Half-life of the $I^{\pi} = 4^{-}$ Intruder State in ^{34}P Using $LaBr_3$:Ce Fast Timing

2012 J. Phys.: Conf. Ser. 381 012063

(http://iopscience.iop.org/1742-6596/381/1/012063)

Journal of Physics: Conference Series **381** (2012) 012063 doi:10.1088/1742-6596/381/1/012063

Half-life of the $I^{\pi} = 4^{-}$ Intruder State in ^{34}P Using LaBr$_3$:Ce Fast Timing

P J R Mason[1], T Alharbi[1,2], P H Regan[1], N Mărginean[3], Zs Podolyàk[1], N Alkhomashi[4], P C Bender[5], M Bowry[1], M Bostan[6], D Bucurescu[3], A M Bruce[7], G Căta-Danil[3], I Căta-Danil[3], R Chakrabarti[9], D Deleanu[3], P Detistov[10], M N Erduran[8], D Filipescu[3], U Garg[11], T Glodariu[3], D Ghiţă[3], S S Ghugre[9], A Kusoglu[6], R Mărginean[3], C Mihai[3], M Nakhostin[1], A Negret[3], S Pascu[3], C Rodríguez Triguero[7], T Sava[3], E C Simpson[1], A K Sinha, L Stroe[3], G Suliman[3] and N V Zamfir[3]

[1] Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK
[2] Department of Physics, Almajmaah University, P.O. Box 66, 11952, Saudi Arabia
[3] Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), R-76900 Bucharest, Romania
[4] KACST, P.O Box 6086, Riyadh 11442, Saudi Arabia
[5] Department of Physics, Florida State University, Tallahassee, Florida, USA
[6] Department of Physics, Istanbul University, 34134 Istanbul, Turkey
[7] School of Computing, Engineering and Mathematics, University of Brighton, Brighton, BN2 4GJ, UK
[8] Department of Computer Engineering, Istanbul Sabahattin Zaim University, Istanbul, Turkey
[9] UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata 700098, India
[10] Institute for Nuclear Research and Nuclear Energy (INRNE), Bulgarian Academy of Sciences, Sofia, Bulgaria
[11] Department of Physics, University of Notre Dame, Notre Dame, Indiana, 46556, USA

E-mail: p.j.mason@surrey.ac.uk

Abstract. The half-life of the $I^{\pi} = 4^{-}$ intruder state at 2305 keV in $^{34}_{15}$P$_{19}$ has been measured using γ-ray coincident fast timing with LaBr$_3$:Ce scintillation detectors. Excited states in ^{34}P were populated in the ^{18}O(^{18}O,pn)^{34}P reaction at a beam energy of 36 MeV at the Tandem Laboratory at the National Institute of Physics and Nuclear Engineering, Bucharest, Romania. A half-life of $t_{1/2} \sim 2$ ns was obtained for the 4^{-} state, giving an $M2$ reduced transition probability consistent with similar transitions in this mass region and confirming the intruder-parity nature of the state.

1. Introduction

Measurement of the half-lives of excited nuclear states gives information on the overlap of the initial and final state wavefunctions through the reduced transition probability. Using germanium detectors, direct measurement of the decay of a state is limited to half-lives greater than ~1 ns due to the intrinsic time resolution of the detectors. The faster response of halide scintillation detectors allows direct measurement of shorter half-lives but scintillation detectors suffer from poorer energy resolution than hyper-pure germanium detectors. The newly developed cerium-activated lanthanum bromide ($LaBr_3$:Ce) scintillation detectors boast excellent timing resolution (down to 100 ps for small crystals) with acceptable energy resolution (typically 2–3% at 662 keV) making them a good choice for measurement of nuclear half-lives in the picosecond-to-nanosecond range. This article reports on the measurement of the half-life of the $I^\pi = 4^-$ intruder state in ^{34}P performed with a mixed array of $LaBr_3$:Ce and high-purity germanium (HPGe) detectors at the National Institute of Physics and Nuclear Engineering, Romania [1].

