8 October 1998

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 437 (1998) 264–272

Competing $T = 0$ and $T = 1$ structures in the $N = Z$ nucleus $^{62}_{31}$Ga

S.M. Vincent [a], P.H. Regan [a], D.D. Warner [b], R.A. Bark [c,1], D. Blumenthal [d], M.P. Carpenter [d], C.N. Davids [d], W. Gelletly [a], R.V.F. Janssens [d], C.D. O'Leary [e], C.J. Lister [d], J. Simpson [b], D. Seweryniak [d], T. Saitoh [c], J. Schwartz [d,f], S. Törmänen [c,g], O. Juillet [h], F. Nowacki [i], P. Van Isacker [h]

[a] Department of Physics, University of Surrey, Guildford, GU2 5XH, UK
[b] CCLRC Daresbury Laboratory, Warrington, WA4 4AD, UK
[c] Niels Bohr Institute Tandem Accelerator Laboratory, Risø, DK-4000 Roskilde, Denmark
[d] Physics Division, Argonne National Laboratory, 9700 South Cass Ave, Argonne, IL 60439, USA
[e] School of Sciences, Staffordshire University, Stoke-on-Trent, ST4 2DE, UK
[f] A.W. Wright Nuclear Structure Laboratory, Yale University, New Haven, CT 06511, USA
[g] Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[h] GANIL, BP 5027, F-14076 Caen Cedex 5, France
[i] Laboratoire de Physique Théorique, F-67084 Strasbourg Cedex, France

Received 18 May 1998; revised 30 July 1998
Editor: J.P. Schiffer

Abstract

The low-lying levels in the odd-odd $N = Z$ nucleus ^{62}Ga have been identified for the first time. These data reveal a cascade of stretched-E2 transitions based on a $T = 0$, 1^+ bandhead which decays directly to the $T = 1$, 0^+ ground state. The observed levels are interpreted in the context of theshell model, using as a basis, the $pf_{5/2}g_{9/2}$ orbits with a ^{56}Ni core.

PACS: 21.10.-k; 21.10.Hw; 21.60.Cs; 27.50.+e
Keywords: Isospin; N = Z; Levels; Shell model

The study of odd-odd nuclei with equal numbers of protons and neutrons can provide a unique insight into the nature of pairing correlations in atomic nuclei. In medium and heavy mass nuclei near the line of stability, the relative displacement of neutron and proton Fermi surfaces implies that the correlations occur between pairs of like nucleons in time-reversed orbits. However, when the quantum states available to each type of nucleon coincide, charge independence of the nuclear interaction mandates that neutron-proton (np) pairs with isospin $T = 1$ must compete on an equal footing with their like-nucleon counterparts. Moreover, np pairs can also have $T = 0$ (parallel spins in contrast to $T = 1$ where they are anti-parallel) and this may give rise to a different type of pairing correlation which competes

[1] Present address: Dept. of Nuclear Physics, R.S.Phys.S.E., Australian National University, A.C.T. 0200 Australia.

PII: S0370-2693(98)00994-0

with the usual $T=1$ mode. The empirical effects of this competition are likely to be most evident in odd-odd nuclei by virtue of the reappearance of a pairing energy gap, associated with this alternative collective mode [1].

While the generalisation of pairing to incorporate *np* pairs has been investigated for nuclei in the *sd* and beginning of the *pf* shells in a Hartree-Fock-Bogoliubov (HFB) approach [2], it has recently been pointed out [3,4] that problems arise due to the lack of isospin invariance in this framework. In particular, in the HFB solutions for light nuclei, only one pairing mode dominates in the ground state, either $T=0$ or $T=1$, $T_z = \pm 1$. More recent studies [3–5] have demonstrated that mixing between $T=0$ and $T=1$ modes and between $T_z = \pm 1$ and $T_z = 0$, $T=1$ modes is unavoidable in an isospin invariant approach. Moreover, the relative dominance of $T=0$ versus $T=1$ pairing in $N=Z$ systems has been shown [5] to be linked to the energy separation of the

