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Coulomb and Inelastic Excitations of Target Nuclei in (^{3}He,n) Two Proton Stripping Reactions on ^{27}Al, ^{59}Co, ^{148}Nd and ^{160}Gd

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High resolution measurements have been made with the (^{3}He,nγ) reaction on targets of ^{27}Al, ^{59}Co, ^{148}Nd and ^{160}Gd using the AFRODITE escape-suppressed γ-ray spectrometer in coincidence with a wall of large scintillator neutron detectors at zero degrees to the beamline. In spite of the geometry strongly favoring only $L=0$ transitions, strongly populated levels are observed that have the spin change between target and residual nuclei $|\Delta J|>0$. The data are discussed in terms of the incoming ^{3}He Coulomb and/or inelastically exciting the target nucleus before the single step transfer of the two protons. Differing line shapes in previous low resolution time-of-flight (^{3}He,n) measurements can be accounted for by this assumption. The inelastic excitation followed by the one-step transfer of two protons opens the opportunity of making (^{3}He,n) measurements on low-lying excited states.

52 International Winter Meeting on Nuclear Physics (Bormio 2014)
January 27 - 31 2014
Bormio, Italy

1 Speaker

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 pairing forces in both spherical and deformed nuclei [1]. For two proton stripping there is no surrogate for the (^{3}He,n) reaction. Heavy-ion reactions can be used, such as (^{16}O,^{14}C) but the cross-sections are even smaller than for light-ion direct reactions. It is difficult to achieve good energy resolutions due to energy losses in the targets and the internal structures of the heavy-ions complicate the interpretation of the data [2]. There is a paucity of accurate experimental information on paired proton components of wave functions. High resolution data using the simplest of two proton stripping reactions, the (^{3}He,n) reaction, is highly desirable [3].

Time-of-flight (T-o-F) measurements of the (^{3}He,n) two proton direct stripping reaction usually had poor energy resolutions of the order of 500 keV. When stripping the two protons onto an even-even nucleus, having its ground state spin 0^{+}, to another even-even nucleus, the T-o-F spectra below the ground state of the final nucleus usually suffered from large backgrounds. The poor resolution, compared to known level spacing, and the large background made measuring the two proton component of excited states very challenging especially for well deformed nuclei. Recently we have shown [4,5] that detecting the (^{3}He,n) two proton direct stripping reaction to excited states with resolutions of the order of 3 keV may be achieved by operating an array of escape suppressed HPGe γ-ray detectors in coincidence with a wall of neutron detectors. Just as in (t,p) and (p,t) two neutron stripping and pick-up reactions, the (^{3}He,n) direct reaction, on even-even targets, will only populate natural parity states with spins of 0^{+}, 1^{-}, 2^{+}, 3^{-}, 4^{+}……. Such states will be populated with angular distributions of the outgoing neutron being characteristic of $L = 0, 1, 2, 3, 4$… transferred angular momentum respectively. The peak differential cross-section of these angular distributions increases as L increases. Thus the $L=0$ angular distribution peaks at zero degrees to the beam direction, the $L=2$ at 15º and $L=3$ at 20º for 25.4 MeV ^{3}He on Nd isotopes [6].

We report here on high energy resolution measurements of the ^{27}Al(^{3}He,n)^{29}P, ^{59}Co(^{3}He,n)^{61}Cu, ^{148}Nd(^{3}He,n)^{150}Sm and ^{160}Gd(^{3}He,n)^{162}Dy reactions to excited states.

2. Experiment

The experimental set-up has been described in [4,5]. For these experiments we used beams of 25 MeV ^{3}He ions from the iThemba Laboratory for Accelerator Based Sciences (LABS) separated sector cyclotron (SSC). The neutrons were detected in a wall of 0.6x0.1x0.1 m^{3} NE102A plastic scintillators viewed at each end by Hamamatsu R329 photomultipliers. These scintillators have no n-γ discrimination so some Pb shielding is used to reduce the γ-ray flash from the target. Otherwise the residual γ-rays were separated from the neutrons by time-of-flight over the 2.0 m from the target to the scintillation neutron detectors and by the energy deposited in the neutron detectors. The 12 neutron detectors were arranged in a double wall 2.0

m down-beam from the target, positioned symmetrically about 0º and subtending scattering angles to the target between 0º and 8.5º The γ-rays from excited states were detected in the iThemba LABS escape suppressed γ-ray spectrometer array AFRODITE [7] consisting of 9 HPGe clover detectors in bismuth germinate (BGO) shields.

The (^{3}He,n) reaction generally has very positive Q-values ranging between 0 and 10 MeV. Thus for 25 MeV beams of ^{3}He the direct reaction neutrons will have energies between 25 and 35 MeV. This is in contrast to the competing statistical neutrons from the (^{3}He,xn) fusion-evaporation reactions which have energies peaking at about 2 MeV. Certainly very few of these statistical neutrons have energies more than 6 MeV. As the velocity of the neutrons is proportional to $\boldsymbol{E_n}^{1/2}$ it follows that the direct reaction neutrons have about twice the velocity of the statistical neutrons and may be separated from them by time-of-flight measurements over relatively short distances of 1 to 2 m. In Table 1 we show the Q-values for the direct (^{3}He,n) reaction and the fusion-evaporation (^{3}He,*x*n) reaction channels, together with their partial cross-sections σ estimated by the PACE4 statistical code [8], for the four targets used. The main exit channels for the lighter targets ^{27}Al and ^{59}Co involve the emission of protons and/or alpha particles.