$^{34}_{15}P_{19}$ lies on the neutron-rich side of the line of stability, just below the $N = 20$ shell-closure approaching the "island of inversion" [2, 3]. The island of inversion is a region of the nuclear chart in which deviations from normal shell structure are observed, centred around $Z \sim 10$ and $N \sim 20$. Isotopes here are found to have deformed ground states based on the $\nu f_{7/2}$ orbital [3, 4] which normally lies above the $N = 20$ shell gap. These observations indicate that the size of the $N = 20$ gap decreases for neutron-rich isotopes, allowing excitations from the $d_{3/2}$ orbital below the shell gap to the $f_{7/2}$ orbital above it to become favoured.

Previous studies of ^{34}P [5, 6, 7] identified an yrast, spin 4 $\hbar$ state at an excitation energy of 2305 keV. This state is thought be associated with excitations into the $\nu f_{7/2}$ orbital and decays via a 1876-keV mixed $M2/E3$ transition to the $I^\pi = 2^+$ yrast state at 429 keV, which implies a negative parity for the state at 2305 keV. The $M2$ component of this decay can be associated with a simple $\nu f_{7/2} \rightarrow \nu d_{3/2}$ single-particle transition across the $N = 20$ shell closure. The partial level scheme for ^{34}P relevant to this work is shown in Fig. 1.

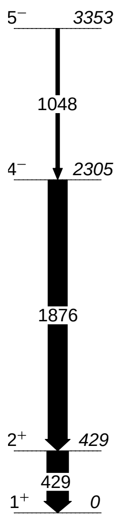

Figure 1. Partial level scheme for ^{34}P relevant to this work, adapted from Refs. [6, 7].

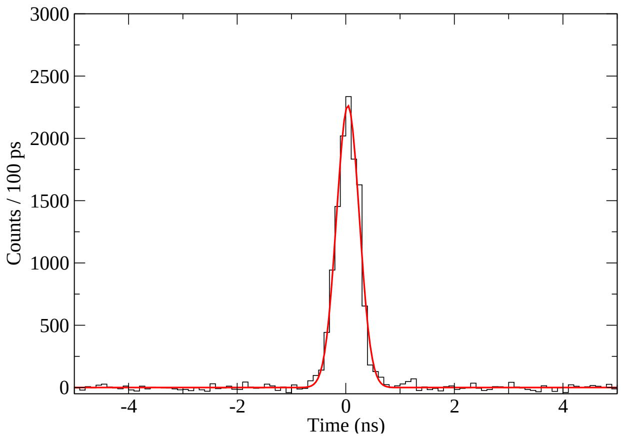

Figure 2. Time-difference spectrum between the 1876- and 429-keV transitions in ^{34}P showing the prompt performance of the $LaBr_3$:Ce detector array. The continuous line is a Gaussian fit to the spectrum giving a prompt timing resolution of 470(10) ps between these transitions.

2. Experiment and Data Analysis

Excited states in ^{34}P were populated in the ^{18}O(^{18}O,pn)^{34}P fusion-evaporation reaction previously employed by Chakrabarti *et al.* [6] and Bender *et al.* [7]. The beam was provided by the Tandem van de Graaff accelerator at National Institute of Physics and Nuclear Engineering, Bucharest at an energy of 36 MeV. The tantalum oxide target was prepared by heating a 50 mg/cm^2 Ta foil in an atmosphere of enriched oxygen producing an ^{18}O equivalent thickness

