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Published in:
Acta Physica Polonica. Series B: Elementary Particle Physics, Nuclear Physics, Statistical Physics, Theory of Relativity, Field Theory

2009

Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 3

THE NORTHWEST FRONTIER: SPECTROSCOPY OF $N \sim Z$ NUCLEI BELOW MASS 100*

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(Received December 31, 2008)

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

The spectroscopy and structure of excited states of $N \sim Z$ nuclei in the mass 70–100 region has been investigated using two techniques. In the $A \sim 70$–80 region fusion evaporation reactions coupled with the recoil-β-tagging method have been employed at Jyvaskyla to study low-lying states in odd–odd $N = Z$ nuclei. Results from these and other data for known odd–odd nuclei above mass 60 will be discussed. In the heavier mass 90 region a fragmentation experiment has been performed using the RISING/FRS setup at GSI. This experiment was primarily aimed at searching for spin gap isomers in nuclei around $A \sim 96$. The objectives of the latter experiment will be discussed.

PACS numbers: 21.10.Re, 21.10.Gv, 25.85.Ge, 27.90.+b

1. Introduction

The spectroscopy of $N \sim Z$ nuclei has been of interest for many years, not least because of the large range of interesting physics issues that result from nuclei in this region of the Segre chart. Examples of topical issues are outlined below, some of which will be discussed further as a result of the present work.

As ^{100}Sn is approached the increasing Coulomb field results in mixing of states with different isospin in mirror nuclei and $N = Z$ nuclei, for which it is expected to be largest. The presence of such mixing can influence both the γ- and β-decays. For example, E1 transitions are forbidden in $N = Z$ nuclei unless isospin mixing is present. Furthermore, if there is no mixing Fermi β-decays are also forbidden in $N = Z$ nuclei — *e.g.* see [1]. The identification of such decays can reveal information about the degree of mixing between the $T = 1$ and $T = 0$ states. Sagawa and Hamamoto [2] have used Hatree-Fock plus RPA calculations to show that there is a global effect due to the increasing nuclear charge that causes isospin purity to slowly break down as the mass increases. The results reveal a $\sim 1\%$ admixture of the $T = 1$ state in the $T = 0$ ground state of ^{56}Ni, rising to $\sim 5\%$ in the ground state of ^{100}Sn, with an approximate Z^2 dependence in between. It is an experimental challenge to investigate these predictions in the heavier $N = Z$ nuclei. It is also of great interest to see if there are other effects that might lead to the break-down of isospin purity as we approach ^{100}Sn.

The existence of large shell gaps at nucleon number 34, 36 for oblate shapes and 38, 40 for prolate shapes plus the well known 40 spherical shell gap leads to the expectation of shape co-existence in $N \sim Z$ nuclei with the above nucleon numbers. There is currently considerable evidence for such shape co-existence in the light Kr isotopes, *e.g.*, see [3–5], as well as in the Se isotopes [6, 7]. The $N \sim Z$ region is also of direct interest from the nucleosynthesis point of view, since nuclei in this region are directly involved in the r–p process via (p, γ) capture reactions. Nuclear structure issues can play an important role in the rapid proton capture reaction rates, *e.g.* see [8–10]. A further issue that is unique to the $N \sim Z$ nuclei is that of *np*-pairing. Away from the $N = Z$ line like nucleon pairing is known to dominate, but on the $N = Z$ line itself *np*-pairing dominates. Because neutrons and protons are different Fermions there are two possible types of pairing for such nuclei, the standard isovector $T = 1$ mode and the isoscalar $T = 0$ mode, which is unique to proton–neutron pairs. A long standing question has been to what extent the isoscalar mode plays a role in the structure of nuclei and how this particular pairing mode reveals itself. It has been suggested that at low spin the np $T = 1$ mode will dominate in $N = Z$ nuclei up to around mass 80, whilst in the mass 90 region the $T = 0$ mode becomes more important (*e.g.* see [11]). Experimental studies of low-lying $N = Z$ nuclei in the latter mass region are awaited with interest.