Table 1. Exit channel reaction Q-values and partial fusion-evaporation cross-sections calculated at a beam energy of 25 MeV with PACE4 [8].

Exit Channel	^{27}Al			^{59}Co			^{148}Nd		^{160}Gd	
	Q (MeV)	σ (mb)	σ %	Q (MeV)	σ (mb)	σ %	Q (MeV)	σ (mb)	Q (MeV)	σ (mb)
(^{3}He,n)	+6.62	2.0	0.4	+6.61	1.0	0.1	+6.51	0.0	+7.08	0.0
(^{3}He,2n)	-11.25	0.5	0.1	-5.10	104	13.5	-1.47	1.3	-1.12	1.7
(^{3}He,3n)	-26.69	-	-	-15.16	2.8	0.4	-7.35	467	-7.57	454
(^{3}He,4n)	-	-	-	-27.92	-	-	-15.49	246	-16.15	210

As the neutron detectors are positioned at less than 10° to the beam direction, the geometry of the apparatus is designed to pick out *L=0* two proton transfers where the emitted neutron angular distribution is peaked around a scattering angle of 0°. This geometry helps the selection of direct reaction neutrons as the statistical neutrons are emitted isotropically in the centre-of-mass. The final states populated will have to have the same spin as the target nucleus as no angular momentum is transferred if *L=0.*

One extra advantage of this experimental arrangement is that relatively thick targets may be used as the high resolution comes from the γ-rays and not from the neutrons.

3. Experimental results

3.1. $^{27}Al(^{3}He,n)^{29}P$

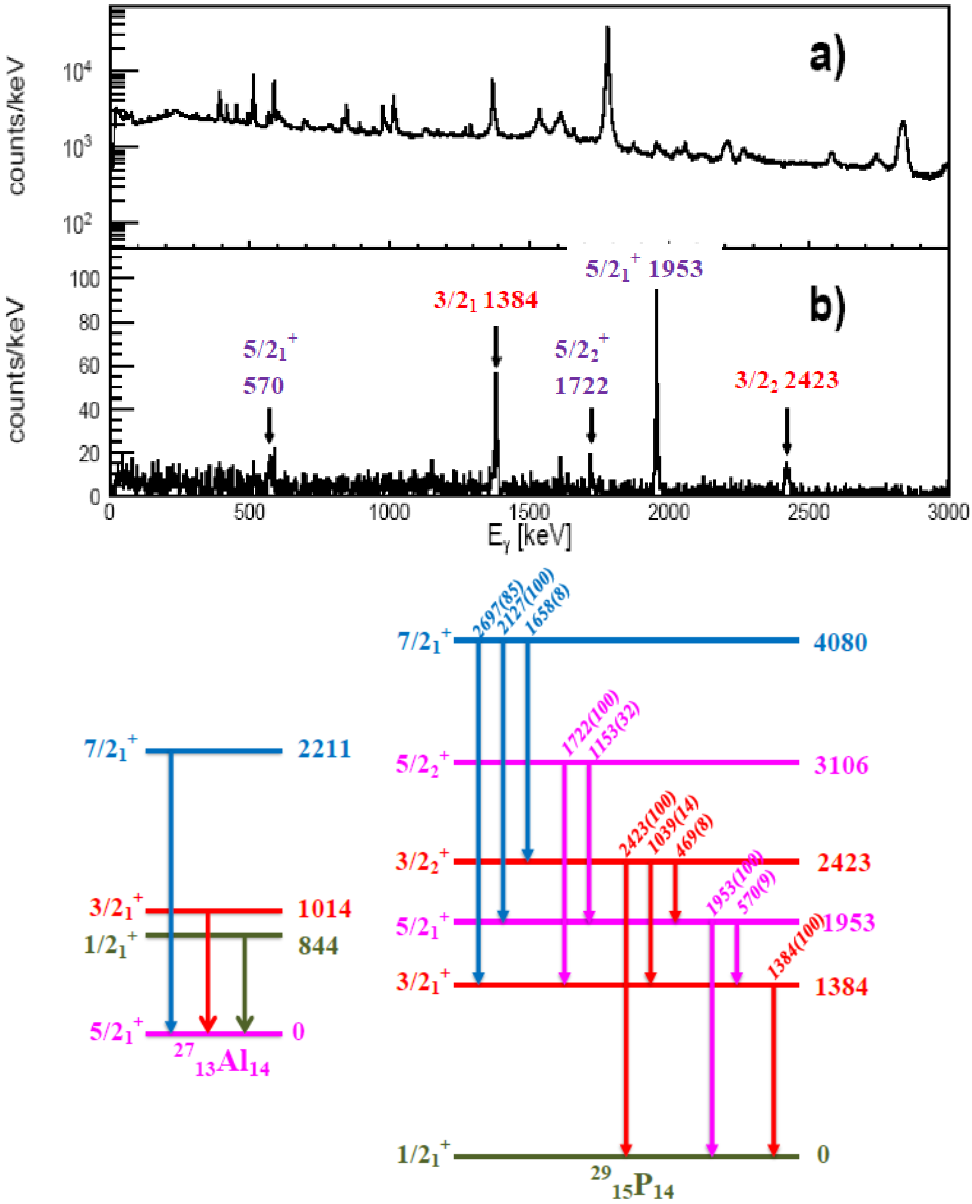

Fig. 1. Total projection (a) and gated by fast neutrons (b) spectra for the $^{27}Al(^{3}He,xn)$ reaction at 22.5 MeV. Below the spectra the decay schemes for the lowest levels in ^{27}Al and ^{29}P are shown.