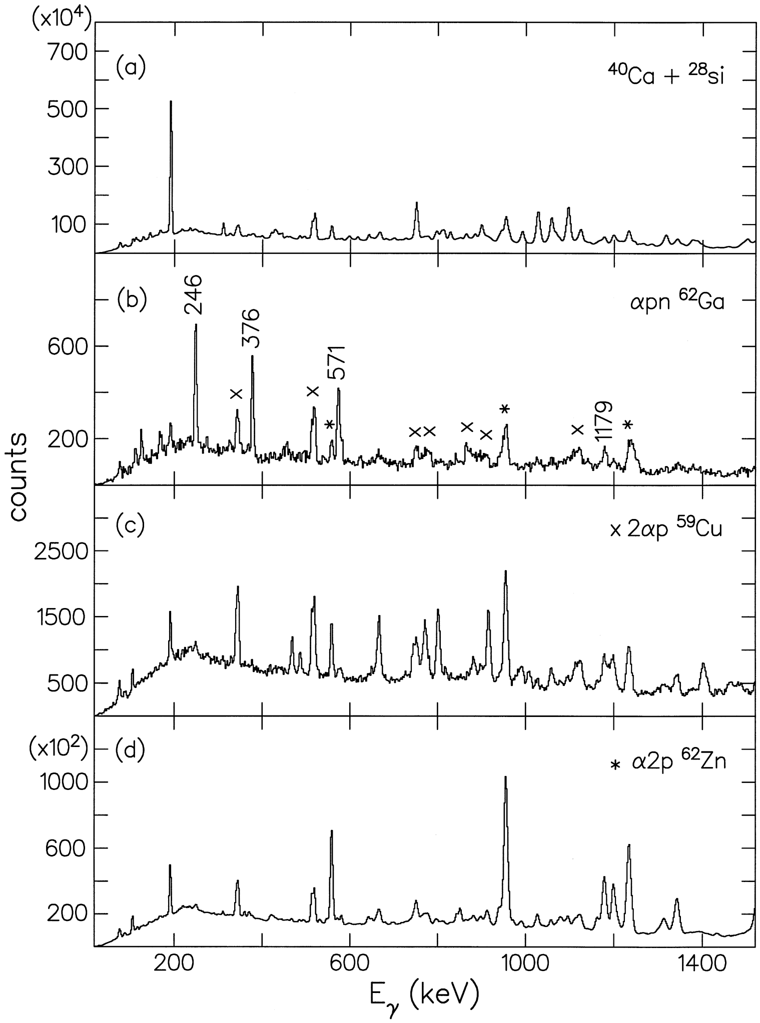

Fig. 1. (a) Total projection of the γ-γ matrix with no channel condition, the dominant peaks are from the 3p evaporation channel ^{65}Ga; (b) projection from the matrix selected by αpn showing the 246, 376, 571 and 1179 keV ^{62}Ga lines and contaminant lines from the α2p channel ^{62}Zn ($*$) and 2αp channel ^{59}Cu ($\times$); (c) projection from the matrix gated by the 2αp channel; (d) projection from the matrix gated by the α2p channel.

two types of pair and hence to the separation of the $T=0$ and 1 states in odd-odd $N=Z$ nuclei.

The ideal region in which to study these features is the $pf_{5/2}g_{9/2}$ shell where the shell is large enough to allow the development of collective features and the $N=Z$ line is still accessible experimentally, albeit at the limits of current sensitivity. In contrast to the situation in the *sd* shell, odd-odd $N=Z$ systems heavier than ^{40}Ca have $T=1$ ground states, the only known exception being ^{58}Cu. Above ^{58}Cu, little or no information on excited states exists, with the exception of the recently studied case of ^{74}Rb [6]. The purpose of this Letter is to provide the first experimental information on the decay scheme of ^{62}Ga and, most importantly, identify the lowest $T=0$ states.

Excited states in ^{62}Ga were populated following two separate fusion-evaporation reactions. Identification of transitions in ^{62}Ga was achieved using the reaction ^{40}Ca(^{28}Si,αpn)^{62}Ga, performed at the Niels Bohr Institute using an 88 MeV beam bombarding a 1 mg/cm^2 self supporting target of enrichment 99.96% in ^{40}Ca. Calculations using the fusion-evaporation code PACE [7] predict a cross-section of approximately 5 mb for the αpn channel, corresponding to around 1% of the total fusion cross-section. The γ-ray detection was afforded by the PEX spectrometer array [8], consisting of four, seven-element germanium cluster detectors [9] each with a BGO suppression shield. Two of the cluster detectors had their central crystals at an angle of 105° to the beam direction, with the other two being at 146°. Information on evaporated charged particles for channel identification was obtained using a 31-element silicon inner ball [10] surrounding the target position, in conjunction with an array of 15 BC501 liquid scintillator neutron detectors [11] positioned at forward angles. Suppressed γ-γ and higher fold germanium coincidence events were written to tape when accompanied by a silicon ball and/or neutron detector events and approximately 5×10^8 γ-γ coincidence events of this type were obtained.