For nuclei below ^{100}Sn both the protons and neutrons are filling the $g_{9/2}$ shell, which may be expected to give rise to strong np correlations. For these near-spherical nuclei spin gap isomers are expected as a result of the large attractive interaction that occurs for maximally aligned particle–particle or hole–hole configurations. Many such isomers are already known, for which arguably the most interesting to date is the 21^+ isomer based on the $\pi g_{9/2}^{-3} \times \nu g_{9/2}^{-3}$ configuration in ^{94}Ag [12]. There are, however, long standing shell model predictions for the existence of 16^+ and $25/2^+$ spin gap isomers in ^{96,97}Cd [13] as well as more recent large scale shell model predictions for a spin gap isomer in ^{98}Cd [14]. Studies of isomers can provide a very sensitive test of effective interactions used in the shell model, so searches for such states and their decay modes are clearly important.

The above is not meant to be an exhaustive discussion of physics topics relevant to $N \sim Z$ nuclei, but merely highlights some of the many interesting areas that result from studies of such nuclei. Several of these are also relevant to the work discussed below. However, other aspects, such as those discussed by J. Hardy at this conference, are of course, also very important.

This paper will focus on the use of the recoil-β-tagging technique to study the low-lying structure of odd–odd $N = Z$ nuclei in the mass 70–80 region and discuss some interesting results that have been revealed by these studies. A brief discussion will also be presented on our recent isomer experiment at GSI to search for spin-gap isomers in the $A \sim 96$ region.

2. Experimental techniques

2.1. β-tagging

The recoil-β tagging experiments were performed at Jyvaskyla using the JUROGAM γ-ray array coupled to the RITU gas filled spectrometer and the the GREAT [15] focal plane detection system. The RITU spectrometer was not designed for light mass reactions, but recent developments have enabled us to pursue such studies, although these have been limited to the production of nuclei populated at or around the Coulomb barrier because of rate limitations in the Si focal plane detectors. The main problem being that RITU is a gas filled spectrometer and hence has no A/Q selection, so all fusion recoils are transported to the focal plane. The β-tagging technique employed has been discussed in detail by Steer *et al.* in Ref. [16], where the first proof of principle experiment is investigated. This technique is ideally suited to the study of odd–odd $N = Z$ nuclei with $60 < A < 100$ as well as several nuclei with $N < Z$ in this mass region, because they decay via Fermi superallowed β-decays, which typically have half-lives of 10's ms and end-point energies of around 10 MeV. Most other nuclei that are populated have half-lives of the order of seconds and end-point energies of 3–5 MeV, thus allowing short correlation times and high β energies to be used to enable us to select the nuclei of interest. This method has been used in the present work to study odd–odd $N = Z$ nuclei such as ^{70}Br, ^{74}Rb, ^{78}Y as well as to search for evidence of γ transitions in the $N < Z$ nuclei ^{70,71}Kr.

2.2. Isomer spectroscopy

The studies carried out to search for spin-gap isomers in the mass 90 region utilised a 0.85 GeV/A ^{124}Xe beam from the GSI facility. The primary beam was directed onto a 4 g/cm^2 Be target at the entrance to the FRS spectrometer. Fragments were then separated in the spectrometer using the $B\rho - \Delta E - B\rho$ technique. The A/Q and Z of the ions were determined on an event-by-event basis using time-of-flight, position sensitive and energy loss detectors. Degraders were used to slow down the ions, with the primary aim being to stop ^{96}Cd ions in the central section of a three layered active stopper. Each layer was composed of three 5×5 cm double sided silicon strip, DSSSD, detectors, each of which had 16×16 strips. Further details of the active detectors used can be found in [17]. The active stopper will be used to search for evidence of particle decay from the predicted spin gap isomers in ^{96,97,98}Cd. The Euroball cluster detectors surrounded the active stopper and were used to search for new γ decaying isomers in the $N \sim Z$, $A \sim 96$ nuclei.