The spectrum of γ-rays we observe in coincidence with all neutrons for the $^{27}Al(^{3}He,xnyp)$ reaction is shown in Fig. 1(a) and those γ-rays that are in coincidence with fast neutrons are shown in Fig. 1(b). After subtracting a background in coincidence with slow neutrons, only γ-rays in ^{29}P are observed from the $^{27}Al(^{3}He,n)^{29}P$ reaction. The figure includes decay schemes showing the spins and parities of the lowest excited levels in ^{27}Al and ^{31}P. As the ground state of ^{27}Al is $5/2^{+}$, only $5/2^{+}$ states should be populated in ^{29}P if the transitions are all $L=0$. However the $3/2^{+}$ excited states are strongly populated as well as the $5/2^{+}$ states. The lowest excited states in ^{27}Al are the 844 keV level with spin $½^{+}$ and the 1014 keV level with spin $3/2^{+}$. To populate the $3/2^{+}$ states directly would require an $L=2$ transition to give $\Delta\pi=0$ but allow the change in spin. The 1014 keV level in ^{27}Al has a strong inelastic connection to the ground state of ^{27}Al by the 1014 keV line seen in all in-beam γ-ray spectra, where neutrons are produced, which inelastically scatter off the Al in the HPGe cryostats. The experimental data suggests that the incoming ^{3}He must Coulomb or inelastically excite the target nucleus to the 1014 keV $3/2^{+}$ state in ^{27}Al and then subsequently have $L=0$ two proton transfer to the $3/2^{+}$ states in ^{29}P.

3.2. $^{29}Co(^{3}He,n)^{31}Cu$

In Fig. 2 we show the spectrum of γ-rays in coincidence with fast neutrons from the $^{59}Co(^{3}He,n)^{61}Cu$ reaction. The target nucleus ^{59}Co has one proton hole in the $f_{7/2}$ shell and four neutrons in the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals from a simple shell model perspective. The target nucleus therefore has spin-parity $7/2^{-}$ so the $L=0$ transitions should only populate the $7/2^{-}$ levels in ^{61}Cu at 1310, 1733 and 1942 keV. Indeed, Fig. 2 shows that these are the strongest states that are populated. Again, on a simplistic shell model and assuming that the levels at 1099, 1434 and 1483 keV in ^{61}Cu contain all the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ single particle strengths respectively, then the population of the $7/2^{-}$ levels in ^{61}Cu should be in the ratio 4: 2: 6. Experimentally we find the ratio is 4: 2.56(0.56): 4.6(1.2).

However we observe that levels with spins not equal to $7/2^{-}$ in ^{61}Cu are also populated. The $3/2^{-}$ levels at 970 and 1394 are also observed although the 970 level is fed strongly by $7/2^{-}$ levels. Also the first excited $½^{-}$ state at 475 keV and a $9/2^{-}$ level at 2612 keV in ^{61}Cu are also populated. The $3/2^{-}$, $5/2^{-}$and $9/2^{-}$ levels would require $L=2$ transitions to ensure no change in parity. The $1/2^{-}$ state at 475 keV requires an $L=4$ transition to populate it. Again, the experimental data suggests that the incoming ^{3}He must Coulomb or inelastically excite the target nucleus. The states in the target nucleus that can be excited by the incoming ^{3}He projectile are the $9/2^{-}$ level at 1190 keV, the $3/2^{-}$ level at 122 keV and the $1/2^{-}$ state at 1434 keV (see Fig. 2).

Table 2. Intensities of two proton stripping to levels in ^{150}Sm

Level	E_{γ} (keV)	Counts in Peaks ^{150}Sm		Relative Intensities ^{150}Sm	
		Γ-rays	Fit to T-o-F	Γ-rays	Fit to T-o-F
0_1^{+}	0	--	469(25)	--	271(25)
2_1^{+}	334	1728(77)	173(20)	100(5)	100
$4_1^{+} + 0_2^{+}$	439	585(56)	38(10)	34(4)	22(6)
6_1^{+}	506	218(38)	--	13(2)	--

