Coulomb Excitation of the N=50 nucleus ^{80}Zn

J. Van de Walle[a], F. Aksouh[b], F. Ames[c], T. Behrens[d], V. Bildstein[e], A. Blazhev[f], J. Cederkäll[g], E. Clément[h], T.E. Cocolios[a], T. Davinson[i], P. Delahaye[g], J. Eberth[f], A. Ekström[j], D.V. Fedorov[k], V.N. Fedosseev[g], L.M. Fraile[g], S. Franchoo[g], R. Gernhauser[d], G. Georgiev[l], D. Habs[c], K. Heyde[m], G. Huber[n], M. Huyse[a], F. Ibrahim[o], O. Ivanov[a], J. Iwanicki[p], J. Jolie[f], O. Kester[q], U. Köster[r], T. Kröll[d], R. Krücken[d], M. Lauer[s], A.F. Lisetskiy[q], R. Lutter[c], B.A. Marsh[g], P. Mayet[a], O. Niedermaier[s], T. Nilsson[q], M. Pantea[t], O. Perru[o], R. Raabe[a], P. Reiter[f], M. Sawicka[a], H. Scheit[s], G. Schrieder[t], D. Schwalm[s], M.D. Seliverstov[u], T. Sieber[g], G. Sletten[v], N. Smirnova[w], M. Stanoiu[q], I. Stefanescu[a], J.-C. Thomas[x], J.J. Valiente-Dobón[y], P. Van Duppen[a], D. Verney[o], D. Voulot[g], N. Warr[f], D. Weisshaar[f], F. Wenander[g], B.H. Wolf[g] and M. Zielińska[z]

[a]*Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Leuven, Belgium*
[b]*Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Leuven, BelgiumCEA Saclay, DAPNIA/SPhN, Gif-sur-Yvette, France*
[c]*Ludwig-Maximilians-Universität, München, Germany*
[d]*Physik Department E12, Technische Universität München, Garching, Germany*
[e]*Physik Department E12, Technische Universität München, Garching, GermanyMax-Planck-Institut für Kernphysik, Heidelberg, Germany*
[f]*Institut für Kernphysik, Universität Köln, Köln, Germany*
[g]*ISOLDE, CERN, Geneva, Switzerland*
[h]*ISOLDE, CERN, Geneva, SwitzerlandCEA Saclay, DAPNIA/SPhN, Gif-sur-Yvette, France*
[i]*University of Edinburgh, Edinburgh, United Kingdom*
[j]*Physics Department, University of Lund, Lund, Sweden*
[k]*Department of High Energy Physics, Petersburg Nuclear Physics Institute, Gatchina, Russia*
[l]*ISOLDE, CERN, Geneva, SwitzerlandCSNSM, IN2P3-CNRS, Université Paris-Sud, Orsay, France*
[m]*Vakgroep Subatomaire en Stralingsfysica, Universiteit Gent, Gent, Belgium*
[n]*Institut für Physik, Johannes Gutenburg Universität Mainz, Mainz, Germany*
[o]*Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France*
[p]*Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*
[q]*Gesellschaft für Schwerionenforschung mbH, Darmstadt, Germany*
[r]*Institut Laue-Langevin, Grenoble, FranceISOLDE, CERN, Geneva, Switzerland*
[s]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[t]*Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[u]*Institut für Physik, Johannes Gutenburg Universität Mainz, Mainz, GermanyDepartment of High Energy Physics, Petersburg Nuclear Physics Institute, Gatchina, Russia*
[v]*Physics Department, University of Copenhagen, Denmark*
[w]*Vakgroep Subatomaire en Stralingsfysica, Universiteit Gent, Gent, BelgiumCENBG, CNRS/IN2P3, Université Bordeaux, Gradignan cedex, France*
[x]*Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Leuven, BelgiumGANIL, IN2P3-CNRS-CEA, Caen, France*
[y]*Instituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[z]*Heavy Ion Laboratory, University of Warsaw, Warsaw, PolandCEA Saclay, DAPNIA/SPhN, Gif-sur-Yvette, France*

CP1012, *Frontiers in Nuclear Structure, Astrophysics, and Reactions: FINUSTAR 2*
edited by P. Demetriou, R. Julin, and S. V. Harissopulos

Abstract. Neutron rich Zinc isotopes, including the N=50 nucleus ^{80}Zn, were produced and post-accelerated at the Radioactive Ion Beam (RIB) facility REX-ISOLDE (CERN). Low-energy Coulomb excitation was induced on these isotopes after post-acceleration, yielding B(E2) strengths to the first excited 2^+ states. For the first time, an excited state in ^{80}Zn was observed and the 2^+_1 state in ^{78}Zn was established. The measured $B(E2,2^+_1 \rightarrow 0^+_1)$ values are compared to two sets of large scale shell model calculations. Both calculations reproduce the observed *B(E2)* systematics for the full Zinc isotopic chain. The results for *N*=50 isotones indicate a good *N*=50 shell closure and a strong Z=28 proton core polarization. The new results serve as benchmarks to establish theoretical models, predicting the nuclear properties of the doubly magic nucleus ^{78}Ni.

