

YRAST STATES IN  $N = 30$   $^{50}\text{Ca}$  AND  $^{51}\text{Sc}$  ISOTONES  
STUDIED WITH DEEP-INELASTIC HEAVY ION  
REACTIONS\*

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Data from three gamma spectroscopy experiments using deep-inelastic heavy ion reactions provided new information on high-spin states in the neutron-rich  $N = 30$ ,  $^{50}\text{Ca}$  and  $^{51}\text{Sc}$  isotones. Shell model calculations restricted to neutron excitations only are shown to reproduce with good accuracy some of the experimental levels. It is demonstrated that proton excitations not accounted in these calculations are abundantly present in the observed yrast structures. High energy of the  $4^+$  state in  $^{50}\text{Ca}$  underlines the validity of the  $N = 32$  shell closure.

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## 1. Introduction

I would like to start by expressing my sincere gratitude to the Organizers of the present Zakopane meeting who decided to distinguish my anniversary in such honorable way. I am deeply touched by the presence of many good

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friends with whom I had a privilege to participate in various research activities and I warmly thank those who contributed to this special session by presenting scientific results framed by many kind words directed to me personally. As my age was publicly disclosed I am tempted to reduce its significance by remark: it is so attractive to be involved in nuclear physics research that one does not notice his own aging. In spectroscopic investigations the permanent challenge to find the best way to study new hard-to-reach nuclei keeps one very active. Particularly now, when the new technical developments lowered significantly the detection limit in the gamma spectroscopy investigations and paved the way to study neutron-rich nuclei where some interesting phenomena are observed and many other anticipated. I am pleased that I am allowed to contribute to this session displaying example of such an effort.

Recent results indicating the  $N = 32$  neutron subshell closure in neutron-rich nuclei with  $Z > 20$  [1, 2] displayed example of phenomena which occur at large isospin values; its deeper understanding invites more experimental efforts in the region. The most direct evidence for the large energy separation between the  $f_{5/2}$  and  $p_{3/2}$  neutron orbitals, which results in the  $N = 32$  closure, comes from the excitation energies of corresponding states observed in the one-neutron  $^{49}\text{Ca}$  isotope [3]. Consequently, the clear demonstration of increased stability at the closed subshell is the high energy of the first  $2^+$  state in the  $^{52}\text{Ca}$  isotope [4] where four neutrons fill the  $p_{3/2}$  orbital. Till now not much was known about  $N = 30$  isotones  $^{50}\text{Ca}$  and  $^{51}\text{Sc}$ , where higher spin states should also be affected by the  $p_{3/2} - f_{5/2}$  energy gap. In  $^{50}\text{Ca}$  the available information was limited to the first  $2^+$  1026 keV excitation and few higher-lying low-spin states with poorly defined energies, studied in the beta decay,  $(t, p)$  and  $(\alpha, 2p)$  reactions [5]. For the  $^{51}\text{Sc}$  isotope experimental information was restricted to the indication of a candidate for the  $11/2^-$  excited state lying at approximately 1062 keV above the  $7/2^-$  ground state [6]. In this contribution I shall present much more complete information on yrast structures of both isotones obtained in deep-inelastic gamma spectroscopy experiments.

## 2. Experiments and results

Three experiments using the  $^{48}\text{Ca}$  beam and thick targets of  $^{48}\text{Ca}$ ,  $^{208}\text{Pb}$  and  $^{238}\text{U}$  located in the center of large gamma arrays, were performed to study yrast states in neutron-rich nuclei from the  $^{48}\text{Ca}$  region by discrete gamma-ray spectroscopy in deep-inelastic heavy ion reactions. The initial measurement  $^{48}\text{Ca} + 210 \text{ MeV } ^{48}\text{Ca}$  performed with the GASP array and the ALPI Linac at the INFN Legnaro was followed by the  $^{208}\text{Pb} + 280 \text{ MeV } ^{48}\text{Ca}$  and  $^{238}\text{U} + 330 \text{ MeV } ^{48}\text{Ca}$  experiments performed with the Gammasphere detector array and the ATLAS accelerator at the Argonne National Labo-

ratory. The high quality gamma coincidence data from all three runs served for complementary analysis providing new information on yrast excitations in several nuclei from the closest neighborhood of  $^{48}\text{Ca}$  [7].

