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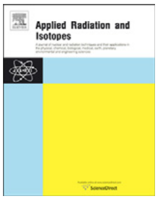

Gamma-ray fast-timing coincidence measurements from the $^{18}O+^{18}O$ fusion–evaporation reaction using a mixed $LaBr_3$-HPGe array

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ABSTRACT

We report on a gamma-ray coincidence analysis using a mixed array of hyperpure germanium and cerium-doped lanthanum tri-bromide ($LaBr_3$:Ce) scintillation detectors to study nuclear electromagnetic transition rates in the pico-to-nanosecond time regime in $^{33,34}P$ and ^{33}S following fusion–evaporation reactions between an ^{18}O beam and an isotopically enriched ^{18}O implanted tantalum target. Energies from decay gamma-rays associated with the reaction residues were measured in event-by-event coincidence mode, with the measured time difference information between the pairs of gamma-rays in each event also recorded using the ultra-fast coincidence timing technique. The experiment used the good full-energy peak resolution of the $LaBr_3$:Ce detectors coupled with their excellent timing responses in order to determine the excited state lifetime associated with the lowest lying, cross-shell, $I^{\pi}=4^{-}$ "intruder" state previously reported in the $N=19$ isotone ^{34}P. The extracted lifetime is consistent with a mainly single-particle M2 multipolarity associated with a $f_{7/2}\rightarrow d_{5/2}$ single particle transition.

1. Introduction

The break down of the $N=20$ spherical magic number has been linked with the population of deformed states which are associated with single-particle configurations arising from intruder configurations (Motobayashi et al., 1995). Microscopically speaking, these structures arise from the population of neutron $f_{7/2}$ orbitals, which, assuming a near-spherical nuclear mean-field, would be expected to lie above the $N=20$ shell closure in the usual nuclear single particle ordering. States associated with such negative-parity, intruder configurations have been discussed in terms of their importance in the structure of well-deformed ground state configurations in the neutron-rich Ne, Na and Mg isotopes, with this region of the nuclear chart being the so-called *island of inversion* (Warburton et al., 1990; Tripathi et al., 2005; Patra et al., 1991). In order to fully understand the underlying single-particle makeup of these well deformed intruder states (in terms of admixtures of spherical shell model configurations), detailed spectroscopy of the neighboring nuclei needs to be performed. One specific aim of such work is the measurement of empirical residual interaction matrix elements between well defined configurations in the normal spherical shell model basis. A number of examples of mixed multipolarity magnetic

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qradrupole/electric octupole (M2/E3) transitions in nuclei with $A\sim 40$ identified associated with single particle transitions between $f_{7/2}$ and $d_{3/2}$ single particle states which show a general suppression of the M2 strength compared to the single-particle Weisskopf estimates by factors ranging from approximately 5–300 (Prosser and Harris, 1971; Keinonen et al., 1976). The current work aims to measure electromagnetic decay transition rates from negative parity states associated with an $f_{7/2}$ intruder in the $N=19$ isotone ^{34}P, which borders the island of inversion, in order to provide input to shell model interpretations of such "cross-shell" structures.

2. Experimental details, data analysis and results

Excited states in the neutron-rich nucleus, ^{34}P were populated using the ^{18}O(^{18}O,pn) fusion–evaporation reaction at beam energy of 36 MeV. The beam was provided by the Tandem van de Graaff accelerator at the National Institute for Physics and Nuclear Engineering, Bucharest, Romania. A sputtering ion source was used to inject the ^{18}O beam to the Tandem accelerator. The beam was made using H_2O enriched 98.2% in the ^{18}O isotope combined with Lithium. The reaction to make the beam material took place in an Ar atmosphere. The lithium hydroxide (Li^{18}OH) material which was obtained was in the form of a white powder. The powder was pressed into cathode cylinder which was then placed in the ion source to produce the relatively high-current ^{18}O beam used in the current work. An isotopically enriched ^{18}O target was prepared by heating a 50 mg/cm^2-thick Ta foil in an atmosphere of enriched oxygen to form Ta_2O_5. The total ^{18}O equivalent thickness was estimated to be 1.6 mg/cm^2 on both sides of the Ta foil. The experiment was performed over a continuous beam time of 7 days, with an average on-target beam current of approximately 20 pnA. The experimental set-up comprised of eight high purity germanium detectors (HPGe) and seven LaBr$_3$:Ce scintillators arranged in a similar configuration to that described in Marginean et al. (2010). Three different-types of detector geometries were used in the present work for the LaBr$_3$:Ce crystals, namely those having crystal dimensions of (a) 2 in × 2 in (three) cylindrical; (b) 1.5 in × 1.5 in (two) cylindrical and (c) 1 in × 1.5 in (two) conical. Energy and efficiency calibrations for the response of the detectors in the array were performed using standard ^{152}Eu, ^{137}Cs, ^{56}Co and ^{60}Co point sources placed at the target position.