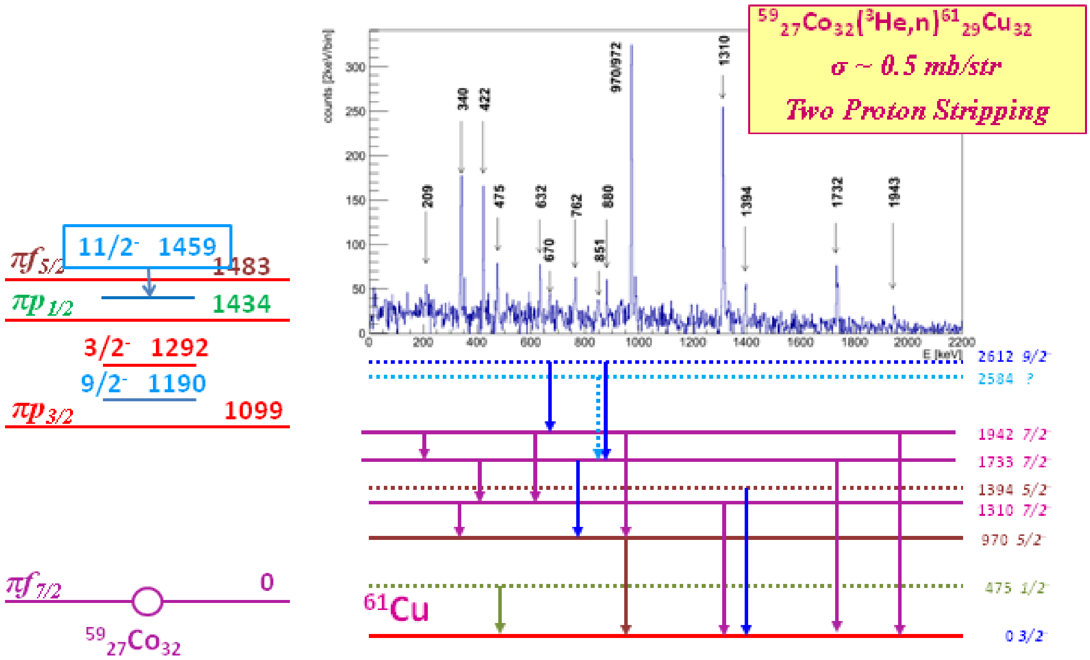

Fig. 2. Spectrum of γ-rays in ^{61}Cu from the two proton stripping direct reaction ^{59}Co(^{3}He,n)^{61}Cu at 22.5 MeV. The decay scheme for ^{61}Cu below the spectrum identifies the γ-rays observed. Low lying levels in the target nucleus ^{59}Co are shown on the left.

3.3. ^{148}Nd(^{3}He,n)^{150}Sm

The γ-rays that we observe in coincidence with fast neutrons from the ^{148}Nd(^{3}He,n)^{150}Sm reaction are shown in Fig. 3. A background has been subtracted of γ-rays in coincidence with slower neutrons. The spectrum contains only a few γ-rays belonging to the ground-state band in ^{150}Sm and the 0_2^+ state which is only very weakly populated. We are surprised to see the yrast states so clearly. The neutron detectors are strongly selecting *L=0* states and the only way the yrast 2^+, 4^+ and 6^+ states should be populated is by *L = 2, 4* and *6* transitions respectively. Again the experimental data suggest that the incoming ^{3}He must Coulomb or inelastically excite the target nucleus to the yrast 2^+, 4^+ and 6^+ states in ^{148}Nd and then subsequently have *L=0* two proton transfer to the yrast 2^+, 4^+ and 6^+ states in ^{150}Sm.

A problem with our experimental technique is that we do not detect the two-proton stripping to the ground state as it does not decay by γ-rays. However a way of estimating the absolute yields is to fit our relative yields of excited states to the line shapes of the low resolution Time-of-Flight (T-o-F) data in Ref. [6]. It is noticeable that the line shapes of the ground state peaks of the various (^{3}He,n) reactions illustrated in Fig. 1 of Ref. [6] show considerable variation. In particular the peak for the ^{150}Nd(^{3}He,n)^{152}Sm reaction is two channels wider than that leading to ^{150}Sm. The ^{152}Sm peak is sharp on its higher energy side and then has a tail on its lower energy side, whereas the ^{150}Sm peak is sharp with a discontinuity on its lower energy side. The shapes are compared in Fig. 4(a). We know that the yrast band in ^{150}Sm is excited up to the 6^+ level (see Fig. 3), which gives an explanation of the different line shapes in the T-o-F data. The nucleus ^{150}Sm is less deformed than ^{152}Sm, their 2_1^+ level energies being at 334 and 122 keV respectively. In Fig. 4(b) we show a fit to the peak seen in the T-o-F ^{148}Nd(^{3}He,n)^{150}Sm data at E_{lab} = 25.4 MeV and zero degrees which used a 9 m flight path and had a time resolution of 1 ns ~ 450 keV. The transitions to the ground 0_1^+ state and the first excited 2_1^+ state at 334 keV are barely resolved in the data of [6]. In the fit we have combined the intensities of the transitions from the 0_2^+ and 4_1^+ states decaying by γ-rays with energies of 406 and 440 keV respectively. In Table 2 we compare the relative intensities of the transition strengths to the lowest states in ^{150}Sm where we have normalized them to 100 for the 2_1^+ state. The data for the 4_1^+ state is in reasonable agreement for both the γ-ray data and the T-o-F data, considering the resolution of the latter and the difficulties in fitting such data. We conclude that the population of the 0_2^+ state is less than about 5% of the transition strength to the ground state. Taken with all the other data on 0_2^+ states, this supports the view that the 0_2^+ state is a neutron pairing isomer. In Fig. 4(c) we show a similar fit to the T-o-F data for ^{152}Sm. Although the ground and first excited 2_1^+ state at 122 keV are not resolved, the observed T-o-F line shape is convincingly fitted. It should be put on record that Ref. [6] had rather better data than they claimed!