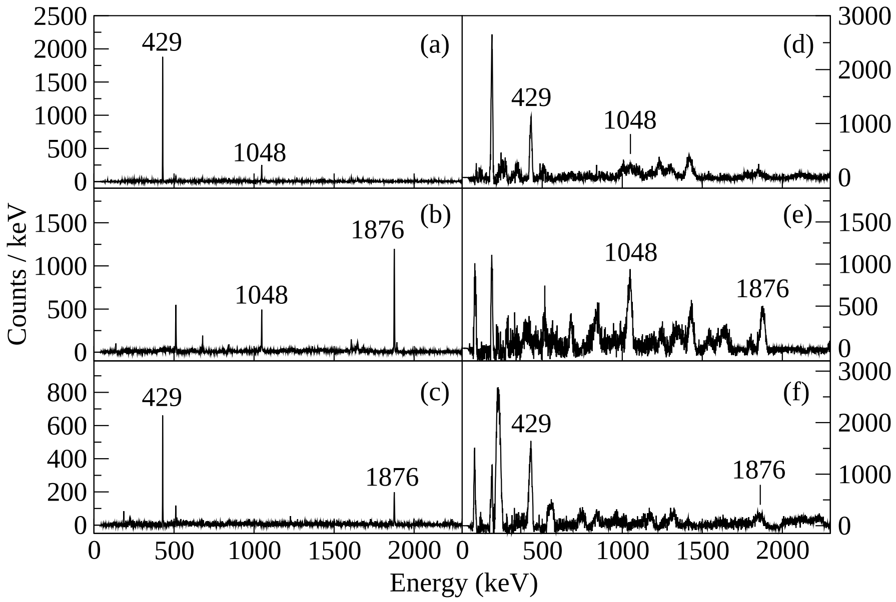

Figure 3. Coincidence γ-ray spectra created from γ-γ matrices in this work. Panels (a), (b) and (c) show spectra from HPGe-HPGe matrices and Panels (d), (e) and (f) show the equivalent spectra from $LaBr_3$:Ce-$LaBr_3$:Ce matrices. The spectra show transitions in coincidence with the ((a) and (d)) 1876-keV, ((b) and (e)) 429-keV and ((c) and (f)) 1048-keV transitions of ^{34}P. Peaks belonging to ^{34}P are labelled by their energy in keV and unlabelled peaks are contaminants.

of ~1.6 mg/cm^2 on both faces of the target. The experiment ran for a total of 156 hours during which the average beam intensity was ~20 particle-nA.

An array of 8 HPGe and 7 $LaBr_3$:Ce detectors was placed around the target chamber to detect γ rays produced in the reaction. 3 of the $LaBr_3$:Ce scintillator detectors were 2" × 2" cylindrical crystals, 2 were 1.5" × 1.5" cylindrical crystals, and 2 were 1" × 1.5" conical crystals [1]. The detectors were calibrated in energy and efficiency with ^{56}Co, ^{60}Co, and ^{152}Eu sources placed at the target position. A run-by-run gain-matching procedure was performed on the $LaBr_3$:Ce detectors to account for the gain drift of the detectors as a function of time. The energy dependence of the timing response of the $LaBr_3$:Ce detectors was calibrated using a ^{60}Co source as described in Ref. [1]. Data were sorted and analyzed with the GASPWARE [8] software suite.

3. Results

Data were sorted into HPGe-HPGe and $LaBr_3$:Ce-$LaBr_3$:Ce γ-γ matrices and $LaBr_3$:Ce $E_{\gamma 1}$-$E_{\gamma 2}$-ΔT cubes, in which the time difference between two transitions observed in the $LaBr_3$:Ce detectors can be projected out by gating on their energy peaks. $LaBr_3$:Ce $E_{\gamma 1}$-$E_{\gamma 2}$-ΔT cubes are described in more detail in Ref. [1]. Figure 2 shows the time difference between the 1876- and 429-keV transitions of ^{34}P, feeding and depopulating the 2^+ state. The half-life of the 2^+ state was limited in Ref. [7] to $t_{1/2} < 1$ ps, which is too short to be measured with direct electronic timing methods. This time difference gives an indication of the prompt timing resolution of the array and a Gaussian fit to the time difference spectrum gives a FWHM of 470(10) ps.

