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2013 J. Phys.: Conf. Ser. 445 012012

(http://iopscience.iop.org/1742-6596/445/1/012012)

Investigating the strength of the $N = 34$ subshell closure in ^{54}Ca

D Steppenbeck[1], S Takeuchi[2], N Aoi[3], P Doornenbal[2], J Lee[2], M Matsushita[1], H Wang[2,4], H Baba[2], N Fukuda[2], S Go[1], M Honma[5], K Matsui[6], S Michimasa[1], T Motobayashi[2], D Nishimura[7], T Otsuka[1,6], H Sakurai[2,6], Y Shiga[8], P-A Söderström[2], T Sumikama[9], H Suzuki[2], R Taniuchi[6], Y Utsuno[10], J J Valiente-Dobón[11] and K Yoneda[2]

[1] Center for Nuclear Study, University of Tokyo, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan
[2] RIKEN Nishina Center, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan
[3] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[4] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China
[5] Center for Mathematical Sciences, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8580, Japan
[6] Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[7] Department of Physics, Tokyo University of Science, Noda, Chiba 278-8510, Japan
[8] Department of Physics, Rikkyo University, Toshima, Tokyo 172-8501, Japan
[9] Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan
[10] Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[11] Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro I-35020, Italy

E-mail: `steppenbeck@cns.s.u-tokyo.ac.jp`

Abstract. Excited states in the exotic $N = 34$ isotope ^{54}Ca have been measured for the first time via in-beam γ-ray spectroscopy with proton-knockout reactions from ^{55}Sc and ^{56}Ti radioactive beams on a Be reaction target at the Radioactive Isotope Beam Factory, Japan. A strong candidate for the transition from the first 2^+ state to the 0^+ ground state has been identified, in addition to several other weaker transitions. The structure of the $N = 33$ isotope ^{53}Ca has also been investigated from the same data. Preliminary γ-ray energy spectra for ^{54}Ca and ^{53}Ca will be presented and the significance of the $N = 34$ subshell closure will be examined. Predictions of several shell-model interactions performed in the fp model space will be discussed in light of the new results.

1. Introduction

Over recent years, the evolution of nuclear shell structure in exotic, neutron-rich nuclei has attracted much attention on both the experimental and theoretical fronts. The theoretical studies of Otsuka *et al* [1, 2], for example, has highlighted the role of the tensor and central forces in changing the traditional ordering of nuclear single-particle orbitals that can, in some instances, lead to the disappearance of magic numbers while other new ones appear. Such

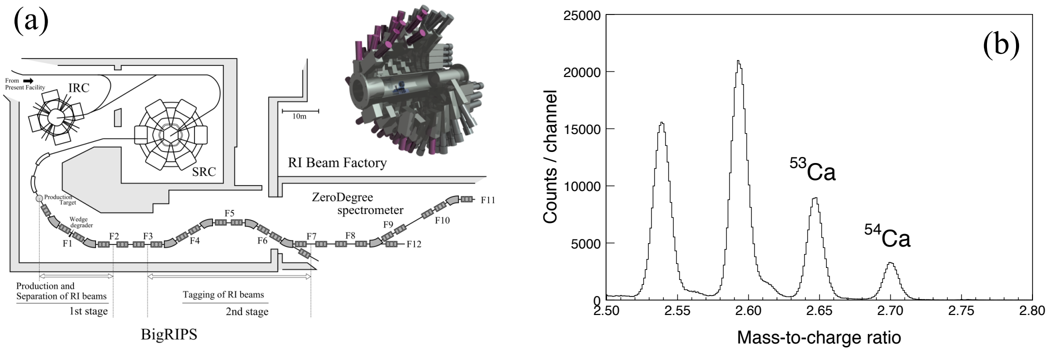

Figure 1. (Colour online) (a) Layout of the RIBF facility at RIKEN Nishina Center. The configuration of the DALI2 array used in the present work is indicated in the top-right corner. (b) Particle identification plot for Ca isotopes measured by ZDS. See text for details.

