Spin-gap isomer in ^{96}Cd

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Abstract. Evidence has been obtained for the existence of the long predicted 16^+ spin-gap isomer in ^{96}Cd**.** The decay of the isomer was identified and studied following the use of an 850 MeV/u beam of ^{124}Xe impinging on a Be target and the fragment recoil separator at the GSI Laboratory. Gamma decays from the fragments were detected using the RISING gamma ray array, in its stopped beam configuration, plus a silicon active stopper. The data obtained have been compared with shell model predictions, which indicate that the isoscalar neutron-proton interaction plays a key role in the formation of the isomer.

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1. Introduction

It is well over a quarter of a century since calculations first predicted the existence of 16^+ and $25/2^+$ spin-gap isomers in ^{96,97}Cd, respectively [1, 2]. However, because of the exotic nature of these nuclides it is only recently that techniques and detector system developments have made it possible to search for the existence of these states. A recent MSU experiment has identified the presence of the $25/2^+$ isomer in ^{97}Cd [3] and our experiment at GSI has both confirmed the presence of that isomer as well as observed the first evidence for the existence of the 16^+ isomer in ^{96}Cd [4].

A more detailed study of the shell model calculations has been performed as part of the present work. This has revealed the importance of the isoscalar neutron-proton (np) interaction in lowering the energy of the 16^+ state to such an extent, relative to the 14^+ and 12^+ states, that it forms a "spin-gap" isomer. Figure 1 shows the results of shell model (SM) calculations performed using the Gross-Frenkel (GF) interaction [5] and a $p_{1/2}$,$g_{9/2}$ model space. The left hand column shows the results of such calculations when all interactions between pairs of protons (pp), neutrons (nn) and neutrons and protons (np) are taken into account. This clearly shows that the 16^+ state is lowered in energy. Furthermore, the E6 decay to the next lowest (10^+) state will not compete with beta or even beta-delayed proton decays from this state. The shell model calculations shown in the centre of Figure 1 have been performed with the same interaction and model space, but this time with the isovector (T=1) neutron-proton (np) interaction switched off. This was achieved by making the relevant matrix elements zero. In this case the 16^+ spin-gap isomer is observed to persist. However, if the T=1 np interaction is active, but the isoscalar (T=0) np interaction matrix elements are switched off then the spin-gap isomer is found to disappear (see Figure 1, right hand column), thus indicating the importance of the isoscalar np interaction in the formation of this isomeric state.