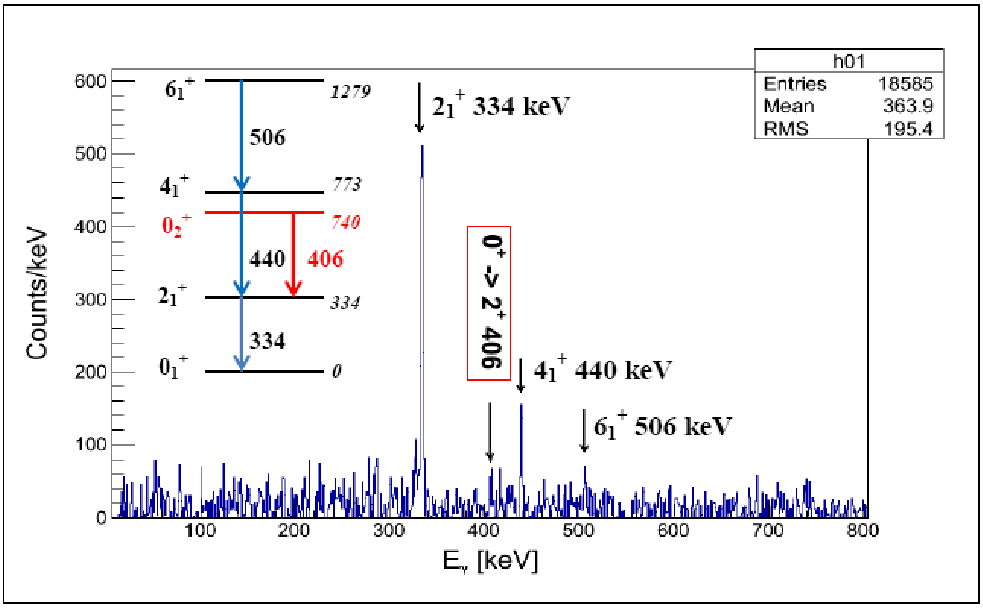

Fig.3. A spectrum of γ-rays from ^{150}Sm in coincidence with direct reaction fast neutrons from ^{148}Nd(^{3}He,n)^{150}Sm at E_{lab} = 25 MeV. A background spectrum in coincidence with slower neutrons has been subtracted. A decay scheme is shown inset of the lowest lying states in ^{150}Sm.