3. Experimental results

3.1. Mass 70–80 Region: Coulomb energy differences

The first application of the β-tagging technique to study γ-rays in a nucleus where none were previously known was in ^{78}Y. Details of the experiment can be found in Ref. [18]. Fig. 1 shows the coincidence γ-ray spectra for the three transitions that were identified as belonging to ^{78}Y. The or-

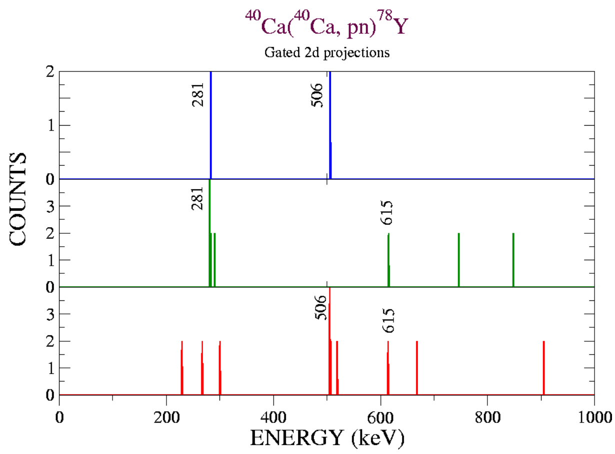

Fig. 1. γ–γ gated spectra showing the 615 (top), 506 (middle) and 281 keV (bottom) gates for transitions in ^{78}Y from the recoil-β tagged γ–γ matrix. The correlation time used was 150 ms with a β energy of > 4 MeV.

dering of the 281 and 506 keV γ-rays was done through a comparison with the analogue states in ^{78}Sr. More recently the technique has been used to provide further evidence for the location of the 6^+ $T = 1$ state in ^{70}Br that was tentatively assigned in Ref. [19].

The results of these experiments and the test experiment have been used to investigate Coulomb energy differences (CED) of $T = 1$ analogue states of $N = Z$ and $N = Z + 2$ nuclei in this mass region. Previous studies in lighter $N \sim Z$ nuclei have shown that the CED are very sensitive to nuclear structure effects (see [20,21]). Fig. 2 shows a plot of the CED values between $N = Z$ and $N = Z + 2$ nuclei from mass 20–30, 40–56 and > 60 regions. Most of the CED values are positive and an explanation for this observation in the lighter mass regions has been given in terms of a pairing effect [22]. The origin lies in the greater reduction in the Coulomb energy that results in the $N = Z + 2$ nuclei, where like-particle pairing dominates, compared to $N = Z$ nuclei, where np pairing is dominant, as angular momentum is generated. The former situation gives rise to a greater reduction in the Coulomb energy as the spin increases because the reduced overlap between the wave functions of pairs of protons is greater in this case than in the $N = Z$ situation, where neutrons are paired with protons.

Fig. 2 reveals that the mass 74, 82 and 86 analogue systems (data taken from Refs. [16, 23, 24]) show a similar behaviour to that exhibited by nuclei in the *sd* and $f_{7/2}$ regions, however the CED for the mass 70 and 78 systems are negative and approximately zero, respectively. The mass 78 data can be understood as resulting from the large stable prolate deformation that is

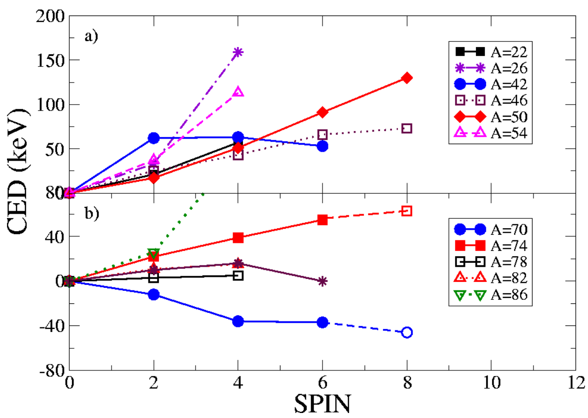

Fig. 2. Coulomb energy differences as a function of spin for (a) a selection of mid-shell *sd* and $f_{7/2}$ shell nuclei and (b) all currently known data for nuclei in the *fpg* shell with $A > 60$. Panel (b) also shows the result of the CED (stars) for mass 70 assuming that both ^{70}Br/^{70}Se exhibit the shape changes predicted by HFB calculations in [7].

expected for nuclei residing around the $N = Z = 38$ shell gap. The shell gap is expected to result in significantly reduced pairing and hence it is perhaps not surprising that the CED is approximately zero for the analogue pair in this case.