examples include the onset of an $N = 16$ subshell closure in neutron-rich oxygen [3] and the quenching of the $N = 20$ shell closure in the well-known "island of inversion" around $Z = 10-12$ [4]. In neutron-rich isotopes of Ca [5, 6], Ti [7, 8] and Cr [9, 10], much recent experimental work has focused on the onset of a new subshell gap at $N = 32$, which is reproduced well by the GXPF1 [11] and KB3G [12] shell-model Hamiltonians. In the framework of Refs. [1, 2], the onset of the $N = 32$ closure results as a direct consequence of a sizable $\nu p_{3/2} - \nu p_{1/2}$ gap, which presents itself as the $\nu f_{5/2}$ orbital moves up in energy due to a weakening of the attractive proton-neutron $\pi f_{7/2} - \nu f_{5/2}$ interaction as protons are removed from the $\pi f_{7/2}$ orbital. The GXPF1 Hamiltonian also predicts the onset of a significant $N = 34$ gap, which appears because the $\nu f_{5/2}$ orbital lies relatively high above the $\nu p_{1/2}$ orbital in that interaction. In fact, the size of the $N = 34$ gap predicted by GXPF1 is comparable to the one at $N = 28$ along the Ca and Ti isotopic chains. However, in the case of the Ti isotopes, recent experimental studies [8, 13] indicate that no subshell closure exists at $N = 34$. This observation led to a modified version of the GXPF1 Hamiltonian, labelled GXPF1A [14], in order to better reproduce the experimental systematics of the $N \approx 34$ isotopes. The updated interaction was found to account for the energy of the first 2^+ state $[E(2_1^+)]$ in ^{56}Ti and states with $J > 6\hbar$ in ^{54}Ti [7], which correspond to neutron excitations above $N = 32$, in a more satisfactory manner. The new interaction was also found to show a systematic improvement in predictions of $E(2_1^+)$ in the Cr isotopes, and the recent assignment of $J^\pi = 1/2^-$ to the ^{55}Ti ground state [15] supports the prediction of the GXPF1A interaction, indicating that the $\nu f_{5/2}$ orbital lies above $\nu p_{1/2}$ in Ti, albeit not high enough to result in a new subshell closure. Despite the imposed modifications, a significant $N = 34$ subshell closure resides in the predictions of the GXPF1A interaction for ^{54}Ca, where the energy of the 2_1^+ state is predicted to lie at about 3 MeV, which is larger than, though comparable to, the size of $E(2_1^+)$ in ^{52}Ca [5, 6]. The latest addition to the GXPF1 family of interactions, the GXPF1B Hamiltonian [16], predicts the 2_1^+ state in ^{54}Ca to lie at 2.6 MeV. It must be stressed, however, that no significant $N = 34$ subshell closure is predicted by other shell-model effective interactions that are commonly used in the fp shell, such as the KB3G Hamiltonian. Thus, the measurement of $E(2_1^+)$ is important not only because it may highlight the doubly magic nature of ^{54}Ca, but also because it will bear important consequences for nuclear shell-model Hamiltonians, irrespective of the strength of the $N = 34$ gap.

2. Experimental details

The structures of ^{54}Ca and ^{53}Ca were investigated using in-beam γ-ray spectroscopy at the Radioactive Isotope Beam Factory [17], operated by RIKEN Nishina Center and Center for

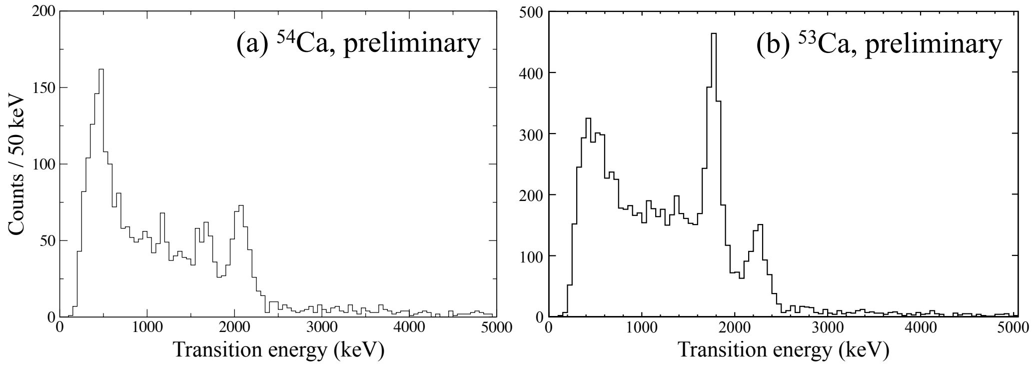

Figure 2. Preliminary Doppler-corrected γ-ray energy spectra for (a) ^{54}Ca and (b) ^{53}Ca deduced in the present work.

Nuclear Study, University of Tokyo. A ^{70}Zn primary beam at 345 MeV/u was delivered to the BigRIPS separator (BRS) [18], where a radioactive beam containing ^{55}Sc and ^{56}Ti was produced and focused on a 10-mm-thick Be reaction target located at the 8$^{\text{th}}$ focal plane of BRS [see Fig. 1(a)]. Typical secondary beam rates were $\sim$ 12 and 125 particles per second, respectively, per 1 pnA of primary beam intensity. The DALI2 array [19] was used to measure γ-ray transitions from excited nuclear states populated via nucleon knockout reactions. The reaction products were identified with the ZeroDegree spectrometer (ZDS) [18] using well established techniques involving measurements of particle magnetic rigidities, time of flights and energy losses in an ionisation chamber on an event-by-event basis (details are provided, for example, in Ref. [20]). A particle identification plot for Ca isotopes in ZDS is presented in Fig. 1(b), indicating the events measured in coincidence with at least one γ ray in DALI2.