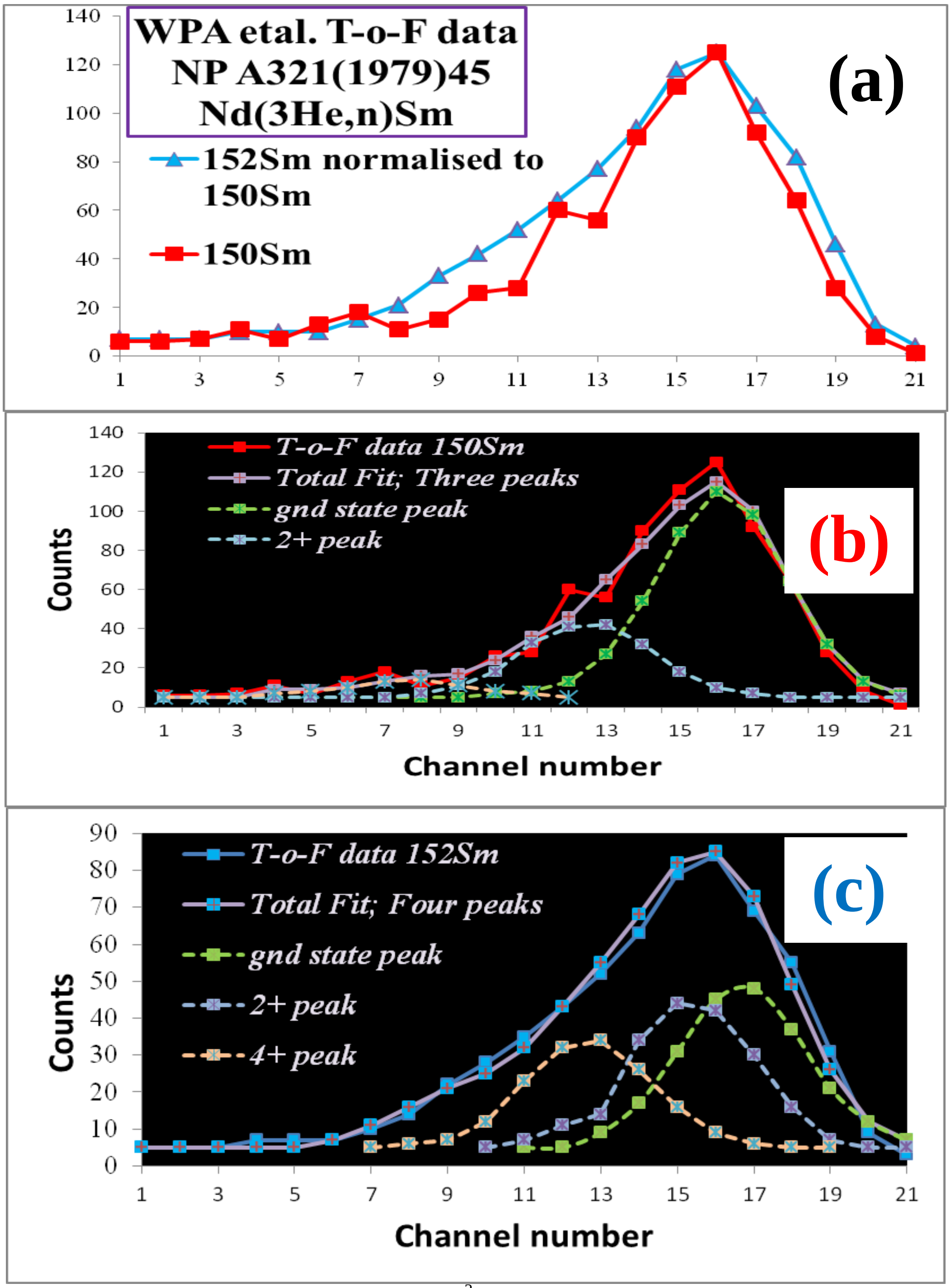

Fig. 4. Near ground state line shapes from Nd(^{3}He,n)Sm neutron Time-of Flight (T-o-F) spectra from Ref. [6]. (a) Comparison of the line shapes for the final nuclei ^{150}Sm and ^{152}Sm. (b) Fit to the ^{150}Sm data taking into account the intensities observed in Fig. 3. (c) A similar fit to the data for ^{152}Sm.

3.4. ^{160}Gd(^{3}He,n)^{162}Dy

In the fourth experiment reported here on ^{160}Gd(^{3}He,n)^{162}Dy at 22.5 MeV we saw the ground state band of ^{162}Dy populated clearly to 6^+ and weakly the 8^+. In Fig. 5(a) we show the total spectrum of γ-rays in coincidence with any neutron. The spectrum is dominated by the ^{160}Gd(^{3}He,3n)^{160}Dy reaction, with spins up to and beyond 10^+ being clearly observed. The 2^+ first excited state is strongly attenuated as we had to put absorber foils in front of the HPGe detectors to cut down the very high rate of X-rays. The spectrum of γ-rays in coincidence with fast neutrons from the ^{160}Gd(^{3}He,n)^{162}Dy reaction is shown in Fig. 5(b). The transition from the 2^+ state is again strongly attenuated due to the absorber foils. The γ-rays from the ground state band 4^+ and 6^+ levels are clearly seen and the transition from the 8^+ level is seen weakly. Yet again the data suggests that the target nucleus is Coulomb excited before $L=0$ two particle transfer take place.

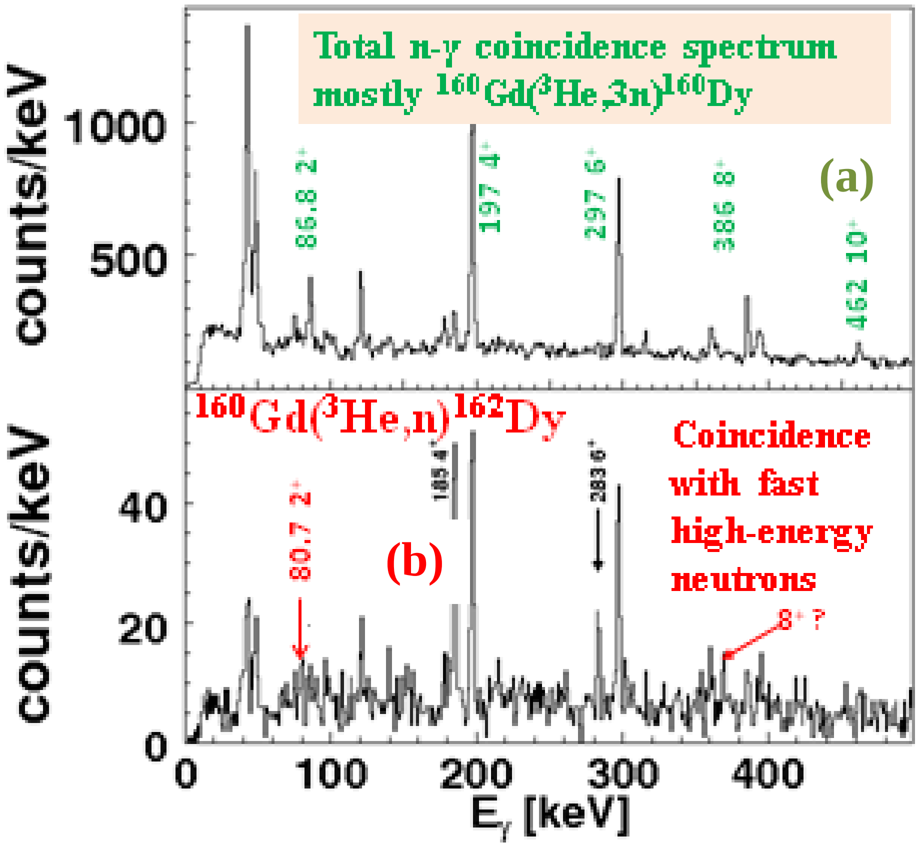

Fig. 5. Total projection (a) and gated by fast neutrons (b) spectra for the ^{160}Gd(^{3}He,xn) reaction at 22.5 MeV.