Fig. 1a-d shows total projection spectra of the γ-γ coincidence matrices formed with several different channel selection criteria. The αpn channel leading to ^{62}Ga is shown in Fig. 1b and clearly identifies the

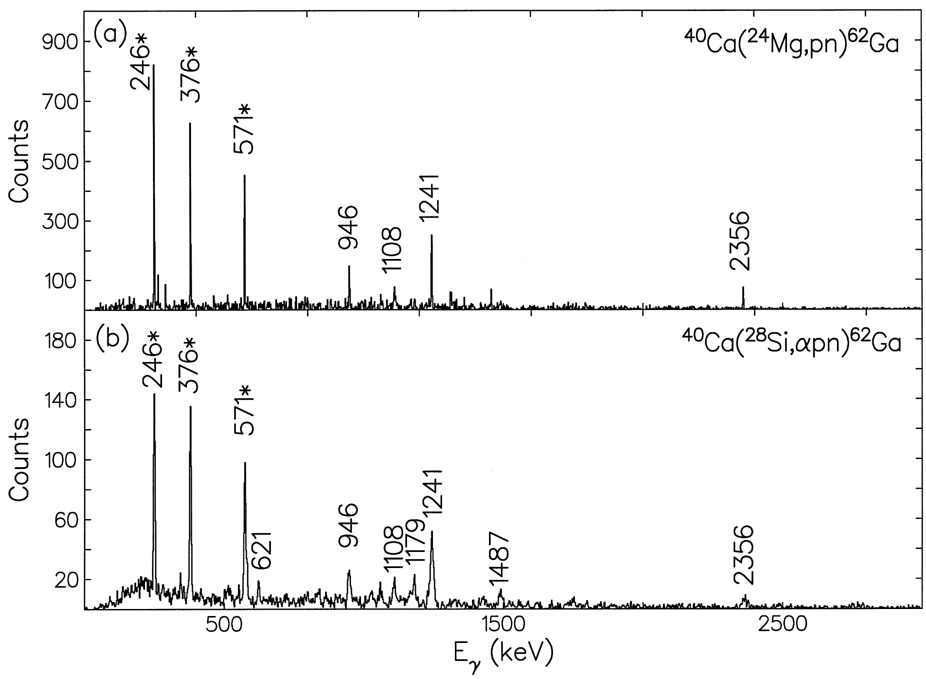

Fig. 2. Transitions in coincidence with the 246, 376 and 571 keV γ rays in ^{62}Ga (marked $*$) from (a) the AYEBALL gold-backed target data and (b) the αpn-gated PEX data.

transitions at 246, 376, 571 and 1179 keV, which we assign to ^{62}Ga. Contaminant lines from the α2p channel (^{62}Zn), and the 2αp channel (^{59}Cu), which appear from a combination of the finite detection efficiency of the silicon ball and the misidentification of γ-ray events in the neutron detectors are also clearly marked. The transitions associated with the ^{62}Ga gate are, in contrast, notably absent from the other two spectra.

States in ^{62}Ga were also populated at the Argonne National Laboratory using the reaction ^{40}Ca(^{24}Mg, pn)^{62}Ga at a beam energy of 65 MeV. Two targets of natural Ca were used, one of which had a thickness of 500 μg/cm^2 with 300 μg/cm^2 gold coating (to reduce oxidization) and 20 mg/cm^2 gold backing which stopped the residual nuclei at the target position, while the other had only a 60 μg/cm^2 backing and allowed the recoils to pass through to the Fragment Mass Analyser [12] where their A and Z could be determined, the latter with the aid of a split-anode, multi-wire ionisation chamber. Gamma rays from excited states were measured using the AYEBALL array [13] consisting of 18 high purity, Compton-suppressed germanium detectors, mounted in four annular rings, at angles 79°, 101°, 134° and 158° to the beam direction. Gamma-gamma coincidence events were written to tape and analysed off-line. The cross-section for the pn evaporation channel to ^{62}Ga was predicted by PACE [7] to be approximately 0.2 mb, or around 0.05% of the total fusion cross-section. In the run using the FMA, statistics were sufficient to associate γ rays with mass 62 but not good enough to unambiguously identify $Z = 31$ and hence the weak pn channel; accordingly, in the backed-target experiment, background-subtracted spectra were generated in coincidence with transitions identified using the PEX experiment. Fig. 2 shows a comparison of the γ-ray spectra in coinci-