The energy resolution achieved using the LaBr$_3$:Ce detectors can be demonstrated in Fig. 1 which shows a comparison between the energy spectra measured for the ^{152}Eu source for a single LaBr$_3$:Ce detector and a hyperpure germanium in the array. Fig. 2 shows the measured FWHM for full-energy peaks measured in the LaBr$_3$:Ce detectors of the array using transitions from the ^{152}Eu, ^{56}Co and ^{60}Co sources. The measured, singles absolute full-energy peak efficiency for the combined LaBr$_3$:Ce detectors was 1.5% at 661 keV, compared to 1.2% for the combined eight Ge detectors. During the experiment data were taken with the validated master trigger conditions of either (i) Ge–Ge–Ge (γ^3) or (ii) LaBr$_3$–LaBr$_3$ (γ^2) gamma-ray energy coincidences. A total of $\sim 10^9$ LaBr$_3$:Ce $\gamma-\gamma$ energy coincidences were recorded during the experiment for off-line analysis.

The main residual products from this reaction were ^{33,34}P, ^{33}S and ^{30}Si from the p2n, pn, 3n, αpn particle evaporation channels respectively. Excitation energy Level schemes for these nuclei have been published previously and can be found in Bender et al. (2009), Chakrabarti et al. (2009), and Basunia (2010). The primary reaction residue of interest in the current work was the relatively weakly populated pn evaporation channel to form ^{34}P, which had a predicted cross-section of approximately 30 mb corresponding to approximately 10% of the total fusion cross-section in this reaction energy range (Bender et al., 2009).

The main aim of the experiment was to measure time differences between different gamma-ray decay sequences in order to establish electromagnetic transition rates for defined decays. In order to achieve this, the method described by Marginean et al. (2010) was used. The instrument time response for each LaBr$_3$:Ce detector and CFD combination in the array required an off-line correction due to time walk. This correction was achieved using the ^{60}Co source whose decay includes two mutually coincident gamma rays (1173 keV and 1332 keV) which are emitted within (typically) one picosecond of each other. The ^{60}Co source was placed at the target position and one of the LaBr$_3$:Ce detector was chosen as a time reference detector. For each of the remaining LaBr$_3$:Ce detectors in the array, a two-dimensional coincidence array was constructed in the off-line analysis of the residual gamma-array energy measured in this detector, with the condition that the 1332 keV full energy peak from the ^{60}Co source was measured in coincidence in the reference LaBr$_3$:Ce detector. This residual energy deposited in the detector from Compton scattered events was then correlated with the measured time difference, ΔT, between the detector and the reference detector. This method provides a time-walk correction function for the full energy coincidence peak (at 1173 keV) and the (continuum) Compton scattered events associated with this transition.

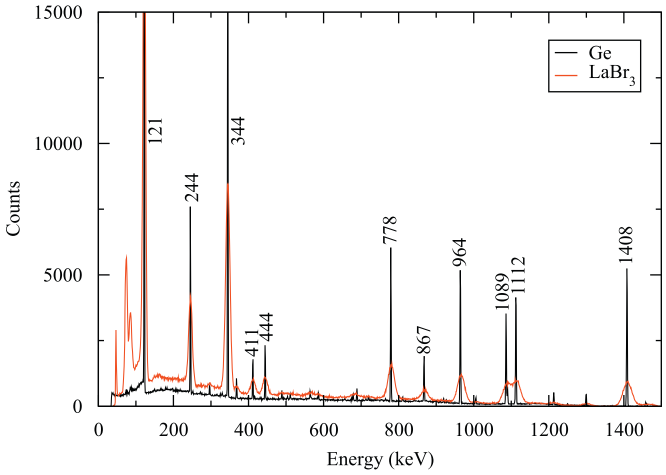

Fig. 1. Comparison of calibration energy spectra of the same ^{152}Eu source with a germanium and LaBr$_3$:Ce detector.