Keywords: Nuclear Structure, Radioactive Ion Beams, Coulomb Excitation
PACS: 21.10.-k,21.60.Cs,23.20.-g,25.70.De

INTRODUCTION

The evolution of shell structure in nuclei with unusual neutron-to-proton (N/Z) ratio's has become an intensive field of research in the past years. In this contribution, experimental results are presented around the *Z*=28 and *N*=50 shell gaps, i.e. the region around the astrophysical r-process waiting-point nuclei ^{80}Zn and ^{78}Ni.

Recent experiments have investigated the strength of the *Z*=28 proton shell gap. Lifetime measurements of excited states in the stable Ni isotopes (*Z*=28) have indicated the need for inclusion of the $1\pi f_{7/2}$ orbital, below the *Z*=28 gap, in the valence space in order to describe the *B(E2)* trend in these isotopes. The recent RIB measurement of the *B(E2)* value in ^{70}Ni [1] has indicated an enhanced proton core polarization when neutrons are added in the $1\nu g_{9/2}$ orbital. Both publications highlight the need for proton scattering across the *Z*=28 shell gap in order to describe the *B(E2)* strengths to the first excited 2^+_1 state.

The *N*=50 shell gap has been investigated in a series of experiments at Legnaro. The level scheme of *N*=50 isotones down to $^{82}_{32}$Ge has been obtained and compared to shell model calculations in [2]. From [2], it was concluded that the 2^+_1 state in *N*=50 isotones down to *Z*=32 have a dominating proton component in the wave function.

Combining the observations around *Z*=28 and *N*=50, one might expect that the 2^+_1 state in $^{80}_{30}$Zn has a dominant proton character and possible weakening of the *Z*=28 shell gap should be reflected in a larger then expected *B(E2)* value for this nucleus. With the presence of a strong *N*=50 shell gap, the 2^+_1 energy in the $_{Z=30}$Zn isotopic chain should increase drastically at *N*=50.

Furthermore, the Zinc isotopic chain exhibits an onset of collectivity around *N*=40, indicated by a smooth decrease of the E(2^+_1) and an increase of the *B(E2)* values in $^{70-74}$Zn [1, 3, 4]. In order to probe the further development of collectivity in neutron-rich Zinc isotopes up to the *N*=50 closed neutron shell, a program of low-energy Coulomb excitation was started at the Radioactive Ion Beam facility REX-ISOLDE [5]. This technique is a very selective tool to investigate low-lying 2^+ states and their *B(E2)* value in even-even isotopes because of the dominating E2 excitation cross section and the accurate description of the inelastic scattering process in terms of the electromagnetic interaction.

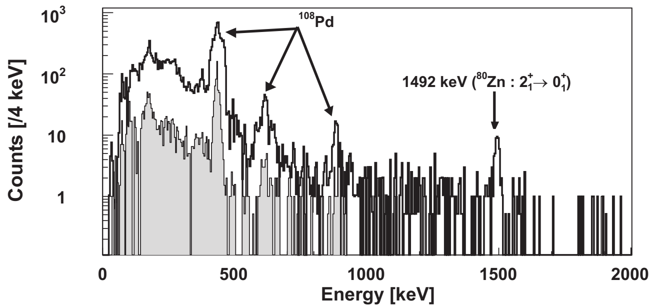

FIGURE 1. γ-spectrum in prompt coincidence with a particle, after random subtraction. The filled grey spectrum is acquired during laser off periods (10 h), the black line is the spectrum during laser on periods (100 h).