The more interesting case is the mass 70 system. Recent data and HFB based configuration mixing calculations suggest that ^{70}Se is oblate at low spin [7]. However, studies of the CED for the ^{70}Br/ ^{70}Se analogue states suggest that the observed negative CED can only be accounted for (assuming that the shape changes in the analogue nuclei are the same) if there is a change from a weakly deformed ($\beta_2 \sim 0.18$) prolate shape at low spin to a more deformed prolate ($\beta_2 \sim 0.33$) shape at spin 4–6 [18]. If the calculated spectroscopic quadrupole moments from [7] are used to obtain the deformations at various spins and then these values are used to determine the CED from the resulting shape changes according to the prescription given in Ref. [18] then the results are found to disagree with the experimental values — see Fig. 2. The experimentally observed CED can be explained if either (a) the prolate stretch scenario outlined in [18] is correct, or (b) that the assumption that the shape changes as a function of spin in the two analogue nuclei are the same is incorrect. This latter scenario would be extremely interesting since it would imply that the analogue states are not pure $T = 1$, resulting in a major breakdown of isospin symmetry. Further measurements, such as low energy Coulomb excitation studies of ^{70}Br/ ^{70}Se are planned to help resolve this issue.

3.2. Isomer studies in the mass 96 region

As discussed in the introduction, the key focus for these studies is the search for the predicted 16^+ and $25/2^+$ spin-gap isomers in ^{96,97}Cd. Fig. 3 shows the results of shell model calculations for ^{96,97}Cd using the Gross–Frenkel interaction and a $g_{9/2}$, $p_{1/2}$ model space. These show that the states in question are particularly favoured from an excitation energy point of view. The lowest multipolarity decay in both cases is E6, which is highly unlikely to occur — the most likely scenario being particle decay. The calculations suggest that in ^{96}Cd the 14^+ state may also be isomeric because of its proximity to the 12^+ state, however, in this case the state should decay by an E2 transition. A 14^+ spin-gap isomer in ^{98}Cd is predicted to exist by large scale shell model calculations. The latter were able to reproduce quite accurately the location of the known 12^+ γ decaying isomer, see Fig. 7 of Ref. [14]. As indicated above, these spin-gap isomers are expected to decay via particle emisson, which in the case of ^{96}Cd could include β, proton, β-delayed proton and even 2 proton decay modes.

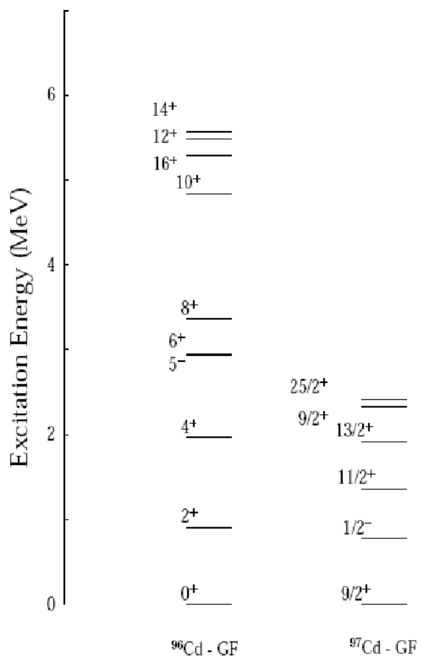

Fig. 3. Shell model calculations using the Gross–Frenkel interaction for ^{97,96}Cd. The favoured $25/2^+$ and 16^+ states resulting from the $\pi g_{9/2}^{-2} \otimes \nu g_{9/2}^{-1}$ and $\pi g_{9/2}^{-2} \otimes \nu g_{9/2}^{-2}$ configurations, respectively, lie at very low excitation energies. These are expected to be isomeric states.