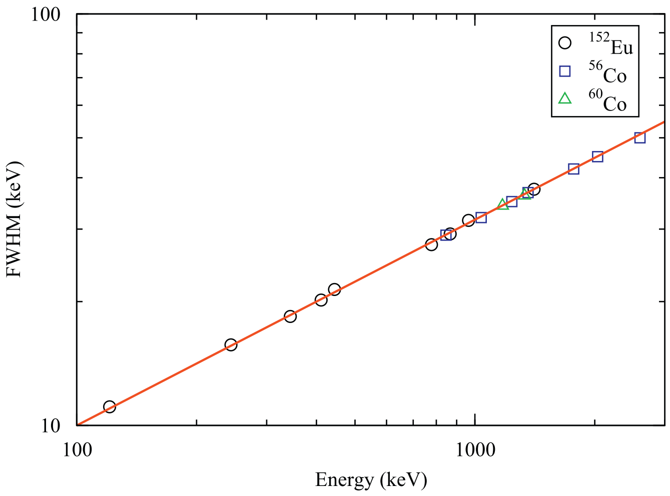

Fig. 2. Measured LaBr$_3$:Ce FWHM as a function of gamma-ray energy using data taken with ^{60}Co, ^{56}Co and ^{152}Eu sources.

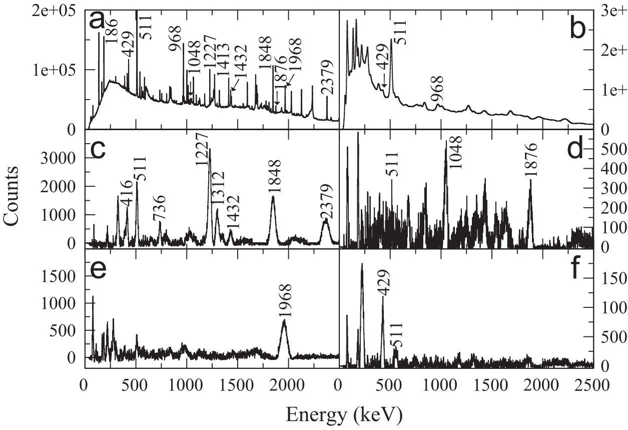

Fig. 3. Example gamma-ray energy spectra from the $^{18}O+^{18}O$ fusion–evaporation reaction at a beam energy of 36 MeV, as used in the current work. Total projection spectrum from (a) Ge and (b) $LaBr_3$:Ce detectors respectively (c) coincidence gate on the 186 keV transition in ^{33}P. (d) and (f) show the resulting gates on 429- and 1048-keV in ^{34}P. (e) shows a gate on 968 keV in ^{33}S.

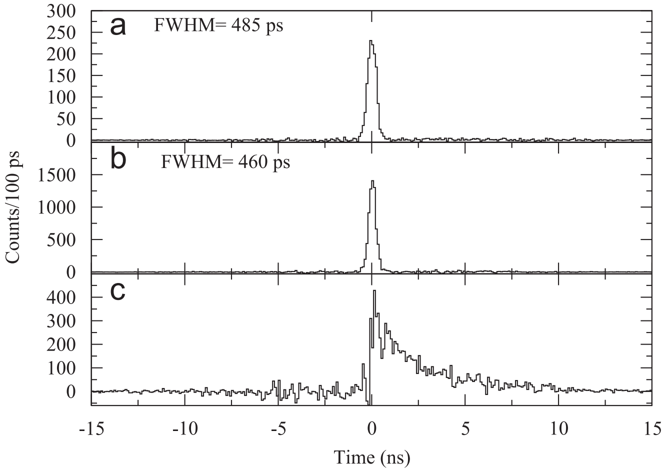

Fig. 4. Time difference spectra showing (a) the *prompt* function response associated with the expected ∼ ps lifetime of the $I^{\pi}=2^{+}$ level at 429 keV in ^{34}P (Bender et al., 2009) measured from the time difference between the 1876 and 429 keV transitions in ^{34}P. (b) The time difference spectra between the 968 and 1968 keV transitions in ^{33}S. (c) Time difference spectra between the 429 and 1048 keV transitions, showing the effect of the ∼2 ns half-life of the 4^{-} state at 2305 keV in ^{34}P.