Figure 3 shows the result of setting coincidence gates in the HPGe-HPGe and $LaBr_3$:Ce-$LaBr_3$:Ce γ-γ matrices on the transitions in ^{34}P. It can be seen that the gated $LaBr_3$:Ce spectra show significant contamination from other nuclei populated in the reaction when compared with the HPGe spectra. However, the $LaBr_3$:Ce spectra gated by the 429-and 1048-keV transitions are clean in the region of these peaks, such that when these gates are set in the $LaBr_3$:Ce $E_{\gamma1}$-$E_{\gamma2}$-ΔT cube, an uncontaminated time-difference spectrum is observed.

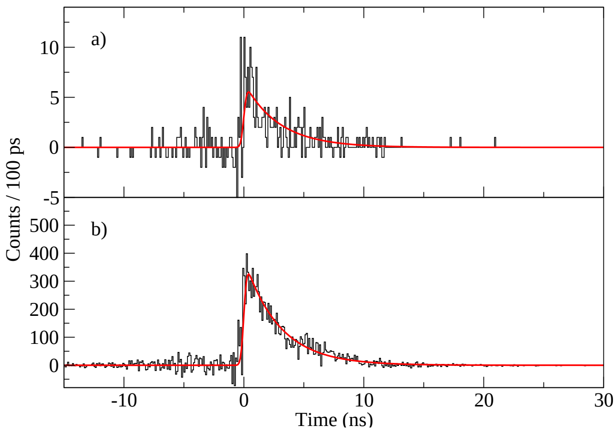

Figure 4. Time-difference spectra between the 1048- and 429-keV transitions in ^{34}P (a) from the $LaBr_3$:Ce $E_{\gamma1}$-$E_{\gamma2}$-ΔT cube gated by the 1876-keV transition detected in the HPGe detectors and (b) from the ungated $LaBr_3$:Ce $E_{\gamma1}$-$E_{\gamma2}$-ΔT cube. The continuous line in Panel (b) is a Gaussian-exponential convolution fit (assuming a prompt FWHM of 470 ps) to the ungated spectrum, giving a half-life of $t_{1/2} \sim 2$ ns for the 4^- state. The line in Panel (a) is the same fit to the ungated spectrum, renormalized to show the correspondence between the gated and ungated data.

Due to low statistics and contamination of the 1048–1876-keV time difference spectra, these transitions directly feeding and depopulating the 4^- state could not be used to extract its half-life. Instead, 1048–429-keV time difference was used, which includes the half-lives of both the 4^- and 2^+ states in ^{34}P. However, the half-life of the 2^+ state is negligible compared with that of the 4^- state and the 1048–429-keV time difference, shown in Fig. 4(b), can be assumed to be solely representative of the half-life of the 4^- state. A Gaussian-exponential convolution fit to this spectrum gives a half-life of $t_{1/2} \sim 2$ ns for the 4^- state. The full details of this measurement will be published in [9]. This half-life gives a reduced transition probability for the 1876-keV transition of $B(M2) \sim 0.06$ W.u. which is consistent with $M2$ strengths for transitions associated with $\nu f_{7/2} \rightarrow \nu d_{3/2}$ single-particle transitions in other nuclei in the $A \sim 30-40$ mass region [10], consistent with the negative parity assignment and thus intruder nature of the 2305-keV state.

