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The yrast spectroscopy of neutron-rich nuclei produced in deep-inelastic processes

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Abstract. The highly sensitive GASP array at the INFN Legnaro Laboratory was used to study the γ-ray de-excitation of neutron-rich nuclei produced in the deep-inelastic processes which occur when 230 MeV ^{36}S ions interact with a target of ^{176}Yb. Yrast decay schemes were identified in over forty target-like fragments and in over twenty projectile-like fragments. Analysis of the data has resulted in extensions to the yrast decay sequences of the target-like species, ^{176}Hf, ^{166}Er, ^{172}Yb, and ^{152}Sm. New transitions have also been observed in a number of projectile-like species including ^{34}P and ^{41}Cl. Experimental results are compared with the results of shell model calculations.

PACS. 23.20.Lv Gamma transitions and level energies – 27.40.+z $39 \leq A \leq 58$ – 27.70.+q $150 \leq A \leq 189$

1 Introduction

The study of neutron-rich nuclei is currently a topic of major interest in nuclear-structure physics. Such nuclei are predicted to reveal new aspects of nuclear structure that challenge established theoretical models. In particular, neutron-rich nuclei around the shell model magic numbers of $N = 20$ and 28 have exhibited properties inconsistent with shell closure. The first experimental evidence for these properties around $N = 20$ came from mass measurements of neutron-rich Mg and Na isotopes [1,2]. Further evidence was based on the subsequent measurements of the excitation energy of the first 2^+ state [3] of ^{32}Mg, which was much lower than expected, and measurements of the $B(E2; 0^+ \to 2^+)$ value [4].

In the $N = 28$ region, measurements by intermediate-energy Coulomb excitation of the $B(E2; 0^+ \to 2^+)$ values involving the 2^+ first excited states of ^{44}S [5] and ^{46}Ar [6] also show evidence of collectivity for these magic-number nuclei. Recent work by Azaiez *et al.* [7,8] has provided evidence for shape coexistence in these nuclei; the second excited 2^+ and 0^+ states would appear to have spherical shapes.

Shell model investigations in the $N = 20$ region [9] have shown that the observed "anomalies" can be understood within calculations which consider the promotion of neutrons from the sd to the fp shell. The residual neutron-proton interaction lowers the energy of configurations with neutrons in the $f_{7/2}$ subshell and protons in the $d_{5/2}$ subshell. This leads to low-lying intruder states.

However, the production of nuclei in this region is difficult due to the limitations of traditional reaction mechanisms. New techniques have now been developed and the deep-inelastic process, for example, has now become a reliable way to populate neutron-rich nuclei.

2 Experimental techniques

The combination of Tandem-XTU and ALPI accelerators at the INFN Legnaro Laboratory, Italy, was used to deliver a beam of ^{36}S ions at an energy of 230 MeV onto a target of ^{176}Yb. The target was isotopically enriched to 97.75% and was of thickness $14\,\mathrm{mg \cdot cm^{-2}}$ with an isotopically enriched ^{208}Pb (98.70%) backing of thickness $35\,\mathrm{mg \cdot cm^{-2}}$. The experiment was designed to study the γ-decay of excited nuclear states with lifetimes longer than the slowing-down time of the recoiling nuclei in the composite target (~ 1 ps) and thus no Doppler correction was necessary. The GASP array was used to measure the γ-de-excitations of reaction products. The electronic trigger conditions were set such that if three or more Ge signals (unsuppressed) and two or more BGO signals were in time coincidence then the event was accepted. Gain matching

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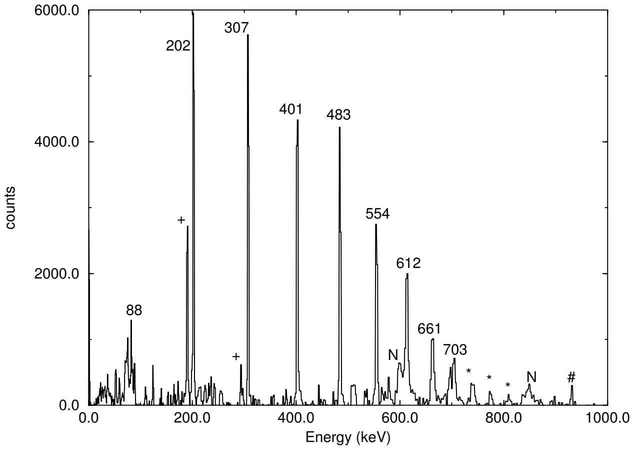