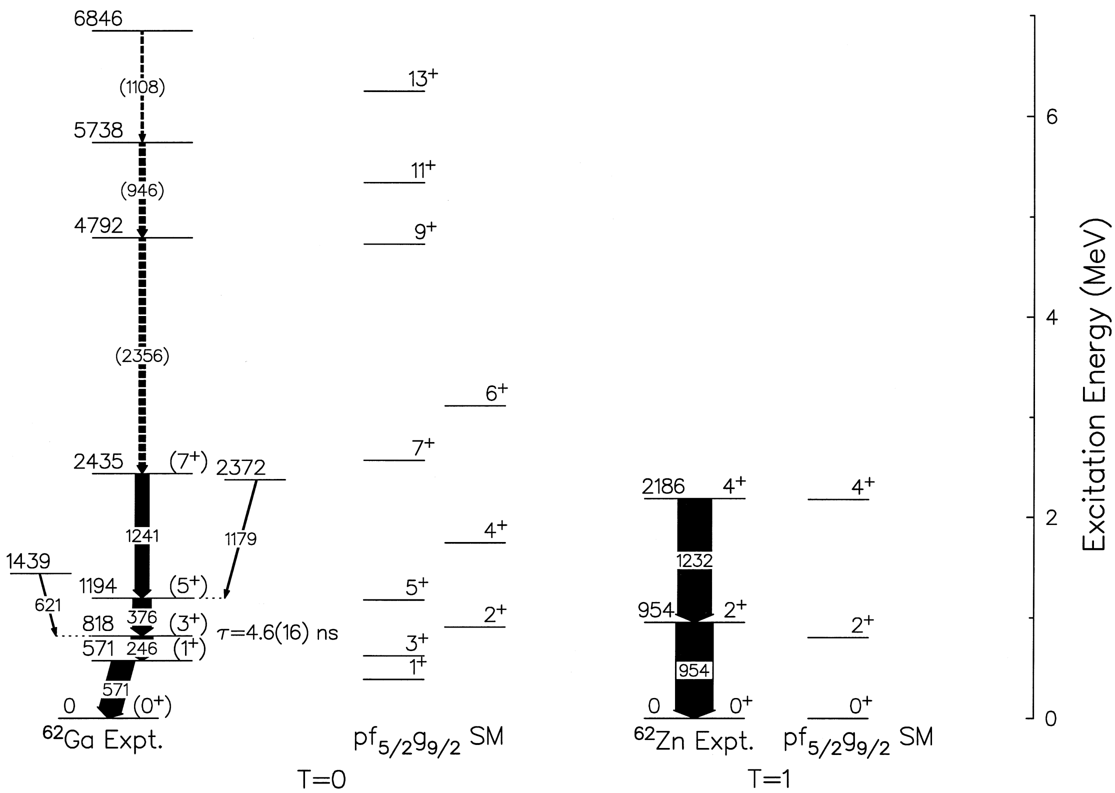

Fig. 3. Decay scheme derived for ^{62}Ga compared to the predictions of the $pf_{5/2}g_{9/2}$ basis shell model. $T = 0$ states are shown on the left, and $T = 1$ states are on the right. The low lying levels in the $T_z = 1$ isobar, ^{62}Zn are included for comparison. Tentative experimental assignments are denoted by dashed lines and parentheses.

dence with the 246, 376 and 571 keV transitions established in ^{62}Ga from both the AYEBALL backed target data and the αpn gated PEX data. A tentative γ-ray spectrum for ^{62}Ga has recently been reported by de Angelis et al. in a conference contribution, although no decay scheme was presented [14]. This spectrum is consistent with Fig. 2 in the current work.

The decay scheme for ^{62}Ga obtained in the current work is shown in Fig. 3 with a list of transition energies given in Table 1. An isomeric state with a mean-lifetime of 4.6 ± 1.6 ns was identified at an excitation energy of 818 keV, from the decay of ^{62}Ga reaction products which had implanted in the stopper foils placed in front of the silicon detectors in the charged particle detector. The lifetime was established using the recoil distance decay technique. The αpn gated data were sorted such that γ rays detected in the pairs of clusters centred at 105° formed one spectrum and those at 146° formed another. These spectra, shown in Fig. 4, show the 571 keV peak centred at 146° to have both a shifted and an unshifted component in its lineshape. An analysis of the peak shape of the 246 keV transition in the 146° gated spectrum shows that this line is also of a two-component nature. The unshifted γ-decays come from ^{62}Ga recoils which have embedded in the stopper foils. The measured ratio of counts in the moving and stopped peaks (1.08 ± 0.13) of the 571 keV transition combined with the target-stopper distance of 11.5 ± 1.4 mm and the recoil velocity of $0.014 \pm 0.002c$ yield the lifetime of the isomeric state after correcting for a $34 \pm 10\%$ loss of stopped decays due to the presence of a 3 mm diameter beam exit hole in the silicon ball. A check was made to test this method using the known isomeric state from the 2pn channel to ^{65}Ge, where the $\frac{9}{2}^+$ state decays via a 326 keV E1 [15], with a lifetime of 7(1) ns. The measured lifetime of this state was found to be consistent with the quoted lifetime.