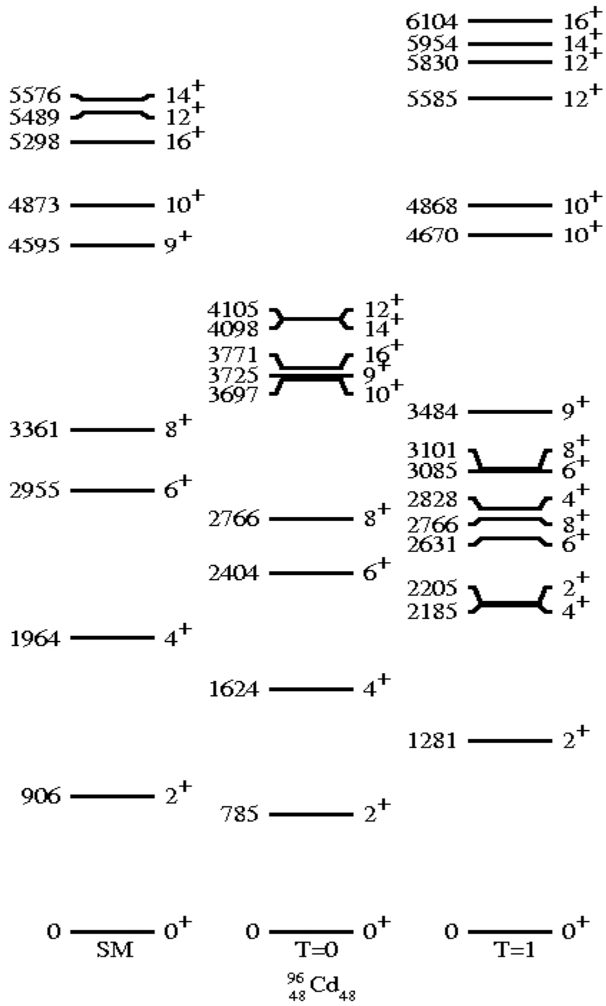

Figure 1. SM calculations using the GF interaction and the $p_{1/2}$,$g_{9/2}$ model space. Calculations labelled T=0 have the np T=1 matrix elements switched off, whilst those labelled T=1 have the np T=0 matrix elements set to zero. Those labelled SM have both T=0 and T=1 np interactions included as well as the T=1 nn and pp interactions.

The experimental verification of the existence of this state is therefore vital in order to provide evidence for the importance of this interaction at high spins in N=Z nuclei. This is particularly crucial given the recently reported evidence for the role played by the isoscalar np interaction in producing equally spaced level energies at low-spins in ^{92}Pd [6].

2. Experimental details

To search for evidence for the existence of the 16^+ isomeric state the ^{96}Cd nuclei were produced using a high energy fragmentation reaction. A 850 MeV/u ^{124}Xe beam impinging on a 4 g/cm^2 Be target, located at the entrance to the fragment recoil separator (FRS) at the GSI laboratory, was used for this purpose. The ^{96}Cd fragments were selected using the FRS and implanted into the middle of an active stopper consisting of 3 rows of 1mm thick Si detectors, with each row consisting of three detectors that had 16 X and 16 Y strips. Degraders were used to ensure that the ^{96}Cd ions, which were fully stripped of electrons, stopped in the central detector in the middle row. Figure 2 shows the implantation and decay maps for these ions along with the Z versus A/Q plot for the ion identification (note, Z=Q in this case since the ions were fully stripped). Further experimental details may be found in Refs. [6,7].

