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High Resolution (^{3}He,n) Two Proton Stripping Reaction to 0^+ States Populated in 2β Decay

P. Papka[*,†], **E. A. M. A. Khaleel, P. Vymers**
Department of Physics, University of Stellenbosch, Private Bag X1, 7602 Matieland, South Africa
E-mail: papka@sun.ac.za

T. S. Dinoko, W. A. Richter[†], **J. F. Sharpey-Schafer**
Department of Physics, University of the Western Cape, Bellville ZA-7535, South Africa

P. Jones, E. A. Lawrie, J. J. Lawrie, S. N. T. Majola, O. Shirinda, M. Wiedeking
iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa

M. A. Stankiewicz
Department of Physics, University of Cape Town, Rondebosch 7700, South Africa

B. A. Brown
Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University East Lansing, Michigan 48824-1321, USA

Over the last decades, (t,p) striping and (p,t) pick-up reaction measurements near and at zero degrees were successfully performed with magnetic spectrometers populating very selective feeding of states with low angular momentum transfer with projectile energy $E_{lab} < 100$ MeV. In this work, a similar type of reaction was utilized with the (^{3}He,n) stripping reaction to populate selectively states where two correlated protons dominate the configuration. In these experiments, excited states are identified with the AFRODITE γ-ray spectrometer tagged with the subsequent detection of the fast neutron at forward angles. Test experiments were performed in various mass regions. This technique is applied to the case of ^{100}Ru and ^{150}Sm to investigate the proton occupation of excited states populated in 2β decay.

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[*] Speaker.
[†] iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa

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1. Introduction

Two neutron stripping data from (*t*,*p*) reactions have provided considerable valuable information on the paired neutron component of the configurations of the excited states of many nuclei. This has been particularly productive in assisting the understanding of the neutron pairing forces in both spherical and deformed nuclei [1]. The counterpart for two proton pairing studies, the (^{3}He,n) reaction, suffers from time-of-flight energy resolutions of the fast direct reaction neutrons which are usually measured in hundreds of keV. In this work we utilize an escape-suppressed array of HPGe γ-ray detectors in coincidence with a wall of neutron detectors placed at forward angles. We have demonstrated the selectivity of the apparatus in various mass regions (^{29}P, ^{61}Cu, ^{162}Dy). The technique was recently applied to investigate the structure of the excited states populated in 2β decay namely ^{100}Ru and ^{150}Sm, preliminary results are presented here.

2. Experimental setup

Typical (^{3}He,n) reactions have positive Q-values and, depending on the excitation energy in the residual nuclei, the outgoing neutrons carry an energy close to the beam energy or higher. This is of interest as the discrimination of γ-rays, statistical neutrons and fast neutrons in the neutron wall is required to identify the events populated in direct reactions. Time-of-flight technique together with large energy deposition in the detectors are used to identify fast neutrons. With the identification of high energy neutrons produced uniquely in the (^{3}He,n) direct reaction, allows single γ-rays measured in coincidence to be firmly assigned to a specific nucleus. Such selection allows to discriminate the direct reaction with a sub mb cross section from fusion evaporation events with typical cross section of 1 b [2].

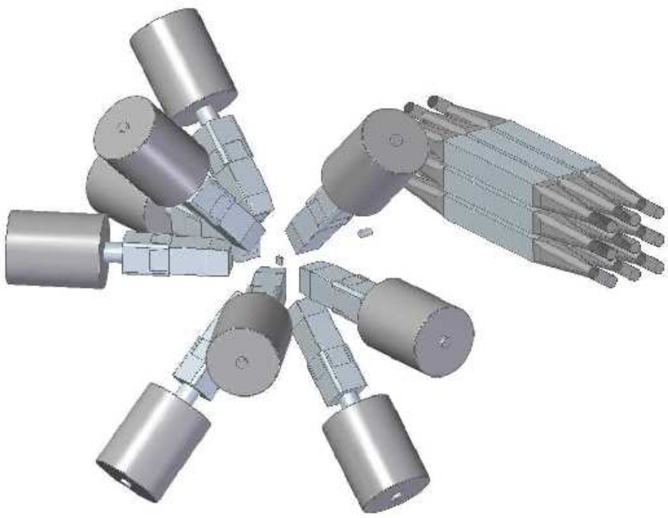

Figure 1: Schematic diagram of the experimental setup. The AFRODITE γ-ray spectrometer consists of 9 escape-suppressed HPGe clover detectors. The neutron detectors were arranged in three layers of three detectors each placed at θ = 0°.