Multipolarities for transitions identified in ^{62}Ga were made using a combination of γ-ray anisotropies from the PEX experiment and a DCO ratio analysis from the backed target AYEBALL data. The angle gated spectra from the PEX experiment as shown in Fig. 4 were used to obtain γ-ray anisotropies using the method described in Ref. [16]. A γ-ray anisotropy A was defined such that

$$A = 2\left(\frac{W(146°) - W(105°)}{W(146°) + W(105°)}\right) \quad (1)$$

where $W(146°)$ and $W(105°)$ are the efficiency corrected intensities measured in the cluster detectors centred at 146° and 105°, respectively. A clear separation was shown between γ rays of a stretched E2 and pure dipole nature with the weighted average for the measured anisotropies for known stretched E2 transitions in ^{62}Zn [17] and ^{65}Ga [18] being 0.20 ± 0.01, compared with -0.16 ± 0.02 obtained for the

Table 1
Transitions identified in ^{62}Ga in the current work. The transition energies and R_{dco} values are taken from the AYEBALL backed target data

E_γ (keV)	Intensity	$E_i \to E_f$ (keV)	$I_i \to I_f$	R_{dco} (376 gate)	R_{dco} (571 gate)
246.3	213(20)	818 → 571	$(3^+) \to (1^+)$	0.98(10)	1.52(11)
376.4	180(20)	1194 → 818	$(5^+) \to (3^+)$		1.87(33)
571.2	225(20)	571 → 0	$(1^+) \to (0^+)$	0.66(8)	
621.4	10(5)	1439 → 818	$(4) \to (3^+)$		
946.3	58(10)	(5738 → 4792)			
1108.3	21(3)	6846 → 5738			
1178.5	12(3)	2372 → 1194	$(6) \to (5^+)$		
1241.3	136(10)	2435 → 1194	$(7^+) \to (5^+)$	1.06(15)	1.24(33)
1486.5	<10				
2356.3	61(8)	(4792 → 2435)			
			E1[a]	0.62(2)	0.92(6)
			E2[a]	0.95(3)	1.60(33)

[a] Weighted average of values obtained from previously assigned transitions in ^{61}Cu.

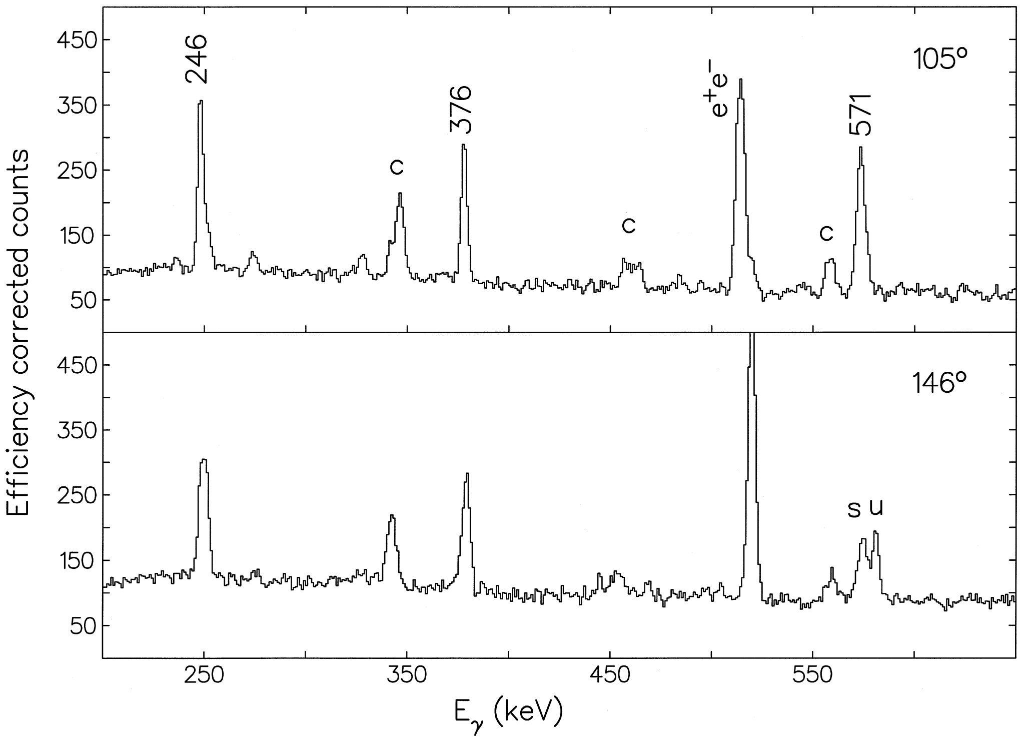

Fig. 4. Efficiency corrected angular γ-ray projections from the PEX data gated by the 1 alpha, 1 neutron and either 0 or 1 protons showing γ rays in ^{62}Ga. The 246 keV and the 571 keV peaks have a shifted (s) and an unshifted (u) component due to the isomeric nature of the feeding state at 818 keV. Contaminant lines from ^{59}Cu and ^{62}Zn (as shown in Fig. 1) are marked (c).