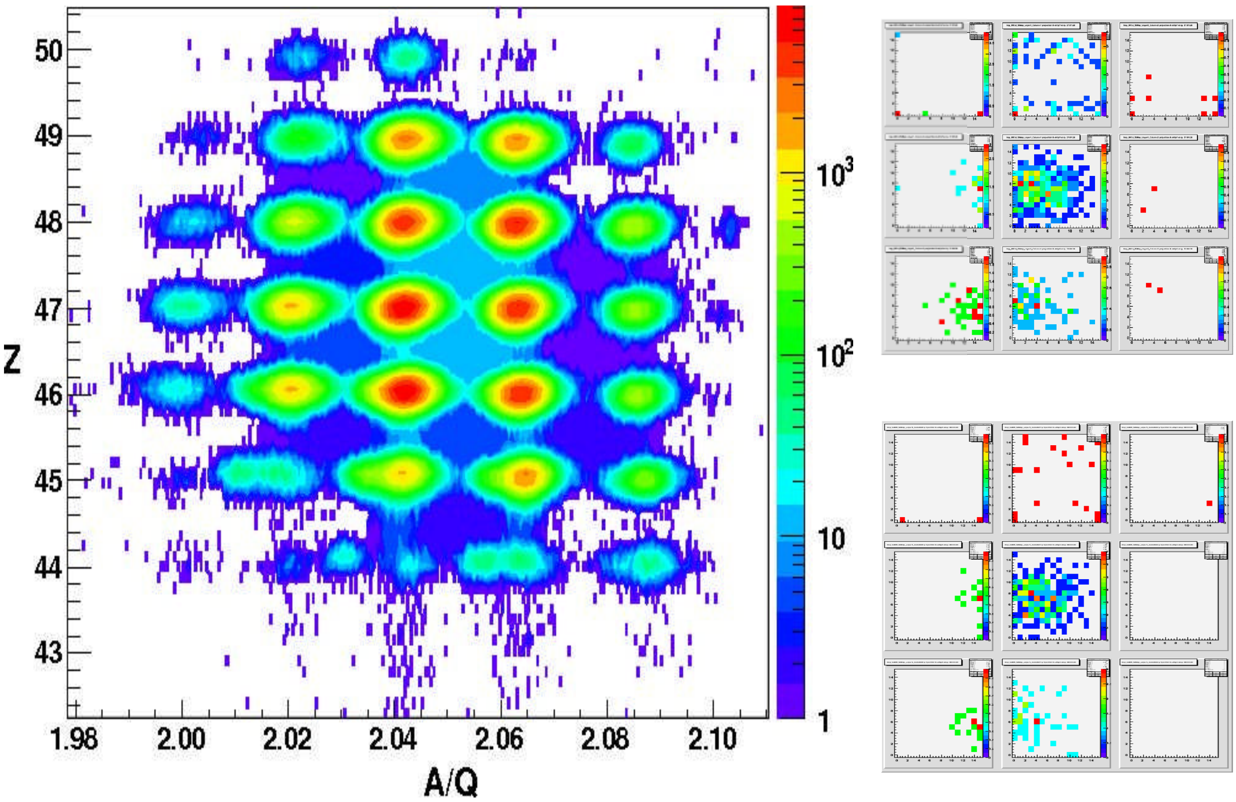

Figure 2. (Left) Particle identification plot. The ^{96}Cd ions are located at Z = 48, A/Q = 2.00. (Right – top) ^{96}Cd ion implantation map for the silicon active stopper. This reveals that most of the ^{96}Cd ions were stopped in the central detector in the middle row. (Right – bottom). Similar to right – top, but in this case the map shows decay events that are associated with the ^{96}Cd ions.

3. Results

Figure 3 (top) shows the prompt (0-200 ns) gamma ray spectrum following identification of a beta-decay signal in the central detector which is also correlated with ^{96}Cd ions within 1 second of implantation. The ^{96}Cd ions are located at Z = 48, A/Q = 2 in Figure 2. This spectrum reveals the expected 511 keV line from the annihilation radiation and a new, previously unobserved, line at 421 keV. The latter gamma ray is believed to result from the decay of the 1^+ state in ^{96}Ag, which is fed by the GT decay of the ^{96}Cd ground state, to the 2^+ state (see section 3). Figure 3 (bottom) shows those gamma rays that are delayed (0.2-4.0 μs) with respect to the beta-decay signal in the central detector, but remain correlated with the ^{96}Cd ions. In this case there is clear evidence for three gamma rays at 470, 667 and 1506 keV. These are the same three transitions that are observed following the decay of the recently observed (15^+) 1.5 μs isomer in ^{96}Ag [7,8]. Figure 4 summarises the decays that have been observed.