The neutron detector setup comprises a set of 9 large volume scintillators (600×100×100 mm^3 each) initially built for the neutron time of flight setup at iThemba LABS, Cape Town, South Africa

[3]. The detectors were arranged in a 3×3 compact geometry placed at θ = 0 ° perpendicular to the beam axis at a distance of 2.1 m downstream of the target. The vertical walls of three detectors placed on the top of each other have a total thickness of 0.3 m. A schematic of the setup is depicted in Fig.1. The beam is intercepted by a lead cup placed 50 cm downstream the target.

Isotopically pure targets with thicknesses in the order of 3-10 mg/cm^2 were bombarded with ^{3}He beams of 22.5-25.0 MeV incident energy from the iThemba LABS Separated Sector Cyclotron (SSC) with beam intensity in the order of 0.5 pnA. Excellent selectivity of direct reaction products were obtained on various test measurements using the ^{27}Al(^{3}He,n)^{29}P, ^{59}Co(^{3}He,n)^{61}Cu and ^{160}Gd(^{3}He,n)^{162}Dy reactions.

The spectra of Fig.2, recorded for the ^{27}Al(^{3}He,n)^{29}P reaction, illustrate the high rejection factor of nearly 1000 of the main fusion evaporation channels, shown in Fig.2(a), and are compared with the fast neutron gated spectrum shown in Fig.2(b). The signal to background ratio in the gated spectrum is excellent. The states populated through low angular momentum transfer decay via a small number of transitions, 1 or 2 at most depending on the spin and parity of the ground state. With such low multiplicity γ-γ coincidence is ineffective as verified by constructing γ-γ matrices during the test experiments.

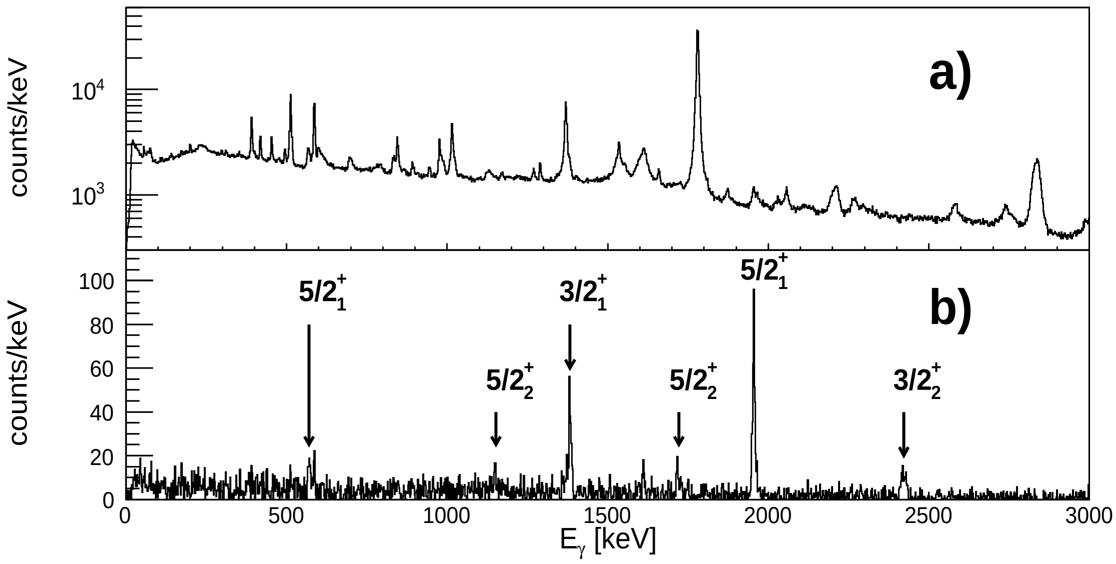

Figure 2: Total projection (a) and neutron gated (b) γ spectra recorded in the ^{27}Al(^{3}He,n)^{29}P reaction at a beam energy of E_{lab} = 22.5 MeV.

The efficiency of the neutron detector is estimated from the counts of fast neutrons in the successive layers. The 9 detectors cover a solid angle of 0.15 sr with an efficiency of approximately 70%. Based on the AFRODITE total efficiency, which is a function of the γ-ray energy, cross sections are estimated. The 1953 keV state in ^{29}P is populated with a cross section of approximately 10 μb/sr. States in ^{61}Cu are populated with larger cross sections of up to 0.4 mb/sr for the 1310 keV state. A cross section of the order of 200 μb/sr is found for the ^{160}Gd(^{3}He,n)^{162}Dy reaction. These cross sections are consistent with the typical cross sections of less than 1mb for L = 0 direct reactions.

