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Voyage to the "Island of Inversion": ^{29}Na

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Abstract. The low energy level structure of neutron-rich ^{28,29}Na has been investigated through β-delayed γ spectroscopy. The present work, which presents the first detailed spectroscopy of ^{29}Na, clearly demonstrates that for Na isotopes between ^{28}Na ($N = 17$) and ^{29}Na ($N = 18$), intruder configurations start dominating the low lying excited states, suggestive of the small $N = 20$ shell gap.

PACS. 23.40.-s β decay; double β decay; electron and muon capture – 23.20.Lv γ transitions and level energies – 21.60.Cs shell model

1 Introduction

Nuclei with $N = 20$ for $Z = 10 - 12$ are characterized by anomalously large binding energies [1] and low-lying first excited states with large $B(E2)$ transition probabilities to the ground state, *e.g.*, in ^{32}Mg [2]. The cause for this behavior, or "inversion" [3], has been attributed to the effects of intruder neutron configurations involving the fp shell in the ground state of these nuclei. Recently, large scale Monte Carlo Shell Model (MCSM) calculations by Otsuka *et al.*, [4] showed that the dominance of intruder configurations is related to the varying gap between the $d_{3/2}$ and $f_{7/2}$ orbitals, which can be explained by the shell evolution mechanism of ref. [5] in terms of the spin-isospin property of the effective nucleon-nucleon (NN) interaction. According to these calculations, the $N = 20$ shell gap should be narrower in neutron-rich nuclei than that in stable nuclei and will be reflected in the ground state properties as well as those of excited states for nuclei having N near 20.

For the Na isotopes, the comparison of the experimental masses to the shell model results within the sd shell [6] suggests that the onset of intruder dominance of the ground state occurs sharply at $N = 20$, consistent with the "island of inversion" picture. However, the electric and magnetic moments of the $N = 19, 20$ Na isotopes cannot be reproduced by the USD model at all, whereas for ^{29}Na ($N = 18$), a $\sim$ 42% mixing of intruder configurations in the ground state of ^{29}Na [7] is required to reproduce the experimental value. The spectrum of excited states provides another way to probe the mixing between normal and intruder configurations which is related to the shell gap. In the present work, we performed detailed β-delayed γ-spectroscopy measurements of ^{28,29}Na ($N = 17, 18$) to investigate the transition from normal-dominant to intruder-dominant states in the chain of neutron-rich Na isotopes.

2 Experimental details

The nuclei, ^{28,29}Ne, were produced by the fragmentation of a 140 MeV/nucleon ^{48}Ca^{20+} beam in a 733 mg/cm^2 Be target located at the object position of A1900 at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The fragments were implanted in a double-sided Si microstrip detector (DSSD), which is part of the NSCL β counting system (BCS) [8]. Fragments were identified by a combination of multiple energy loss signals and time of flight. Fragment-β correlations were established in software. The β-delayed γ rays were detected using 12 detectors of the SEgmented Germanium Array (SEGA) [9] arranged around the BCS. The Ge detectors were energy and efficiency calibrated using standard calibrated sources. Details of the experiment and analysis are discussed elsewhere [10].

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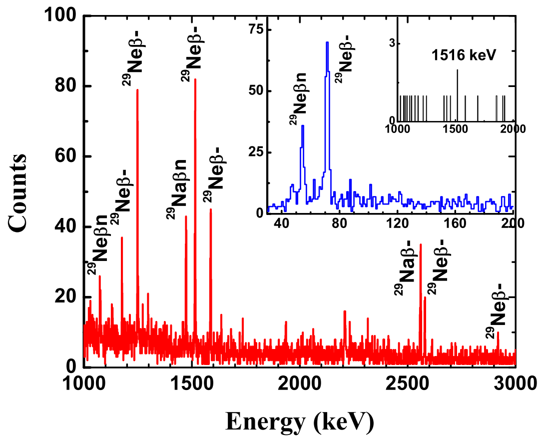

Fig. 1. β-delayed γ-ray spectra for events coming within the first 100 ms after a ^{29}Ne implant. The insert shows the β-γ-γ coincidence between the 72 keV and 1516 keV transitions.