The data were sorted off-line into a range of gamma-ray energy and time difference coincidence matrices and cubes which were then interrogated with different, gamma-ray energy conditions. The total projection spectrum of the $E_{\gamma}-E_{\gamma}$ coincidences matrices from the $^{18}O+^{18}O$ fusion–evaporation reaction are shown in Fig. 3 for (a) Ge–Ge and (b) $LaBr_3$–$LaBr_3$ coincidences respectively. The main populated nuclei in the present experiment were $^{33,34}P$, ^{33}S and ^{30}S. In Fig. 3(c) the transitions 416-, 736-, 1227-, 1312-, 1432-, 1848- and 2379 keV were observed by gating on 186 keV in ^{33}P. The spectrum shown in Fig. 3(d) was obtained by gating on the symmetric ($LaBr_3$,$LaBr_3$) coincidence energy matrix by the 429 keV transition in ^{34}P. The spectrum clearly identifies the 1048- and 1876-keV transitions as expected. Fig. 3(f) shows the equivalent spectrum gated on the 1048 keV transition with the 429 keV decay clearly identified. In Fig. 3(e) the 1968 keV transition is clearly identified by gating on 968 keV in ^{33}S.

The level structure of ^{34}P has been investigated in a number of previous studies (Ollier et al., 2005; Chakrabarti et al., 2009; Bender et al., 2009). These studies identified the ground state to have $I^{\pi}=1^{+}$ with the first excited state at excitation energy of 429 keV which has $I^{\pi}=2^{+}$. In terms of single particle wavefunctions, these two states correspond predominantly to the two couplings of the $(\pi s_{1/2}\otimes \nu d_{3/2})$ two-nucleon multiplet. The lowest lying, negative parity state, which corresponds mainly to the "cross-shell" excitation of a neutron from the $d_{3/2}$ orbital into a $f_{7/2}$ orbital, has been proposed to be the level at 2305 keV which has been assigned $I^{\pi}=4^{-}$. These studies assigned this state as negative parity on the basis of (i) gamma-ray angular correlation data which are consistent with an M2 multipole transition, possibly with some small E3 admixture (Bender et al., 2009; Chakrabarti et al., 2009) and (ii) other experiments using deep-inelastic reactions which have established limits of the lifetime of the decay of this state to the $I^{\pi}=2^{+}$ state at 429 keV of between 0.3 and 2.5 ns (Ollier et al., 2005).

Fig. 4 shows the resulting prompt coincidence time spectrum for the 429 keV level, resulting from gating on the gamma-ray energies of 1876 and 429 keV in the $LaBr_3$:Ce detectors and projecting their time difference, ΔT. Fig. 4(c) shows the time difference spectra associated with the 2305 keV state in ^{34}P. This spectrum was obtained when the *start* signal for the time difference analysis was provided by the transition above the level of interest (1048 keV) and *stop* signal from a transition in the prompt cascade de-exciting the level (429 keV). The measured half-life of the $I^{\pi}=4^{-}$ state in ^{34}P is established in the current work to be approximately 2 ns, which corresponds to a single particle strength of approximately 0.07 Wu, in line with a single particle M2 decay and a negative parity assignment for the 2305 keV level (Keinonen et al., 1976).

3. Conclusions

A lifetime measurements on the first negative parity state in the $N=19$ isotone ^{34}P using the fast gamma-ray coincidence timing method using $LaBr_3$:Ce scintillation detectors was performed. The electromagnetic transition rate from the yrast $I^{\pi}=4^{-}$ state at 2305 keV in ^{34}P on the boundary of the island of inversion has been determined for the first time, with a half-life of 2 ns established for the decay of this state. This result, together with the previously measured M2/E3 mixing ratio (Bender et al., 2009; Chakrabarti et al., 2009) will allow a detailed comparison with limited valence-space configuration mixing shell model calculations (Bender et al., 2009) which include excitations in the proton and neutron $f_{7/2}$ shell.

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