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Excited states with low angular momentum transfer are observed in both ^{29}P and ^{61}Cu, whereas ^{162}Dy seems to be populated at higher spin states possibly through the evaporation of a single neutron. However, the neutron detector setup covers a solid angle of $\Omega < 0.1$ sr which reduces the detection efficiency for statistical isotropic neutrons. The geometry is optimised for L = 0 angular momentum transfer when the neutrons are emitted at forward angles with maximum cross section for $\theta_{lab} < 15°$. Also, it is speculated that the incoming ^{3}He Coulomb excites the target nucleus followed by the transfer of two protons to the 2^+, 4^+ and 6^+ levels of the ground state band in ^{162}Dy.

3. Investigation of 2β decay nuclei: ^{100}Ru, ^{150}Sm

New results have firmly demonstrated the oscillation between the neutrino flavours [4] which allows the mass differences between the three flavours to be deduced. However, the type and absolute mass of the neutrinos are still unknown. Also, it is not clear if the neutrinos are Majorana or Dirac particles and CP violation in neutrino physics are still pending questions. Large scale experiments are devoted to the study of rare events involving neutrino particles namely 2β decay studies as described in the review paper of Ref.[5]. The decay rate of 2β decay nuclei, involving a simultaneous decay of two nucleons via the weak interaction, is extremely low, therefore, half-lives of $T_{1/2} > 10^{18}$ to 10^{21} years have been measured.

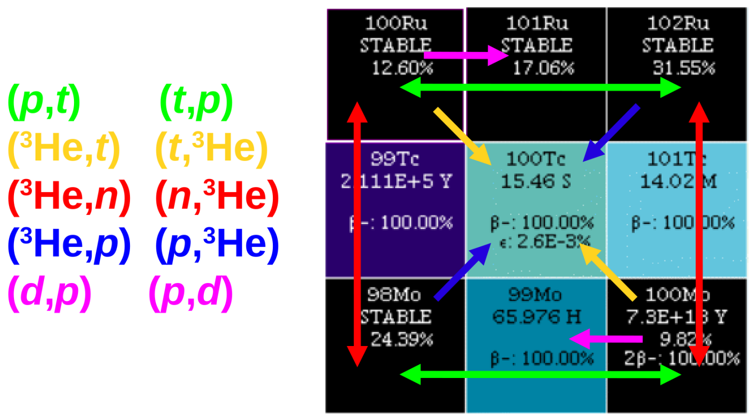

Figure 3: Various nuclear transfer and charge exchange reactions to study the states of parent, transition and daughter nuclei of 2β decay leading to ^{100}Mo.

Based on the nature of the neutrino, two scenarios are envisaged. In the context of Dirac neutrino particles, a simultaneous 2β decay would result in 2β2ν emission with a calculated decay rate of:

$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta},Z)|M_{2\nu}|^2 \qquad (3.1)$$

where $G_{2\nu}$ ($Q_{\beta\beta}$,Z) is the phase space term. $M_{2\nu}$ is the matrix element, which represents the transition probability related to the change in the wavefunctions between parent, transition and daughter nuclei through their excited states and virtual states. This decay rate is insensitive to the mass of the neutrinos.

The decay rate within the Majorana scenario is expressed as:

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2 \tag{3.2}$$

which is sensitive to the absolute mass of the neutrinos, m_k, through the effective mass:

$$< m_{\beta\beta} > = |\sum_k m_k U^2_{ek}| \tag{3.3}$$

where ${U_{ek}}^2$ are the mixing elements of the PMNS-matrix defined from the mixing angles within the neutrino flavors.

In both cases, the calculated decay rates depend upon theoretical matrix elements and large uncertainties may arise. The determination of the matrix elements requires knowledge of the states involved, i.e. their structure and nucleon occupancy should be known. Experimental studies should be performed using the typical stable beam nuclear reactions indicated in Fig.3 to probe the states of the parent and daughter nuclei but also the excited states of the transition nucleus which interfere below the ground state.

In most cases, the daughter nuclei produced in 2β decays are populated in their ground state except for ^{100}Ru and ^{150}Sm where the $2\beta 2\nu$ decay to excited 0^+ states has been observed due to large Q-values [6]. To date, the experiments are not sensitive enough to identify a possible decay to excited states in other nuclei. In this work, the excited 0^+ states of ^{100}Ru and ^{150}Sm are populated by means of the (^{3}He,n) L = 0 reaction to probe their 2p occupancy. This is equivalent to the measurements using the ^{98}Ru(t,p), ^{102}Ru(p,t) [7], ^{148}Sm(t,p) or ^{152}Sm(p,t) reactions probing the two neutron occupancy of the states.