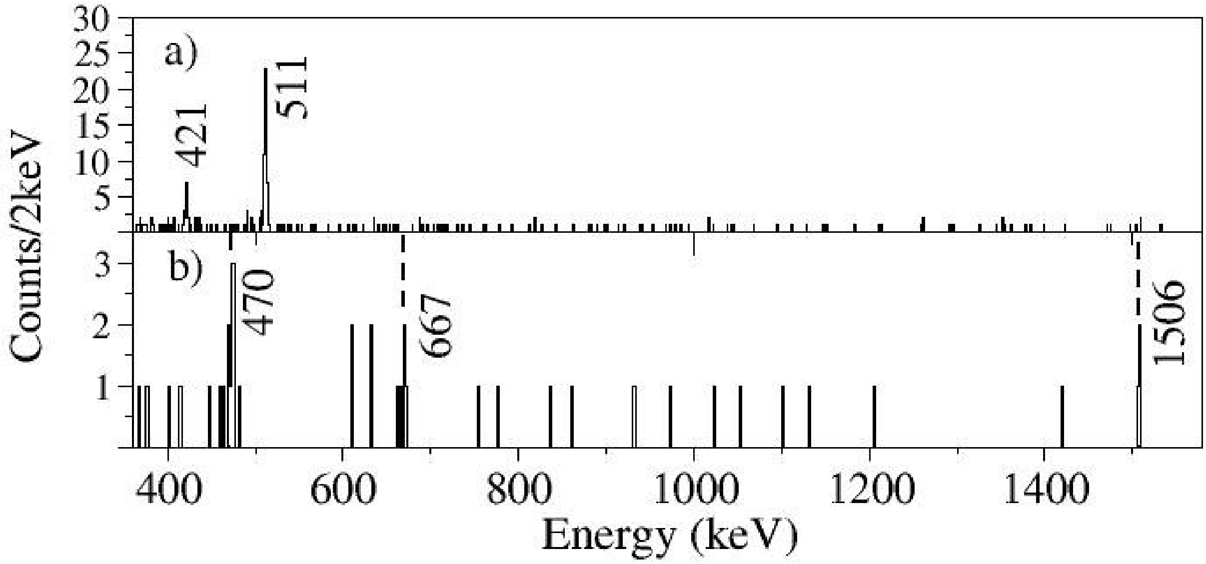

Figure. 3 Spectra showing gamma decays following implantation of ^{96}Cd ions into the geometrically central DSSSD detector of the active stopper and their subsequent beta decay. (Top) Events with gamma ray times between 0-200 ns following the beta signal detected in the DSSSD. (Bottom) Same as top spectrum except that the time between the beta and gamma ray events is now 0.2 – 4.0 μs.

4. Discussion

Shell model calculations using the Gross-Frenkel (GF) interaction or the SLGT0 interaction [9] and the $p_{1/2},g_{9/2}$ model space both predict the presence of a long lived, low lying 2^+ state in ^{96}Ag – see Table 1. Indeed with the SLGT0 interaction the 2^+ state is predicted to be the ground state rather than the 8^+ state, which is favoured by the GF interaction. However, the excitation energy of the 1^+ state relative to the 2^+ state in both cases is of the order of 350 – 400 keV. Thus, we believe that the 421 keV line represents the transition between these two states.

The observation of the GT decay of the 16^+ state in ^{96}Cd to the (15^+) isomer in ^{96}Ag provides strong evidence for the importance of the T=0 np interaction at moderate spins in this region. Moreover, it provides possibly even more convincing support to the arguments presented in Ref. [6] for the role of this interaction in determining the nuclear structure in N=Z nuclei in the mass 90 region. This result also confirms the early shell model calculations of Ogawa [2] and the predictions of Goodman [10], who suggested that the T=0 neutron-proton interaction should play a key role for N = Z nuclei in the mass 90 region.

The correlation time between the events in the 421 keV gamma ray shown in Figure 3 (top) and the ^{96}Cd ions implanted in the central silicon detector has been determined and fitted using a maximum likelihood method. The result produces a half-life of 0.67 ± 0.15 s, which is in reasonable agreement

Table 1. Shell model predictions of excitation energies of the lowest 1^+ and 2^+ states in ^{96}Ag using the GF and SLGT0 interactions.

Interaction	J^π	E_x (keV)
GF	1+	356
	2+	12
SLGT0	1+	382
	2+	0

with the previously published result for the decay of the ^{96}Cd ground state from MSU of . : s [11] and also with the result of 0.99 ± 0.13 s obtained by the ^{100}Sn experiment collaboration at GSI (see contribution by K Eppinger to this conference). The important point about the measurement from the present work is that we can be sure that it is not influenced by the decay of the isomer, which was not the case for the MSU work at the time of their publication.