Fig. 1. γ-ray spectrum corresponding to a sum of double gates for the yrast decay sequence of ^{176}Hf. New transitions are marked by *; neutron peaks by N; ^{176}Yb transitions by + and ^{34}Si transitions by # (complementary fragment).

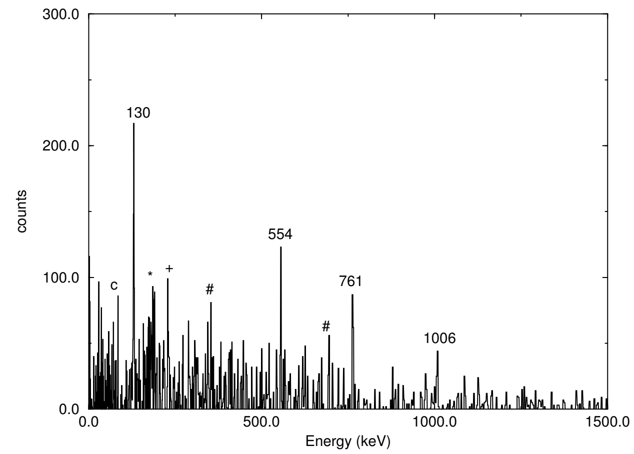

Fig. 2. A sum of double gates set on the 130-, 761- and 554-keV transitions in ^{41}Cl. Also observed are transitions from ^{169}Tm (+), ^{167}Tm (#), ^{176}Yb (*) and contaminants (c).

of the detectors and data sorting were performed off-line and a $\gamma\gamma\gamma$-cube with no conditions was constructed.

3 Results and discussion

In the analysis of this work we have identified over forty target-like nuclei and over twenty projectile-like nuclei populated through deep-inelastic processes. For the target-like fragments, extensions were made to the yrast sequences in a number of nuclei. An example can be seen in the γ-ray spectrum of fig. 1 which shows the yrast decay sequence of ^{176}Hf. This figure shows three new transitions in the yrast band at energies of 736, 771 and 802 keV.

Extensions to yrast decay schemes of the projectile-like fragments were also observed. Recent experimental work by Liang *et al.* [10], involving studies of the γ-de-excitation

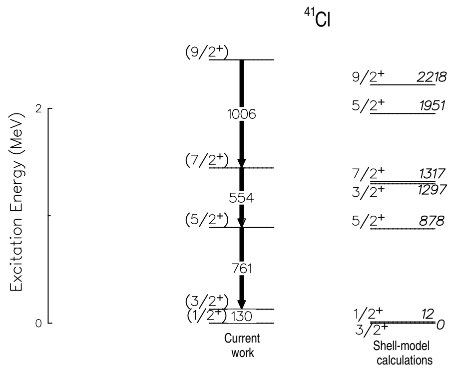

Fig. 3. The yrast decay scheme of ^{41}Cl with the results of shell model calculations [11].

of fragments from deep-inelastic processes, has established excited states of ^{41}Cl at 130 keV and 891 keV. By double gating on these transitions we have been able to extend the yrast scheme by a further two transitions at 554 and 1006 keV (see fig. 2). Measurements of the intensities of these two photopeaks yield the ordering shown in fig. 3. Also shown here are the results of shell model calculations for ^{41}Cl based on the Wildenthal "universal" interaction [11]. Comparison of the experimental and shell model level schemes would suggest J^π assignments of $7/2^+$ and $9/2^+$ for the new levels at excitation energies of 1445 keV and 2451 keV, respectively.

In summary, we have seen in this work that the deep-inelastic process is a powerful tool for studying the yrast spectroscopy of neutron-rich target-like and projectile-like species.

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