3. Results and discussion

Several new γ-ray transitions have been identified in the present work for ^{53,54}Ca. A preliminary spectrum for ^{54}Ca is presented in Fig. 2(a), where ^{54}Ca events in ZDS measured in coincidence with either ^{55}Sc or ^{56}Ti in BRS and a single γ ray have been selected. The peak at 2.07 MeV[1] is assigned as the $2_1^+ \rightarrow 0_1^+$ transition based on the relative intensities of the transitions and systematics of even-even nuclei. Two weaker lines at 1.69 and 1.19 MeV are also present in the spectrum of Fig. 2(a). Based on the measured relative intensities, it is likely that the 1.69-MeV transition depopulates a level at 3.76 MeV and feeds the 2_1^+ state discussed above. Placement of the 1.19-MeV γ ray in the ^{54}Ca level scheme is, however, uncertain at present and cannot be deduced by intensity sum rules alone.

Systematics of $E(2_1^+)$ for the Ca isotopic chain are displayed in Fig. 3(a). The result of the present study indicates a reduction of $\sim$ 0.5 MeV in $E(2_1^+)$ relative to ^{52}Ca, suggesting a slightly weaker $N = 34$ subshell closure than the one at $N = 32$ for Ca. Systematics of $E(3_1^-)$ are also plotted in Fig. 3(a). The result for the 3.76-MeV level appears to continue the general trend of the data well and, therefore, a spin-parity assignment of 3^- appears plausible for this state. It must be stressed, however, that spin-parity assignments and $\gamma\gamma$ coincidences will be investigated further in the future. In Fig. 3(b), predictions of $E(2_1^+)$ by several shell-model Hamiltonians are presented as examples. It is clear that while the older GXPF1 and KB3G interactions deviate significantly from the new experimental result, the modified interaction GXPF1B provides a more satisfactory description. Numerous other predictions for the Ca isotopes are available, for example, those performed in the *sdfp* model space [21] and those involving three-body forces [22, 23]. It is noted that $E(2_1^+)$ is reproduced rather well in some cases.

[1] A preliminary uncertainty of $\pm$0.05 MeV is given for all transitions deduced in the present work.

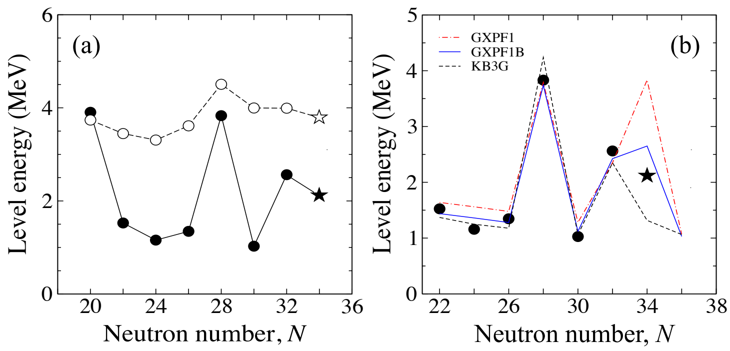

Figure 3. (Colour online) (a) Systematics of $E(2^+_1)$ [filled markers] and $E(3^-_1)$ [open markers] for Ca isotopes. (b) Examples of shell-model predictions of $E(2^+_1)$ along the Ca isotopic chain.

The structure of ^{53}Ca should also provide important information that may help shed light on the nature of the $N = 34$ subshell closure. A preliminary spectrum for ^{53}Ca deduced in the present work is is provided in Fig. 2(b). The 1.77-MeV transition is reported here for the first time, while the line at 2.24 MeV is consistent in energy with a transition previously reported in a β-decay study [24]. The relative intensities of the two γ rays in the spectrum of Fig. 2(b) and the result of Ref. [24] suggest that the transitions do not form a cascade sequence, indicating that an excited state at 1.77 MeV exists in ^{53}Ca in addition to the one at 2.24 MeV. Moreover, the observation of two states at ~ 2 MeV that are separated by ~ 0.5 MeV appears consistent with the predictions of shell-model Hamiltonians, for example, the interactions of Refs. [16, 22], among others. It is stressed, however, that the spins and parities of the two states could not be deduced from the experimental data. In the future, $\gamma\gamma$ coincidences will be investigated to confirm the suggested structure of ^{53}Ca based on the arguments presented above.

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