$\Delta I = 1$ dipole decays. The anisotropy obtained for the 376 keV line in ^{62}Ga was found to be 0.14 ± 0.06, consistent with a stretched E2 decay.

Multipolarities for the other transitions in ^{62}Ga were then derived from DCO ratios [19] using the backed target AYEBALL data. In this analysis, a γ-γ coincidence matrix was constructed with events measured in detectors at 158° versus events in any of the 79°, 101° or 134° detectors. By gating on a transition of known multipolarity on each axis of this matrix in turn and measuring the efficiency corrected relative intensity of the projected γ rays on the other axis, the DCO intensity ratios, R_{dco} shown in Table 1 were obtained. Again, coincidences between previously assigned stretched E2, $\Delta I = 1$ E1 and $\Delta I = 1$ M1 transitions from the strongly populated channel of ^{61}Cu [20] were used to verify and calibrate this method. Fig. 5 shows the DCO projection spectra gated by the 376 keV and the 571 keV transitions in turn. It is clear that whilst the 246 keV and the 1241 keV lines are the same intensity in both projections of the 376 keV gate, the 571 keV lines are different. Also, although the 246, 376 and 1241 keV transitions gated by the 571 keV transition are different in the two projections, they have the same relative intensities in each case. Table 1 shows the R_{dco} values for gates set on the 571 keV and 376 keV lines in ^{62}Ga from the backed target, AYEBALL data. Assuming a stretched E2 multipolarity for the 376 keV transition (from its measured anisotropy in the PEX data), the 571 keV transition has a DCO ratio consistent with $\Delta I = 1$. By comparison, the ratios obtained for the 246 keV and the 1241 keV transitions are consistent with stretched quadrupole decays.

The ordering of the γ rays above the isomer comes from their measured γ-γ coincidence intensities, in the backed target AYEBALL data, normalised to the intensities of the 246, 376 and 571 keV lines in the PEX data, αpn gated total projec-