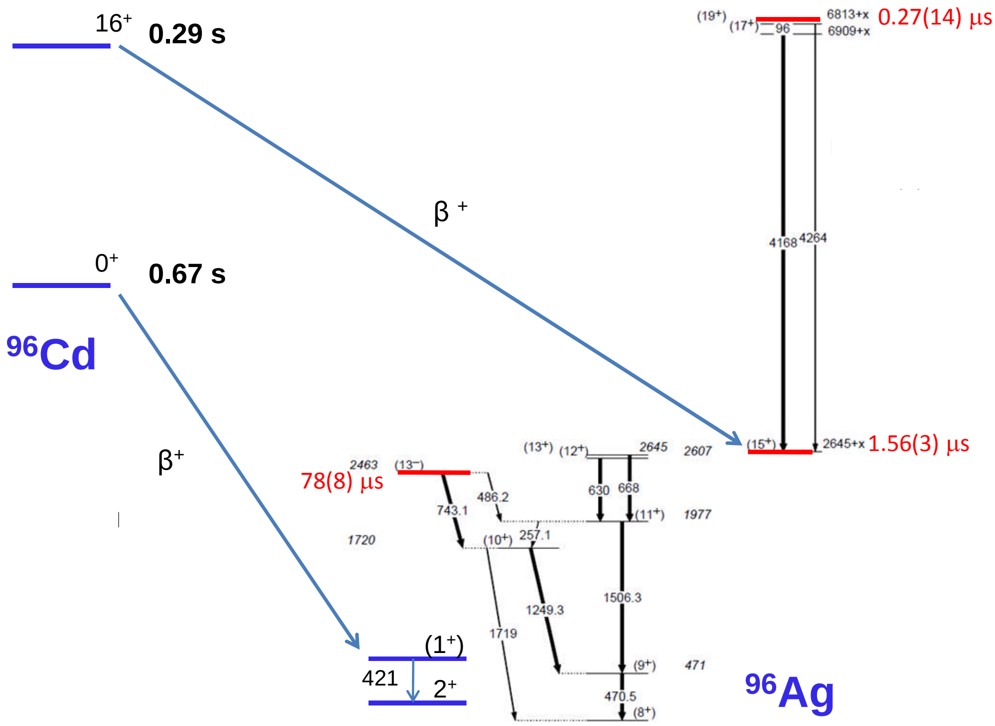

Figure. 4. Schematic figure showing the beta decay of the 16^+ spin-gap isomer and ground state of ^{96}Cd. Data for ^{96}Ag are taken from Ref. [7]. The energies of the 16^+, 0^+ states in ^{96}Cd are not to scale.

Similarly the time correlation between the events in the 470, 667 and 1506 keV gamma rays and the implanted ^{96}Cd ions was also determined [4]. Again, using a maximum likelihood method the results reveal that the lifetime for the 16^+ spin-gap isomer is . : s. This compares favourably to the value expected by Ogawa [2], which was of the order 0.5 s.

In the $p_{1/2},g_{9/2}$ model space the decay of the 16^+ spin-gap isomer in ^{96}Cd to the 15^+ isomer in ^{96}Ag takes 100% of the GT strength and the calculated B(GT) value is 0.14. The experimental value, obtained using our lifetime, is . : . This clearly agrees very well with the calculated value, albeit with large error bars. However, in order to investigate the effects of an extended (gds) model space large scale shell model (LSSM) calculations were performed (see Ref [4] for further details). In this case the B(GT) value to the 15^+ isomeric state in ^{96}Ag is found to be 0.07 (i.e. about 50% of the value obtained using the $p_{1/2},g_{9/2}$ model space). Furthermore, the calculations reveal that there is a large strength to three resonance states with spins of 15^+, 16^+ and 17^+ in ^{96}Ag that reside between 9.5 and 10.6 MeV excitation energy. Moreover, these states lie above the proton decay threshold and are hence expected to have beta-delayed proton branches. Because of phase space factors (i.e., β-decay energy differences) the feeding to these states is only about 1/3 of the total decay intensity from the 16^+ isomer. The LSSM calculations indicate that 2/3 of the decay from these three resonance states is expected to occur via M1 or E2 gamma rays to the isomeric 15^+ state in ^{96}Ag, with the remaining decays being via beta-delayed protons to states in ^{95}Pd. The current experiment was not sensitive enough to detect either of these decay modes, hence it will be important to search for them in future experiments in order to obtain the full B(GT) distribution. Moreover, the identification of such decay modes will be important in determining whether core excitations play a role in the structure of the 16^+ state and other high-spin states. See ref [4] for further discussions on this issue.

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