RESULTS

The neutron-rich Zinc beams were produced at ISOLDE with a standard ISOLDE UCx target and 1.4 GeV protons from the CERN PS Booster. Details on the production method can be found in [6] and [7]. The Zinc ions were post-accelerated by the REX linear accelerator [5] to a final energy of 2.87 MeV/nucleon (*A*=74,78), 2.83 MeV/nucleon (*A*=76) and 2.79 MeV/nucleon (*A*=80). The post-accelerated beam was Coulomb excited on a 2.3 mg/cm^2 ^{120}Sn target (*A*=74,76) and a 2.0 mg/cm^2 ^{108}Pd target (*A*=78,80). The γ-rays following the de-excitation process were detected by the MINIBALL Germanium detector array [8]. The scattered particles were recorded in a 500 μm thick double sided silicon strip detector (DSSSD), covering laboratory angles between θ=29°-52° (*A*=74,76,78) and θ=16.4°-52° (*A*=80). Nuclei scattered in these angular ranges stem from collisions where the distance between the nuclear surfaces does not drop below 5 fm, ensuring that the observed excitation is induced by the electromagnetic interaction. Typical average beam intensities at the secondary target were 3.0×10^5 (*A*=74), 1.1×10^5 (*A*=76), 4.3×10^3 (*A*=78) and 3.0×10^3 (*A*=80) particles per second. The beam purity was determined by switching the laser ionization periodically on and off. The difference in particle scattering in the DSSSD during laser on and off periods gives the ratio of surface (Ga,Rb) over laser ionized species (Zn). The purity (=Zinc content) of the RIB's was 83(4)% (*A*=74), 73(7)% (*A*=76), 64(13)% (*A*=78) and 43(5)% (*A*=80).

β-decay activity and room background in random coincidence with elastic scattered particles were subtracted from the prompt coincident γ-spectra. Comparing γ-ray spectra accumulated with the lasers on and with the lasers off allowed to discriminate between lines originating from the Coulomb excitation of Zinc, isobaric contaminants and the target. In the A=78 and A=80 experiments, the $2_1^+ \rightarrow 0_1^+$ transitions could be established unambiguously from this comparison of laser-on and laser-off spectra, thereby fixing the 2_1^+ state in ^{78}Zn to 730 keV and in ^{80}Zn to 1492 keV (see Fig. 1 for the ^{80}Zn laser-on and laser off-spectrum).

The known $0_1^+ \rightarrow 2_1^+$ (E2) excitation cross section of the even-even target nucleus served as normalization to determine the excitation cross section of the Zinc isotopes, which depends on the unknown *B(E2)* value. The cross sections were deduced using the coupled channels Coulomb excitation code GOSIA [9]. For ^{120}Sn and ^{108}Pd nuclei, adopted *B(E2)* values [10, 11, 12] between all states involved in the excitation process were used in the calculation. The calculated de-excitation cross section depends on the re-orientation matrix element ($<2_1^+||E2||2_1^+>$), related to the spectroscopic quadrupole moment of the 2_1^+ state. In all the current calculations, this matrix element was fixed to 0.0 eb. When fitting the $<0_1^+||E2||2_1^+>$ matrix element, assuming a rotational quadrupole moment for the 2_1^+ state, the *B(E2)* value increases by 22%(18%,15%) for prolate deformation and decreases by 13%(12%,11%) for oblate deformation for A=74(A=76,A=78). In those cases, the resulting quadrupole moments have a magnitude of 0.40(0.35,0.25) b for A=74(76,78) for both prolate and oblate deformation. Lifetime measurements of the 2_1^+ state in these isotopes can provide constraints on the *B(E2)* values and would enable us to fit the re-orientation matrix-element.

DISCUSSION

The resulting *B(E2)* and E(2_1^+) values are summarized in Fig. 2. Two shell model calculations (SMC) are included in the figures. The first set of SMC (dotted line, SMI) was performed with the shell model code ANTOINE and the realistic effective nucleon-nucleon interaction based on G-matrix theory by M. Hjorth-Jensen [13] with monopole modifications by Nowacki [14]. The model space consisted of proton/neutron $2p_{3/2}$,$1f_{5/2}$,$2p_{1/2}$ and $1g_{9/2}$ orbits around an inert ^{56}Ni core. High proton/neutron effective charges of 1.9e/0.9e were used to compensate for the large ^{56}Ni core polarization. The second set of SMC (dashed lines, SMII) were obtained with the JJ4B effective interaction [15] which is an extension of the renormalized G-matrix interaction based on the Bonn-C NN potential (JJ4APN) constructed to reproduce the experimental data for exotic Ni, Cu, Zn, Ge and *N*=50 isotones in the vicinity of ^{78}Ni. π/ν polarization charges of 1.76e and 0.97e were used. Both SM calculations reproduce the *B(E2)* trend in the Zinc isotopic chain (see Fig. 2). Around *N*=40, the SMII results are sensitive to the position of the excited 0_2^+ state. A similar problem in the Ge isotopes has been discussed in [16]. The calculated *B(E2)* strength for the *N*=50 isotones is solely due to proton excitations, since neutron excitation across the *N*=50 gap are not included in the valence space. The first set of SMC overestimates the *B(E2)* strength around mid-shell between *Z*=28 and *Z*=40, whereas it reproduces the two *B(E2)* values in ^{82}Ge and ^{80}Zn. The use of a high proton effective charge seems to be needed for these two isotopes, which have a limited numbers of valence protons outside the *Z*=28 core (four and two, resp.). This hints to a higher proton core polarization close to *Z*=28. The second set of SMC reproduces the full trend of *B(E2)* values for the *N*=50 isotones down to ^{80}Zn. Possible proton excitations across the *Z*=28 shell should be incorporated in the empirical set of matrix elements.