The production of the  $^{50}\text{Ca}$  and  $^{51}\text{Sc}$  isotopes suitable for spectroscopic analysis could be observed in all three experiments and important initial identifications were obtained from the analysis of the  $^{48}\text{Ca}$  and  $^{208}\text{Pb}$  target run data. However, the much more favorable yield observed in the  $^{238}\text{U}$  target experiment provided the highest statistics data which allowed to extract main information on yrast structures of these  $N = 30$  isotones.

### 2.1. $^{50}\text{Ca}$

With the initial knowledge of the first excited  $2^+$  state at 1026 keV the analysis of the data revealed a strongly populated sequence of 595, 3488 and 1027 keV yrast transitions, which could be safely identified with the  $^{50}\text{Ca}$  on the basis of gamma cross-coincidence analysis. This is demonstrated in Fig. 1,

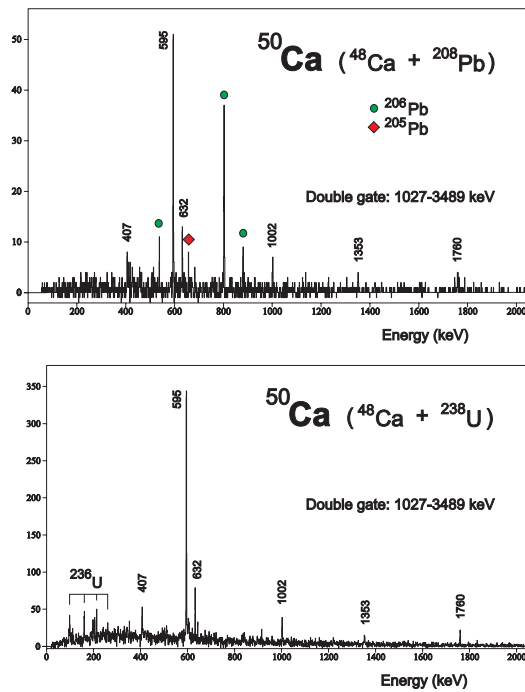


Fig. 1. Gamma coincidence spectra obtained for 1027–2489 keV double gates in two different experiments. Indicated cross-coincidence gamma lines arising from reaction partner nuclei prove the  $^{50}\text{Ca}$  identification. Other lines marked by energies correspond to higher-lying transitions of  $^{50}\text{Ca}$ .

where fairly clean coincidence spectra obtained from two sets of data (indicated in the figure) by selecting the double 1027–3488 keV transition gates are shown. In the upper spectrum, along with several new transitions of  $^{50}\text{Ca}$ , one observes lines corresponding to the well known gamma transitions in the  $^{206}\text{Pb}$  and  $^{205}\text{Pb}$ , which are the expected main reaction partner nuclei. In the lower spectrum a presence of weak intensity lines from correspondingly the  $^{236}\text{U}$  ground state rotational band confirms this identification and the approximately 7 times higher statistics observed for the  $^{50}\text{Ca}$  lines demonstrates the superior quality of the  $^{238}\text{U}$  data used in the final analysis. Indeed the detailed inspection of this data which exploited predominantly triple gamma coincidences and was accompanied by continuous checking with the data from two other experiments allowed to construct a very complete  $^{50}\text{Ca}$  level scheme. It is shown in Fig. 2 and includes all transitions that could be safely identified with this isotope. The tentative spin-parity assignments indicated in Fig. 2 are based on yrast population arguments, the observed gamma decay and are also guided by the shell model calculations as will be discussed in the next section.