The data from the GSI experiment were taken in summer and are still in the early stages of analysis. However, it is already clear that new γ decaying isomers and/or new isomeric transitions exist in the $T_z = 1$ isotopes, ^{98}Cd, ^{96}Ag, ^{94}Pd. Fig. 4 shows one example: the implant correlation spectrum for ^{94}Pd, with a correlation time of $\sim$ 1–2μs. The known decays from the 14^+ isomer [25] can clearly be seen along with three new γ-ray lines. Two of these (268 and 408 keV transitions) are in fact known γ-rays from the decay of the tentatively assigned $J^\pi = (15^+)$ and (16^+) states immediately above the isomer. These transitions were identified by Plettner *et al.* [26] as being observed in the decay of the reported 21^+ isomer in ^{94}Ag. The new transition at 1650 keV has a similar intensity to the known 268 and 408 keV γ-rays. It is too early at this stage to confirm that the three newly observed lines are in coincidence, however, the 1650 keV and 408 keV transitions appear to have a very similar lifetime, which is somewhat shorter than that of the known 14^+ isomer (530 ± 10 ns). This fact suggests that the 1650 keV γ-ray comes from a state directly above the (16^+) state. This could come from the decay of a new isomer directly or there could be a, as yet unknown, low energy γ-ray which emanates from the new isomeric state. The confirmation of which scenario is correct will have to await further analysis.

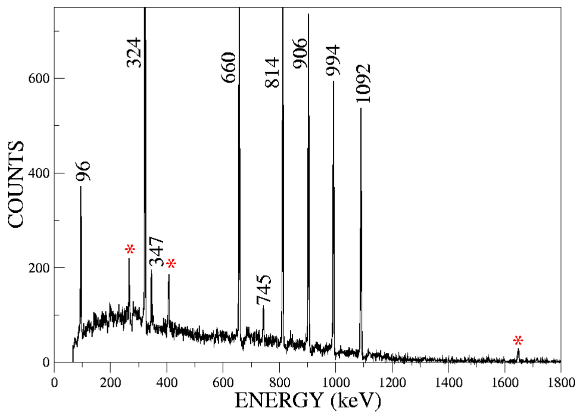

Fig. 4. Spectrum showing transitions in ^{94}Pd following the decay of isomeric states. The implant-γ correlation time is of the order of 1 μs. Transitions marked with a star were not reported in previous isomer studies of this nucleus.

4. Summary and conclusions

It is now clear that the recoil β-tagging method can be used to study excited states in $N \leq Z$ nuclei in the $A \sim 70$–80 region. However, the present work has also revealed that these studies would be made much easier if the experiments could be carried out with a vacuum mode separator rather than a gas filled separator such as that which has been used to date in Jyvaskyla.

Furthermore, the ability to select A/Q will remove the need to carry out experiments at Coulomb barrier energies, thus allowing studies of low-lying states of odd–odd $N = Z$ nuclei above mass 80, for example, via the $p3n$ reaction channel.

Studies of Coulomb energy differences of nuclei in the fpg shell reveal an interesting anomally for the mass 70 $T = 1$ states in ^{70}Br/ ^{70}Se when compared with other isobaric multiplets in the region. This clearly merits further experimental investigation since the results suggest that either the interpretation of the low-lying states in ^{70}Se in terms of an oblate shape is incorrect, or that ^{70}Br and ^{70}Se have different shapes, thus requiring isospin symmetry to be broken.

The recent experiment at GSI should reveal whether or not the predicted spin-gap isomers in ^{96,97,98}Cd exist and also provide information on their decay modes. The outcome will have to await further analysis. The experiment, which was performed in July 2008, has already revealed evidence for new γ-decaying isomers and/or isomeric transitions in the $T_z = 1$ nuclei ^{98}Cd, ^{96}Ag and ^{94}Pd. Further details of these results will be presented over the coming months.

This work has been supported by the EU-FP6-I3 project EURONS No. 506065, the Academy of Finland (CoE Nuclear and Accelerator Based Physics Programme at JYFL, grants to PTG (111965) and CS (209430)), the EC Marie Curie Fellowship and the UK EPSRC/ STFC. We thank the UK/France (EPSRC/IN2P3) Loan Pool and the GAMMAPOOL European Spectroscopy Resource for the loan of detectors for JUROGAM.

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