ-ray decay occurring from isomeric states is not present. This can be seen by the contaminant peaks at 1057 and 1083 keV, originating from below an isomeric state in ^{88}Zr, being present in (a) and (b) but not in (c) and (d).

The double-gated spectra in figure 4 (e) and (f) show newly observed γ rays that comprise the revised decay scheme in figure 3. The spectrum in 4(e) is gated on 311 keV and 327 keV, it should therefore only show transitions coincident with both of these. This is the case as transitions in the cascade above 327 keV are shown as are those in the main cascade below 734 keV. However, the γ-ray transitions above and including 734 keV are not shown implying that the 327 keV branch enters as shown in figure 3. Figure 4(f) shows the sum of double

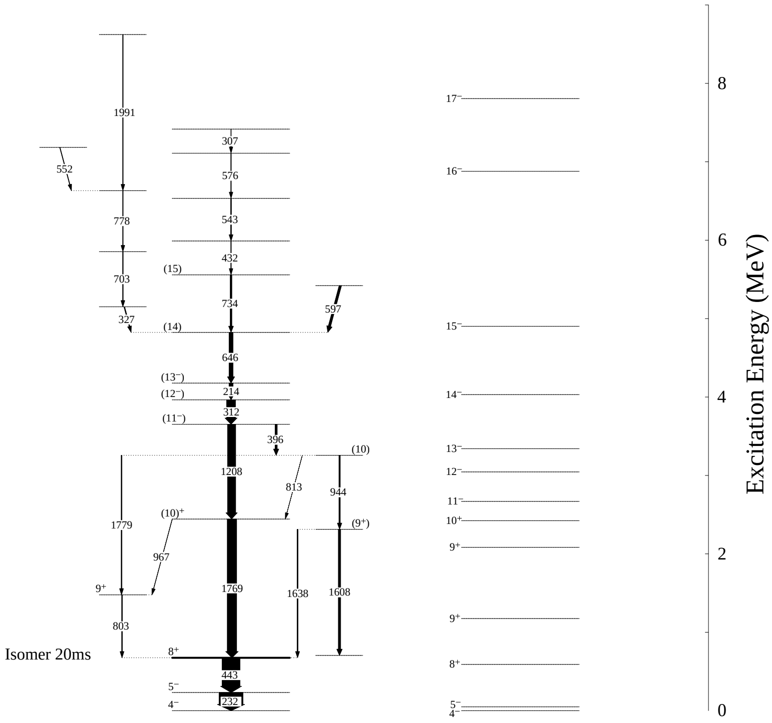

Figure 3: Preliminary results (left) Level scheme with previously unobserved levels (right) Calculated level scheme (`NuShell` [14]) with levels corresponding to observed levels shown.

gates between 311 keV and the strongest transitions in the main cascade (1769, 1208, 214, 646 keV). This is done to highlight the newly observed γ-rays placed above the main cascade. The 432, 543, 576 and 307 keV transitions can clearly be seen. Also present are the 597 keV transition and 1608 keV transition. At present no evidence has been observed for a decay from the 705 keV state populated by the 1608 keV γ-ray. It is possible that this state is isomeric and its depopulating transition too weak to be seen in this experiment. The newly placed levels discussed in the scheme show no spin or parity assignments. The work on DCO ratios and linear polarisation measurements are ongoing.

The right hand side of figure 3 shows theoretical shell model calculations performed using the `NuShell` code [14]. The calculation shown allowed for the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ to be occupied for both protons and neutrons, with truncations applied to both. The interaction used for the calculation was `jj44bpn` [15]. The theoretical model seems to describe the nucleus well up to $\sim 10\hbar$. At this point the large energy gap (1208 keV) between the 10^+ and 11^- is underestimated. However, above this spin the model does well at predicting the energy spacings, with a large energy gap between the 15^- and 16^- states of $\sim$2 MeV which could correspond to the previously unreported 1991 keV transition.

5. Conclusion and Outlook

A new preliminary level scheme extending known states in^{88}Y to higher excitation energy and spin has been constructed. Further work is required including DCO ratios and linear polarisation measurements for spin and parity assignments. Analysis also needs to be performed for the thin target data where higher spin levels should, in principle, be populated. Shell model calculations using the `NuShell` code have been performed. The preliminary results agree well with the experimentally observed states in^{88}Y.

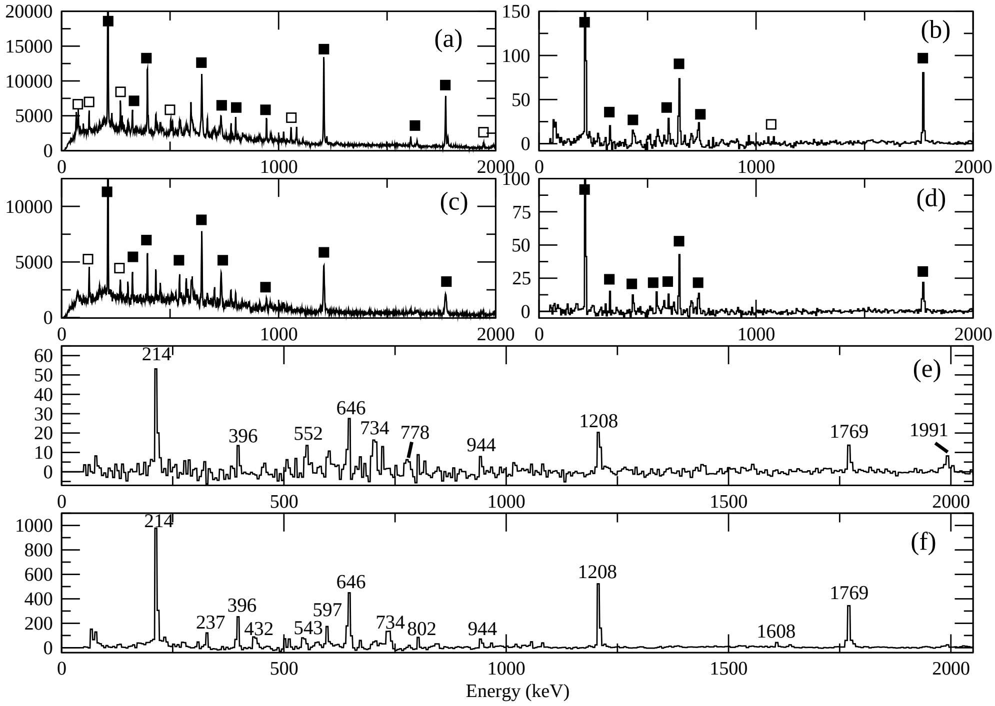

Figure 4: γ-ray coincidence spectra, filled squares are transitions attributed to ^{88}Y, empty squares correspond to contaminant γ-rays from other populated nuclei (a) Transitions coincident with 311 keV γ-ray, backed target data at 60 MeV. (b) Transitions coincident with both 311 and 1208 keV, backed target data at 60 MeV. (c) Transitions coincident with 311 keV γ-ray, thin target data at 90 MeV (d) Transitions coincident with both 311 and 1208 keV, thin target data at 90 MeV (e) Transitions coincident with both 311 and 327 keV, backed target data at 60 MeV (f) Sum of spectra requiring transitions to be coincident with 311 keV and 1769, 1208, 214, 646 keV, backed target data at 60 MeV.

Acknowledgements

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