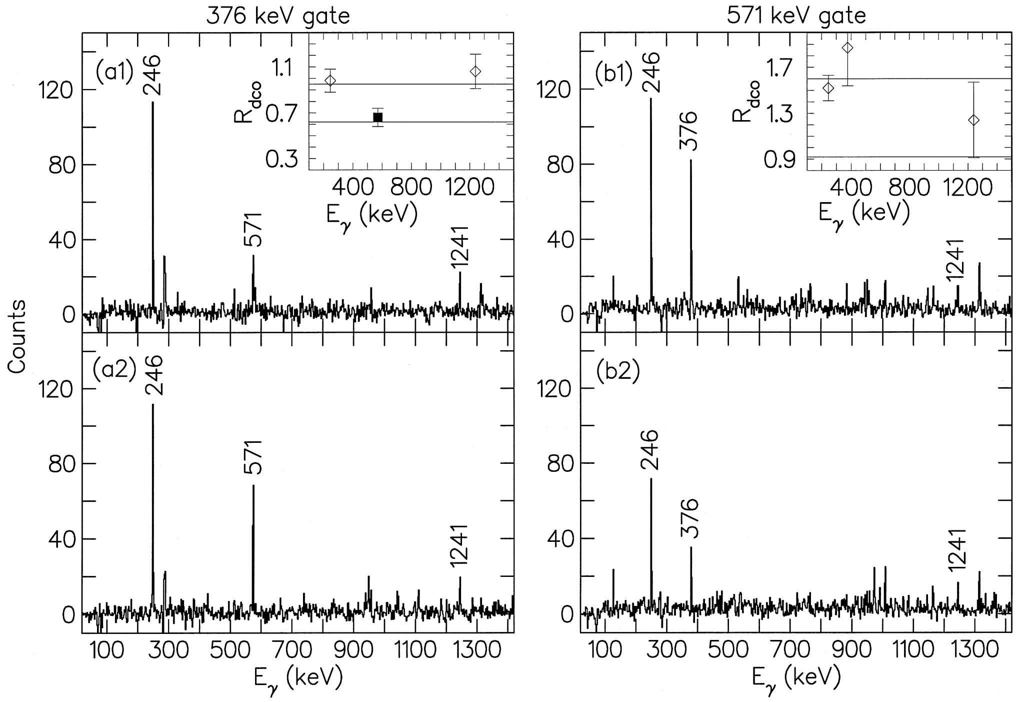

Fig. 5. DCO projections from the gold-backed target AYEBALL data, efficiency corrected for gate and projection energy. Projected from the A = 62 gated DCO matrix, gated by; (a) the 376 keV transition and (b) the 571 keV transition. (1) gated at 79° + 101° + 134°, and projected onto the 158° axis; (2) gated at 158°, and projected onto the 79° + 101° + 134° axis. The insets show the DCO values of the projected transitions in the 376 keV and the 571 keV gate, with weighted averages of transitions of known multipolarity indicated as lines (see text). Open diamonds are assigned as quadrupoles, the filled square is assigned as a dipole. This data is tabulated in Table 1.

tion. The intensity of the 946 keV and 2356 keV transitions are the same within experimental uncertainties and hence their ordering can not be determined with absolute confidence. Note that while the intensities of the 571 keV dipole and the 246 keV stretched quadrupole are the same within experimental errors, we strongly favour the placement of the 571 keV line below the 246 keV transition on the basis of transition rate arguments. The measured lifetime of the excited state at 818 keV of 4.6 ± 1.6 ns, corresponds to a transition strength of $7.3 \pm 2.5 \times 10^{-7}$ Wu or $1.0 \pm 0.4 \times 10^{-5}$ Wu for a 571 keV E1 or pure M1 respectively. While both are possible in principle, these values are very small compared with other measured transition strengths for similar multipolarity decays in this mass region [21]. However, the corresponding value of 13.5 ± 4.7 Wu for a 246 keV stretched electric quadrupole decay is very typical for the region [21].

The spin parity assignments are thus made assuming the 571 keV transition feeds the 0^+ ground state identified in previous beta decay studies [22] and the preferential population of near yrast states in fusion evaporation reactions. Given the difficulty of generating low-lying negative parity states from the available single particle orbitals, the 571 keV dipole transition would correspond to a pure magnetic dipole $1^+ \rightarrow 0^+$ decay with no E2 admixture. The experimentally derived DCO ratio for this transition when gated by an E2 transition is 0.66 ± 0.08, which is consistent with this picture.

Fig. 3 shows a comparison of the decay scheme proposed for ^{62}Ga with the low-lying states in the $T_z = 1$ isobar, ^{62}Zn [17]. In contrast to the ^{74}Rb/^{74}Kr pair [6], there is no observable population of the isobaric analogue states in the odd-odd nucleus. However, due to its lower deformation, the first excited state in ^{62}Zn lies at 942 keV so that, if the

Table 2
Values of $B(E2;3^+ \rightarrow 1^+)$ in $e^2 fm^4$

Shell model ($pf_{5/2} g_{9/2}$)	Shell model ($pf_{5/2}$)	Experiment
139	89	197(69)

assumption of the direct feeding of a 0^+ ground state from a $T=0$ state in ^{62}Ga is correct, then the first 2^+, $T=1$ state is likely to be non-yrast.

The observed levels in ^{62}Ga and the lowest isobaric analogue states in ^{62}Zn have been interpreted using a shell model analysis. There are two natural shell-model spaces that can be adopted for ^{62}Ga: one consists of the entire *pf* shell with a ^{40}Ca core and the second of the $pf_{5/2} g_{9/2}$ orbits with a ^{56}Ni core. We have found that the latter gives superior results and these are shown in Fig. 3. The effective interaction is a realistic *G* matrix whose monopole part has been phenomenologically adjusted and which has been used previously in ^{76}Ge and ^{82}Se [23]. Calculations are done with the shell-model code ANTOINE [24]. The difference between the $T=0$ and $T=1$ states is well reproduced as is the band structure on top of the 1^+ state. The shell model gives levels with spin 9^+, 11^+ and 13^+ at energies of 4728, 5339 and 6249 keV, respectively, which are close in energy to the levels observed above the 7^+ state. Moreover, as shown in Table 2, the calculated value of B(E2;$3^+ \rightarrow 1^+$) agrees with that deduced from the measured mean life of the 818 keV level.

A second shell model calculation has been performed, using the model space and interaction of [25] which is restricted to $pf_{5/2}$. Not surprisingly, the restricted-basis shell model calculation does not match the quality of agreement with the experimental data offered by the $pf_{5/2} g_{9/2}$ shell model calculation. Indeed, this restricted-basis calculation does not reproduce either the predicted B(E2) value (given in Table 2), or the regularity and spacing of the 1^+ band. Judging by this, it would seem that, even at this low mass, the $g_{9/2}$ intruder orbital is important in providing the required degree of collectivity.