In conclusion, these set of Coulomb excitation experiments at low energy on neutron-rich Zinc isotopes have provided *B(E2)* and E(2_1^+) values up to the *N*=50 nucleus ^{80}Zn. The E(2_1^+) systematics of *N*=50 isotones shows a small increase in excitation energy for the 2^+ state in ^{80}Zn, with only two protons added to the assumed doubly magic ^{78}Ni. In comparison with SMC, it can be concluded that the *N*=50 neutron shell gap is still a good shell closure down to *Z*=30. No definite conclusions can be drawn on the strength of the

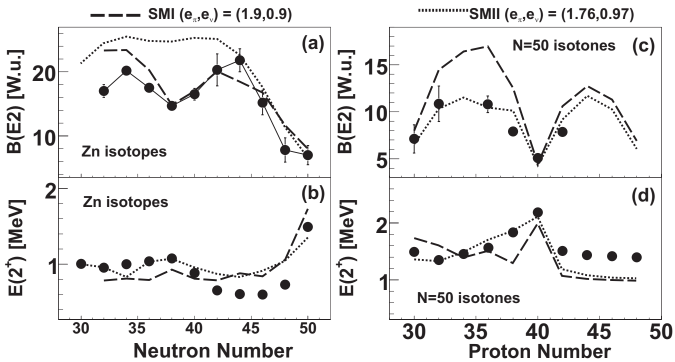

FIGURE 2. E(2) and *B(E2)* values for Zn isotopes (a,b) and *N*=50 isotones (c,d). Two sets of SMC are included, labeled by SMI and SMII, see text for details on the calculations.

Z=28 shell gap, though, the need for high proton effective charges with few valence protons outside the *Z*=28 shell gap indicate a strong proton core polarization.

ACKNOWLEDGMENTS

This work was supported by the European Union Sixth Framework through RII3-EURONS (Contract Co. 506065), the German BMBF Grant No. 06KY205I, the BriX-IAP Research Program No. P06/23, NSF Grant No. PHY-0555393, and FWO-Vlaanderen (Belgium).

REFERENCES

1. O. Perru *et al.*, *Phys. Rev. Lett.* **96**, 232501 (2006).
2. Y. Zhang *et al.*, *Phys. Rev. C* **70**, 024301 (2004).
3. S. Leenhardt *et al.*, *Eur. Phys. J. A* **14**, 1 (2002).
4. J. Van Roosbroeck *et al.*, *Phys. Rev. C* **70**, 054307 (2005).
5. O. Kester *et al.*, *Nucl. Instr. Meth. B* **204**, 20 (2003).
6. U. Köster *et al.*, *AIP Conf. Proc.* **798**, 315 (2005).
7. J. Van de Walle *et al.*, *Phys. Rev. Lett.* **99**, 142501 (2007).
8. J. Eberth *et al.*, *Prog. Part. Nucl. Phys.* **46**, 389 (2001).
9. T. Czosnyka *et al.*, *Bull. Am. Phys. Soc.* **28**, 745 (1983).
10. S. Raman, *At. Data Nucl. Data Tables* **78**, 1–128 (2001).
11. URL `http://www.nndc.bnl.gov/nndc/nudat/`.
12. L. Svensson *et al.*, *Nucl. Phys. A* **584**, 547 (1995).
13. M. Hjorth-Jensen *et al.*, *Phys. Rep.* **261**, 125 (1995).
14. N. Smirnova *et al.*, *Phys. Rev. C* **69**, 044306 (2004).
15. A. Lisetskiy *et al.*, *Phys. Rev. C* **70**, 044314 (2004).
16. M. Hasegawa *et al.*, *Nucl. Phys. A* **789**, 46–54 (2007).