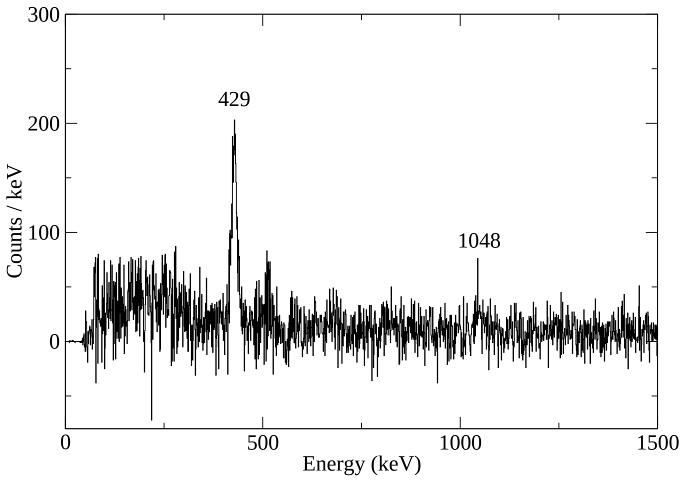

Figure 5. Spectrum showing the projection along an energy axis of the $LaBr_3$:Ce $E_{\gamma1}$-$E_{\gamma2}$-ΔT cube, gated by the 1876-keV transition observed in the HPGe detectors. The 429- and 1048-keV peaks belonging to ^{34}P are labelled by their energy.

To rule out contamination from other transitions in the $LaBr_3$:Ce energy gates, a $LaBr_3$:Ce $E_{\gamma1}$-$E_{\gamma2}$-ΔT cube, gated by the 1876-keV transition observed in the HPGe detectors, was created. This created somewhat cleaner $LaBr_3$:Ce energy spectra compared to the simple $LaBr_3$:Ce only gated spectra for the 1048- and 429-keV peaks in ^{34}P. The projection of an energy axis of HPGe-gated $LaBr_3$:Ce $E_{\gamma 1}$-$E_{\gamma 2}$-ΔT cube is shown in Fig. 5. Projecting out the time differences, shown in Fig. 4(a), from the HPGe-gated cube did not give sufficient statistics from which to accurately fit the half-life. However, renormalizing the fits to the ungated time differences in Fig.2 4(b) and overlaying them onto the HPGe-gated spectra showed the gated and ungated spectra to be in good agreement.

4. Summary

An array of $LaBr_3$:Ce detectors has been employed to measure the half-life of the 4^- intruder state in ^{34}P. The prompt time resolution for the array measured from the time difference between the 1876- and 429-keV transitions in ^{34}P was measured to be 470(10) keV. The good energy resolution of the $LaBr_3$:Ce detectors has made it possible for in-beam lifetime measurements to be performed without imposing additional selectivity and the time-difference spectrum extracted using this method is consistent with that obtained when an additional gate with HPGe detectors is employed to create very clean $LaBr_3$:Ce energy spectra. A half-life of $t_{1/2} \sim 2$ ns was obtained for the 4^- state, giving an $M2$ reduced transition probability consistent with similar transitions in this region.

Acknowledgements

We would like to thank the staff of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Romania for their support during this experiment and to John Greene from Argonne National Laboratory for preparing the target. This work was supported by the Science and Technology Facilities Council, STFC(UK), The Romanian Ministry for Education and Research (contracts Module3-24EU-ISOLDE and PN-II-ID-PCE-2011-3-0367(UEFISCDI)), ANCS(Romania), The Scientific and Technological Research Council of Turkey (TÜBİTAK) under the International Bilateral Cooperation project 109T613 and the U.S. National Science Foundation (Grant Nos. PHY07-58100, PHY-1068192, and PHY-07-56474). TA acknowledges the support of Almajmaah University, Saudi Arabia.

References

[1] Mărginean N *et al.* 2010 *The Eur. Phys. J.* A **46** 329
[2] Thibault C *et al.* 1975 *Phys. Rev.* C **12** 644
[3] Wildenthal B H and Chung W 1980 *Phys. Rev.* C **22** 2260
[4] Warburton E K, Becker J A and Brown B A 1990 *Phys. Rev.* C **41** 1147
[5] Ollier J *et al.* 2005 *Phys. Rev.* C **71** 034316
[6] Chakrabarti R *et al.* 2009 *Phys. Rev.* C **80** 034326
[7] Bender P C *et al.* 2009 *Phys. Rev.* C **80** 014302
[8] Bazzacco D and Mărginean N Private Communication.
[9] Mason P J R *et al.* in preparation (unpublished).
[10] Keinonen J *et al.* 1976 *Phys. Rev.* C **14** 160