3 Results and discussion

The energy spectrum of β-delayed γ rays emitted within 100 ms ($\sim$ 5 half lives) of a valid ^{29}Ne implant is shown in fig. 1, where transitions associated with the β-decay of ^{29}Ne are identified. Decay curves generated in coincidence with these γ lines yielded half lives consistent with each other, justifying their placement in the level scheme of ^{29}Na, which is shown in fig. 2. The observation of pairs of lines, 1177 keV ($5\% \pm 1\%$)-1249 keV ($12\% \pm 1\%$) and 1516 keV ($16\% \pm 2\%$)-1588 keV ($11\% \pm 2\%$) differing by 72 keV and the observation of the 72 keV ($54\% \pm 9\%$) transition itself, confirmed the first three excited states. Also coincidences were observed between the 72 keV and the 1516 keV transition (insert in fig. 1). The other strong γ-rays, 2578 keV ($5\% \pm 1\%$) and 2917 keV ($3.5\% \pm 0.5\%$) depopulate the 4166 keV level. The β-decay branching and the log ft values for the observed levels are shown in fig. 2. As the Q-value and the half life are known with good accuracy, the error in the branching is the main source of uncertainty in the log ft values.

The comparison of the level scheme for ^{29}Na established in the current study with shell model calculations using the USD interaction [6] clearly shows marked discrepancies (fig. 2). The measured ground state spin of ^{29}Na is $3/2^+$ [11] instead of $5/2^+$ and the large β branch to the 72 keV level makes it a likely candidate for the $5/2^+$ state. This implies that the order of the predicted ground state doublet is reversed. The predicted β-decay branch ($\sim$ 20%) [12] to the ground state is not observed experimentally. The experimental levels at 1249 keV and 1588 keV have large β-decay branches, implying spin assignments of $1/2^+$ to $5/2^+$ (J^π of ^{29}Ne ground state is calculated to be $3/2^+$). However the USD calculation predicts only one state in this spin range below 2.8 MeV with a weak β-decay branch. This is an indication of the failure of the USD shell model to explain the β-decay of ^{29}Ne. The MCSM calculations using SDPF-M interaction [7], which allow for excitations across the shell gap and mixing between the normal and intruder configurations, predict 3

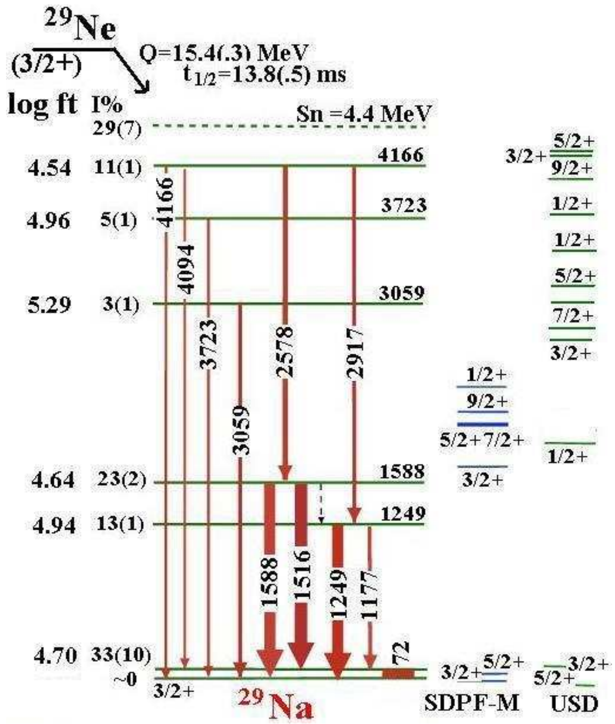

Fig. 2. Proposed level scheme for ^{29}Na. The absolute β-decay branching to each level per 100 decay is indicated along with the calculated log ft values. The neutron decay branches as well as the half life were taken from the present study. Also shown are USD shell model calculation and Monte-Carlo Shell Model (MCSM) calculations with SDPF-M interaction.

states within this spin range below 2.5 MeV. The $3/2_2^+$, $5/2_2^+$ states which have dominant $2p$-$2h$ intruder configuration are good candidates for the 1249 keV and 1588 keV experimental levels.

The better agreement between the experimental results and the MCSM calculations for ^{29}Na suggests that $2p$-$2h$ excitations play an important role in the low-energy level structure of $N = 18$ isotope. Contrary to this, the level scheme for ^{28}Na [10] shows good agreement with USD calculations, suggesting that ^{28}Na can be described rather well with pure *sd* shell configurations without invoking interference of intruder configurations. Thus the transition from normal to intruder domination for the Na isotopes happens between $N = 17$ and $N = 18$ as reflected in the low-energy excitations.

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