A similar origin may be attributed to another feature of the data presented here, which show that the $T=0$ states lie 571 keV above the $T=1$ ground state in ^{62}Ga. This can be viewed in the context of the $T=0$ ground state in ^{58}Cu and the higher lying (1006 keV) first $T=0$ state in ^{74}Rb, so that a picture begins to emerge of a gradual rise in the excitation energy of the $T=0$ states as mass increases along the $N=Z$ line in this shell, this rise being accompanied by a gradual reduction in the contribution of $T=0$ pairs. The wave functions of the $pf_{5/2} g_{9/2}$ shell model calculations show significantly larger components of the $g_{9/2}$ orbital in the $T=1$ states, suggesting that it may be the stronger attractive interaction in this intruder orbital which is responsible for the gradual favouring of the $T=1$ ground state as the shell is filled.

Clearly, the overall degree of collectivity is limited in ^{62}Ga, and more information on non-yrast states would be necessary to distinguish the presence of any degree of coherent n-p pairing. However, while the full shell model calculation gives a very satisfactory result in this nucleus, such a method will become increasingly intractable as the number of valence nucleons, and hence collectivity, increases along the $N=Z$ line. For this reason, a further calculation has been performed in the framework of an isospin invariant form of the Interacting Boson Model [26] which involves both $T=0$ and $T=1$ *np* bosons. The model is referred to as IBM-4 [27], and the results will be published separately [28].

Acknowledgements

This work has been partially supported by the Franco-British Alliance Grant No. PN 96-058, and the Engineering and Physical Sciences Research Council.

References

[1] D.D. Warner, Perspectives for the Interacting Boson Model, in: R.F. Casten et al. (Eds.), World Scientific, Singapore, 1988, p. 373.
[2] A.L. Goodman, Adv. Nucl. Phys. 11 (1979) 263.
[3] D.J. Dean, S.E. Koonin, K. Langanke, P.B. Radha, Phys. Lett. B 399 (1997) 1.
[4] J. Engel, K. Langanke, P. Vogel, Phys. Lett. B 389 (1996) 211.
[5] P. Van Isacker, D.D. Warner, Phys. Rev. Lett. 78 (1997) 3266.
[6] D. Rudolph et al., Phys. Rev. Lett. 76 (1996) 376.
[7] F. Pühlhofer, Nucl. Phys. A 280 (1977) 267.
[8] H. Grawe et al., Z. Phys. A 358 (1997) 185.

[9] C.W. Beausang, J. Simpson, J. Phys. G 22 (1996) 527.
[10] T. Kuroyanagi et al., Nucl. Instr. and Meth. A 316 (1992) 289.
[11] S.E. Arnell et al., Nucl. Instr. Meth. A 300 (1991) 303.
[12] C.N. Davids, B.B. Back, K. Bindra, D.J. Henderson, W. Kutschera, T. Lauritsen, Y. Nagame, P. Sugathan, A.V. Ramayya, W.B. Walters, Nucl. Instr. Meth. B 70 (1992) 358.
[13] M.P. Carpenter, Z. Phys. A 358 (1997) 261.
[14] G. de Angelis at al., Nucl. Phys. A 630 (1998) 426c.
[15] D. Sohler et al., Z. Phys. A 357 (1997) 239.
[16] K.R. Pohl et al., Phys. Rev. C 53 (1996) 2682.
[17] K. Furutaka et al., Z. Phys. A 358 (1997) 279.
[18] M.R. Bhat, Nucl. Data Sheets 69 (1993) 209.
[19] K.S. Krane, R.M. Steffen, R.M. Wheeler, Nucl. Data Tables 11 (1973) 352.
[20] C. Zhou, Nucl. Data Sheets 67 (1992) 271.
[21] P.M. Endt, Atomic Data and Nuclear Data Tables 23 (1979) 547.
[22] C.N. Davids, C.A. Gagliardi, M.J. Murphy, E.B. Norman, Phys. Rev. C 19 (1979) 1463.
[23] E. Caurier, F. Nowacki, A. Poves, J. Retamosa, Phys. Rev. Lett. 77 (1996) 1954.
[24] E. Caurier, code ANTOINE (1989).
[25] J.E. Koops, P.W.M. Glaudemans, Z. Phys. A 280 (1977) 181.
[26] F. Iachello, A. Arima, The Interacting Boson Model, Cambridge University Press, Cambridge, 1987.
[27] J.P. Elliott, J.A. Evans, Phys. Lett. B 101 (1981) 216.
[28] O. Juillet et al., to be published.