4. Discussion

Inelastic excitations in direct reactions have been studied extensively by Ascuitto and colleagues [9-11], in particular for two neutron transfer reactions (p,t) and (t,p) [9,10] and also for (p,d) and (d,p) [11]. Although their Coupled Channels Born Approximation (CCBA) analysis has been very successful in explaining how some states are populated, the relative cross-sections to such states and their anomalous angular distributions, this physics is not widely used in most reports of direct reaction measurements and in reviews of direct reaction mechanisms [12,13]. Indeed, more emphasis is placed on discussions of one-step (p-t) versus two-step (p-d-t) pick-up than on inelastic (p-p'-t) excitations.

In our ^{148}Nd(^{3}He,n)^{150}Sm experiment we see (Fig. 3) the yrast 2^+, 4^+ and 6^+ states in ^{150}Sm. The main fusion-evaporation channel in the reaction, ^{148}Nd(^{3}He,3n)^{148}Sm, populates states strongly up to at least twice the angular momentum at 12^+. The ^{148}Nd target is also relatively weakly excited by the incoming ^{3}He beam, the angular momentum transferred being much less than in the fusion-evaporation reaction. It is clear that the angular momentum associated with the (^{3}He,n) reaction is comparable with the inelastic scattering rather than with the fusion-evaporation reaction. The fits to the quasi-elastic peaks (Fig. 4(b&c)) seen in the Nd(^{3}He,n)Sm reaction T-o-F spectra of Ref. [6] show that the 2^+ states in the Sm isotopes are significantly excited, compared to the ground states (Table 2). The strength of the 2^+ population in the residual nuclei increases with deformation as the energies of the 2^+ states are lowered in the target nuclei. The outgoing neutron could inelastically excite the residual nucleus (^{3}He-n-n'), but to do this it would have to transfer sufficient angular momentum and be scattered to angles outside the range of our neutron detectors. For example, angular distributions of $L=6$ transitions, in the ^{120}Sn(p,t)^{118}Sn reaction at 21 MeV, peak at a scattering angle near 50º with differential cross-sections very much reduced compared to the $L=0$ differential cross-section at zero degrees [14]. It would therefore seem unlikely that the outgoing neutron contributes significantly to the inelastic excitation, especially as there will be no Coulomb component to the interaction with the nucleus.

The data from the other reactions, ^{27}Al(^{3}He,n)^{31}P, ^{59}Co(^{3}He,n)^{61}Cu and ^{160}Gd(^{3}He,n)^{162}Dy, support the (^{3}He-^{3}He'-n) interpretation. States that are populated that do not have spin $J = J_{target}$ all have the same spin J that can be strongly excited in the target by inelastic scattering. If a significant fraction of the cross-section to these states was due to a very weak fusion-evaporation channel (^{3}He,n)$_{f\text{-}e}$, then this channel would decay primarily to intermediate states, due to their high density, and not directly to states just above the ground state. Also there would not be the selectivity of the excited states that we observe in the final nuclei. The T-o-F line shapes of Ref. [6] help to demonstrate that the excited states we observe in ^{150}Sm are fed directly. In addition, the angular distributions of these composite quasi-ground state peaks have been accurately measured (see Fig. 8 of Ref. [6]) and are elegantly $L=0$ with exactly the same shape of the $L=0$ angular distribution to the ground state in the ^{142}Nd(^{3}He,n)^{144}Sm reaction, where the first excited 2^+ state at 1.68 MeV is well resolved from the ground state (see Fig. 5 of

Ref. [6]). Clearly we now have an experimental technique, with sufficient energy resolution, to check that this is so.

One advantage of detecting γ-rays is that their angular distributions can also be measured. The spins of all the states we have observed to date have been measured. But the expected γ-ray angular distributions can give a measure of the nuclear alignment imparted by the reaction. An $L=0$ transition cannot give any angular momentum to the final state different from that of the target state when the neutron is emitted. Hence all states populated directly in a one-step (^{3}He-n) process with $L=0$ will emit isotropic radiation as the target nuclei are not aligned. If, however, the target has undergone inelastic scattering *before* the one-step transfer of two protons (^{3}He-^{3}He'-n), then alignment will have been conferred to the target and the γ-rays will be anisotropic according to the nature of the inelastic process. In our present experiments we do not have enough statistics in the γ-ray spectra to check this.

Although forward-peaked angular distributions have been observed to states which should have $L>0$ in (t,p) reactions [9,15] and (d,p), (p,d) reactions [10] on W and Yb targets, forward peaking is not always observed in transitions involving hydrogen beams on deformed nuclei [15-20]. Beams of He ions have charge $Z=2e$ and will have a greater cross-section for inelastically exciting target nuclei, due to the Coulomb excitation probability being proportional to the square of the Sommerfeld parameter $\eta = Z_1Z_2e^2/\hbar v$ [21]. We expect the Coulomb interaction to be the predominant inelastic interaction at the beam energies considered here. One test of the inelastic conjecture is to carry out excitation functions at increasing beam energies to see if (^{3}He-^{3}He'-n) progressively populates the ground state bands at correspondingly increasing spins.