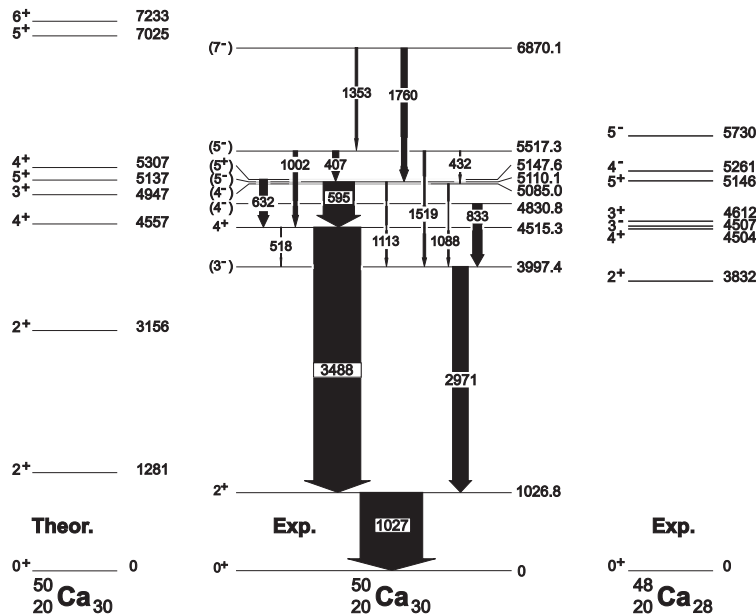


Fig. 2. Level scheme of  $^{50}\text{Ca}$  yrast states established in the present work. Shell model calculated states involving only neutron core excitations are shown to the left. On the right the experimental yrast states of  $^{48}\text{Ca}$  core nucleus are given for comparison.

2.2.  $^{51}\text{Sc}$

Although the observed production yield of the odd proton  $^{51}\text{Sc}$   $N = 30$  isotope was larger than that for the  $^{50}\text{Ca}$  case, this isotope was more difficult to study since generally in the odd mass nuclei yrast excitations are less distinctly populated. The earlier tentative location of the  $11/2^-$  state at 1062(1) keV was again the starting point of our analysis. The identification

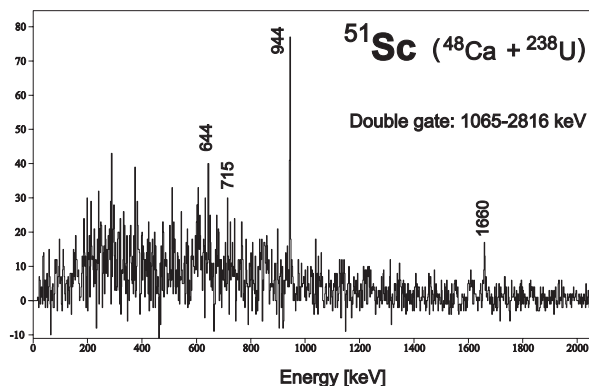


Fig. 3. Gamma coincidence spectrum obtained in the  $^{238}\text{U}$  target experiment with double gate set on lowest yrast transitions identified with  $^{51}\text{Sc}$ .

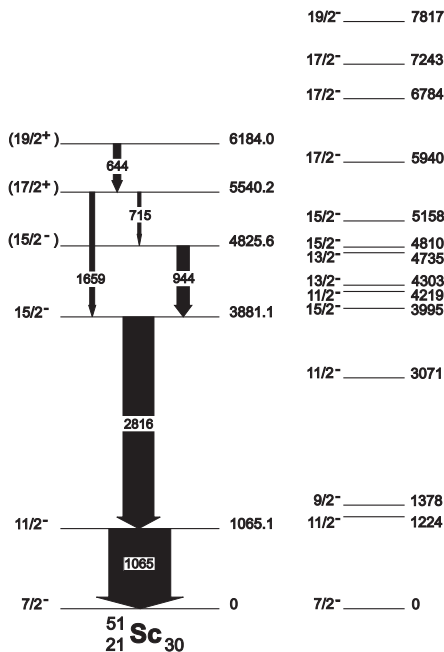


Fig. 4. Level scheme of yrast states in  $^{51}\text{Sc}$  established in the present work.

procedures established the 1065–2816 keV coincident transitions to form the lowest yrast sequence in the  $^{51}\text{Sc}$ . This was based on the unambiguous observation of several gamma lines in the coincidence spectra from the  $^{48}\text{Ca}$  and  $^{208}\text{Pb}$  target experiments which confirmed the presence of correspondingly expected K and Tl isotopes as reaction partners. With this firm identification the  $^{238}\text{U}$  target experiment data were used and Fig. 3 shows the gamma coincidence spectrum obtained by setting double gate on the 1065–2816 keV transition pair, which displayed higher lying transitions. The more detailed inspection allowed to construct the simple level scheme of yrast excitations in  $^{51}\text{Sc}$  shown in Fig. 4 with tentative spin-parity assignments discussed below.