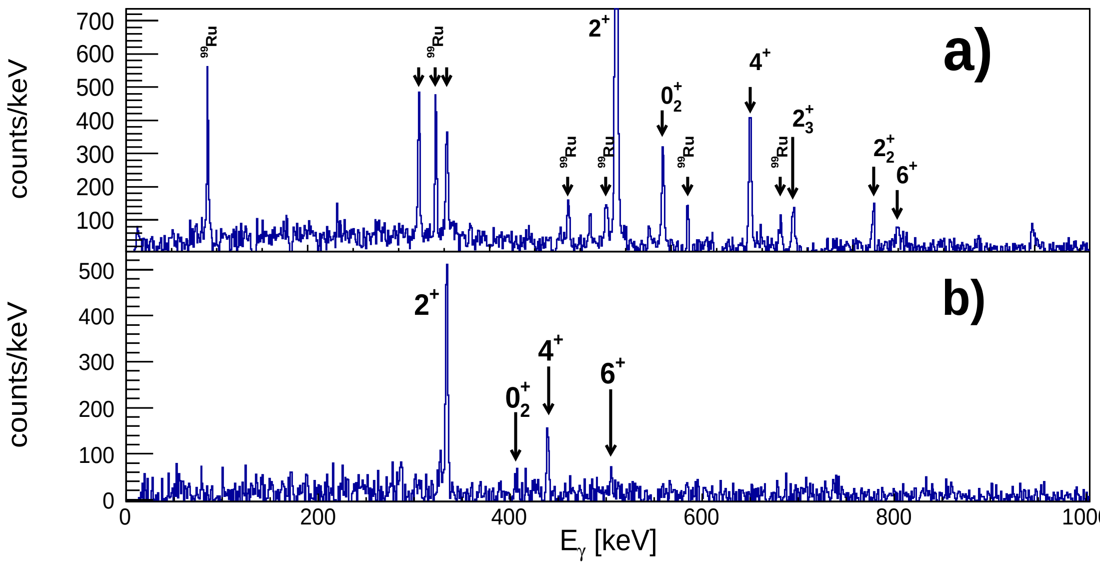

Figure 4: Background subtracted γ spectra of ^{100}Ru (a) ^{150}Sm (b) gated on fast neutron using the ^{98}Mo(^{3}He,n)^{100}Ru and ^{148}Nd(^{3}He,n)^{150}Sm reactions at a beam energy of E_{lab} = 25 MeV.

4. Preliminary results

Two experiments were recently performed using the (^{3}He,n) reaction on isotopically pure ^{98}Mo and ^{148}Nd targets following the technique detailed above. The preliminary spectra of Fig.4 show that the first 0^{+} excited states of ^{100}Ru (1130 keV) and ^{150}Sm (740 keV) were populated though rather weakly for the samarium isotope. For both nuclei, higher spin states are also populated with rather large intensities as in the case of ^{162}Dy. From CASCADE calculations, the ^{148}Nd(^{3}He,n)^{150}Sm fusion evaporation channel accounts for 100 μb to all states.

The population strength of the 0^{+} states are being extracted and corrected for the feeding from higher excited states. From comparison with *(p,t)* data [7] the first excited 0^{+} states are populated very weakly which indicates a large 2n occupancy.

5. Conclusion

The challenge in achieving high resolution measurements using (^{3}He,n) reactions is addressed in this work by combining a γ-ray spectrometer together with a neutron detector array placed at small angles. Test experiments were performed on various systems. States with $L = 0$ momentum transfer were populated very selectively and excellent signal to background ratio was achieved. This type of measurement is equivalent to the (p,t) or (t,p) reactions studied extensively with magnetic spectrometers. In this work, we have employed the (^{3}He,n) reaction to probe the excited states of the only two nuclei ^{100}Ru and ^{150}Sm where the 2β decay to excited states was observed. Population strengths are being extracted in order to determine the 2p and 2n occupancy of the relevant states.

Acknowledgements

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References

[1] D. M. Brink and R. A. Broglia, Nuclear Superfluidity; Pairing in Finite Systems, Cambridge Monographs on Part. Phys. Nucl. Phys. and Cosm. 24, CUP (2005).

[2] W. P. Alford et al., Nucl. Phys. A321, 45 (1979).

[3] V. M. Tshivhase, PhD thesis, University of Cape Town 1997.

[4] G. J. Feldman, J. Hartnell and T. Kobayashi, Adv. in High Energy Phys 2013, 475749 (2013). http://dx.doi.org/10.1155/2013/475749

[5] K. Zuber, J. Phys. G: Nucl. Part. Phys. 39 124009 (2012) doi:10.1088/0954-3899/39/12/124009

[6] A. S. Barabash, P. Hubert, A. Nachab, and V. I. Umatov1 Phys. Rev. C **79**, 045501 (2009).

[7] J. S. Thomas, Phys. Rev. **C 86**, 047304 (2012).