The original motivation for studying the ^{148}Nd(^{3}He,n)^{150}Sm reaction was to determine the two proton component of the wave function of the 0_2^+ state in ^{150}Sm at 740 keV. It is important to understand the exact wave function of this state [22] as it and the 0_2^+ state in ^{100}Ru are the only two states to be observed in double beta decay [23,24]. There had been a suggestion [25] that it might be a two proton pairing isomer [26], in which case it should have a sizeable cross-section in the (^{3}He,n) reaction. The very small population of this state (Fig. 2(a) and Table I) in two proton stripping negates this conjecture and supports the interpretation of the low-lying 0_2^+ states in N=88 and 90 nuclei as neutron pairing isomers [26-28]. Similar paring isomers have previously been observed in W nuclei [14,15].

In conclusion, we have presented strong experimental evidence that the (^{3}He,n) two proton stripping reaction can involve inelastic excitation of the target nucleus in cases where low-lying excited states are strongly coupled to the ground state of the target nucleus. To properly calculate the cross-sections and angular distributions of such reactions will require resuscitation of the Coupled Channels Born Approximation approach of Ascuitto and colleagues [9-11]. This result opens up the possibility of carrying out direct reaction experiments on low-lying states such as in the Mossbauer nuclei. We have also confirmed that the 0_2^+ state at 740 keV in ^{150}Sm is primarily a two neutron configuration with only a very small two proton component [29].

Acknowledgments

We would like to thank the National Research Foundation, the conference organisers and the University of the Western Cape, South Africa for financial support. We also thank the crew of the iThemba LABS Separated Sector Cyclotron for the ^{3}He beam and general assistance.

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] C. A. Ogilvie et al., Phys. Rev. **C39**, 139 (1989).

[3] J. L. Wood, Nucl. Phys. **A421**, 43c (1984).

[4] P. Papka et al., Proc. *LI* Int. Winter Meeting on Nucl. Phys., Bormio, Italy. PoS(Bormio2013)038.

[5] P. Jones et al., Proc. 2nd Heavy Ion Accelerator Symposium (HIAS2013), ANU Canberra, Australia; EPJ Web of Confs. **63** (2013) 01015.

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

[7] J. F. Sharpey-Schafer, Nucl. Phys. News. Int. **14**, 5 (2004).

[8] O. B. Tarasov and D. Bazin, NIM **B266**, 4657 (2008).

[9] R. J. Ascuitto and Bent Sørensen, Nucl. Phys. **A190**, 297 (1972).

[10] C. H. King, R. J. Ascuitto, N. S. Stein and Bent Sørensen, Phys. Rev. Lett. **29**, 71 (1972).

[11] R. J. Ascuitto, C. H. King and L. J. McVay, Phys. Rev. Lett. **29**, 1106 (1972).

[12] W. T. Pinkston and G. R. Satchler, Nucl. Phys. **A383**, 61 (1982).

[13] Masamichi Igarashi, Ken-ichi Kubo and Kohsuke Yagi, Phys. Rep. **199**, 1 (1991).

[14] P. Guazzoni, L. Zetta, A. Corvello, A. Gargano, B. F. Bayman, T. Faestermann, G. Graw, R Hertenberger, H.-F. Wirth and M. Jaskola, Phys. Rev. **C74**, 054605 (2006).

[15] M. H. Mortensen, R. R. Betts and C. K. Brockelman, Phys. Rev. **C21**, 2275 (1980).

[16] D. E. Nelson, D. G. Burke, J. C. Waddington and W. B. Cook, Can. J. Phys. **51**, 2000 (1973).

[17] G. Løvhøiden and D.G. Burke, Can. J. Phys. **51**,2354 (1973).

[18] M. Jaskoła, K. Nybø, P. O. Tjøm and B. Elbek, Nucl. Phys. **A90**, 52 (1967).

[19] H.-F. Wirth et al., Phys. Rev. **C69**, 044310 (2004).

[20] D. Bucurescu et al., Phys. Rev. **C73**, 064309 (2006).

[21] Carlos Bertulani, arXvi:0908.4307vl [nucl-th] 29 Aug 2009.

[22] S. P. Bvumbi et al., Phys. Rev. **C87**, 044333 (2013).

[23] A. S. Barabash, Ph. Hubert, A. Nachab and V. I. Umatov, Phys. Rev. C **79**, 045501 (2009).

[24] M. J. Hornish, L. De Draeckelear, A. S. Barabash and V. I. Umatov, Phys. Rev. C **74**, 044314.

[25] J. L. Wood, private communication.

[26] I. Ragnarsson and R. A. Broglia, Nucl. Phys. **A263**, 315 (1976).

[27] J. F. Sharpey-Schafer *et al*., Eu. Phys. J. **A47**, 5 (2011).

[28] J. F. Sharpey-Schafer *et al*., Eu. Phys. J. **A47**, 6 (2011).

[29] J. F. Sharpey-Schafer *et al*., Proc. Int. Nucl. Phys. Conf. (INPC2013) Florence, Italy; EPJ Web of Confs. **66**, 02116 (2014).