### 3. Discussion

Yrast structures established in this work for both  $N = 30$  isotones have to be discussed in a somewhat speculative way since at present no rigorous spin-parity assignments could be made for the observed states. Moreover the presently performed shell model calculations were restricted to include only neutron excitations of the  $^{48}\text{Ca}$  core since many important interactions involving proton hole states below  $Z = 20$  are rather poorly known [8]. This deficiency deserves special attention, since recently identified states in nuclei that are closest neighbors to the doubly-magic  $^{48}\text{Ca}$  isotope indicate rather important role of the proton particle–hole excitations in building yrast structures [7]. They are usually well distinguished from neutron excitations by having opposite parities and within general considerations can be well understood qualitatively. On the other hand the calculation results involving neutrons are verified in several cases [1, 2] and the achieved quantitative predictive power allows to identify such states safely in the experimentally established level schemes.

On the left hand side of the  $^{50}\text{Ca}$  level scheme in Fig. 2 the calculated yrast and near yrast shell model states involving neutron excitations only are shown. All of them are naturally of positive parity, but apparently only three of them can be clearly attributed with the observed experimental levels. The assignment of the yrast  $4^+$  state at 4515 keV energy has to be considered as rather certain. The calculation attributes it with the neutron particle–hole core excitation rather than the much higher lying second  $4^+$  state which involves the high energy  $f_{5/2}$  orbital. Apparently in the  $^{50}\text{Ca}$  isotope, the second unobserved  $4^+$  state must be located at yet higher energy which reemphasizes the validity of the  $N = 32$  shell closure originating from the large energy gap between the  $p_{3/2}$  and  $f_{5/2}$  neutron orbitals. Initially the strongly populated yrast state at 5110 keV was anticipated to be the calculated  $5^+$  arising from the same neutron particle–hole excitation, however,

the identification of the  $3^-$  state at 3997 keV energy and the connecting transition of 1113 keV excluded such possibility. The location of the 3997 keV level assigned as  $3^-$  was confirmed in the data of all three experiments and is consistent with the earlier identified level at 3993(15) keV and assigned as  $3^-$  in the  $(t, p)$  reaction [5]. The most likely assignment for the 5110 keV level is therefore  $5^-$  and the  $5^+$  assignment is subsequently attributed to the close lying and relatively strongly populated level at 5147 keV energy, which fits even better the calculated  $5^+$  state.

On the right hand side of Fig. 2 the lowest  $^{48}\text{Ca}$  core excitations are shown to be compared with the level energies observed in  $^{50}\text{Ca}$ . In this comparison the negative parity proton core excitations not accounted in calculations are most important. It is obvious that in the  $^{50}\text{Ca}$  case the possible coupling with the low energy  $2^+$  excitation of two extra neutrons gives rise to the additional negative parity states which assume near yrast positions. Some of these states appear in the experimental spectrum and assignments indicated is the best choice based on the gamma feeding and gamma decay considerations. The highest energy level at 6870 keV is suggested to be the  $7^-$  yrast state with maximum spin  $5^-$  available for the proton particle-hole coupled with the neutron  $2^+$  excitation.

In the  $^{51}\text{Sc}$  isotope case shell model calculations were restricted to the coupling of the  $f_{7/2}$  proton with neutron excitations and the resulting negative parity levels which could possibly enter the yrast structure are shown to the right of Fig. 4. The  $11/2^-$  and  $15/2^-$  assignments for correspondingly the 1065 and 3881 keV levels are consistent with calculations and strong feeding observed in experiment confirms their distinct yrast nature.

Apart from the 4826 keV level which might correspond to the calculated second  $15/2^-$  state assignments indicated in Fig. 4 for higher lying states are less clear. It is likely that these states correspond to positive parity states arising from the proton core excitations which were not included in the calculation. The most important feature is that the observed yrast  $15/2^-$  level which corresponds to the  $4^+$   $^{50}\text{Ca}$  yrast excitation is lowered in energy by more than 600 keV and that this lowering is well accounted by interactions used in calculations.

In summary, the gamma spectroscopy experiments using deep-inelastic heavy ion reactions provided new information on the hitherto largely unknown yrast structures in neutron-rich  $N = 30$  isotones. Shell model calculations reproduce with good accuracy experimental levels for excitations involving neutron orbitals. The proton core excitations play a significant role in the observed yrast structure and efforts to establish appropriate effective interactions able to involve such states in calculations seems to be an urgent task for theoreticians.

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