Inelastic scattering of neutron-rich Ni and Zn isotopes off a proton target†

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One of the most important insight on nuclear structure obtained from studies performed at radioactive ion beam facilities is the modification of the shell closures with varying number of protons and neutrons.[1)] This shell-evolution has been widely studied, in particular on the neutron-rich side of the nuclear chart. Experimental evidence suggests, for example, the appearance of new magic numbers at $N = 32$, 34 in Ca isotopes,[2,3)] as well as the disappearance of the shell closures at $N = 8$, 20 and 28[1)] in various neutron-rich isotopes. For the Ni isotopic chain, the reduced transition probability, $B(E2)\uparrow$, measured between $N = 28$ and $N = 40$, shows a parabolic trend which indicates a subshell closure at $N = 40$. A measurement of the $B(E2)\uparrow$ value of ^{70}Ni indicated an enhanced collectivity for $N = 42$,[4)] thus a possible weakening of the $Z = 28$ gap towards ^{78}Ni. In contrast, measurements of ^{72,74}Ni[5,6)] show a reduced $B(E2)\uparrow$ value for these isotopes, corroborating the magic character of the $N = 50$ and $Z = 28$ shell gaps.

In the experiment, performed at the RIBF as part of the first SEASTAR campaign, a ^{238}U primary beam with an energy of 345 MeV/nucleon and an average intensity of 12 pnA impinged on a 3 mm thick ^{9}Be target at the entrance of BigRIPS.[7)] After selection and identification, ^{72,74}Ni and ^{76,80}Zn ions were focused on the MINOS device,[8)] composed of a 102(1) mm long liquid hydrogen target surrounded by a Time Projection Chamber (TPC). Due to the low efficiency of MINOS for the (p,p') reaction, the information of the TPC was not used, leading to a decrease of the resolution of 1 MeV γ-rays from a typical 9% using MINOS, to 14%. Reaction products were identified using the ZeroDegree spectrometer,[7)] and γ rays were detected with the DALI2 array,[9)] composed of 186 NaI(Tl) detectors. The full-energy-peak efficiency of the array was determined using a detailed Geant4 simulation and was found to be 14% at 1.33 MeV with an energy resolution of 6.2% (FWHM) for a stationary source.

Direct proton inelastic scattering cross sections to the 2_1^+ and 4_1^+ states were inferred from the γ-ray spectrum of each isotope. Such cross sections were analyzed considering two reaction models. First, a microscopic approach, based on transition densities obtained from Quasiparticle Random Phase Approximation (QRPA) and the Jeukenne-Lejeune-Mahaux (JLM) potential,[10)] was used to calculate theoretical inelastic scattering cross sections. To deal with the high energies of the beam in front of the target (≈ 270 MeV), an extension of the JLM folding model above 200 MeV/nucleon was developed. This approach provided the theoretical cross sections for inelastic scattering to the 2_1^+ state of ^{72,74}Ni and ^{80}Zn. By comparing the theoretical and experimental cross sections, neutron-to-proton matrix element ratios, M_n/M_p, were obtained. The results suggest that for the Ni isotopes $(M_n/M_p) > (N/Z)$, which implies that the contribution of the neutrons to the collectivity is enhanced. For ^{80}Zn, the calculation yields $(M_n/M_p) < (N/Z)$, which is in agreement with an increased role of the protons to the collectivity. Second, deformation lengths for the first quadrupole excitation of each isotope were obtained using the ECIS-97[11)] code. The calculations included a collective vibrational model and used the KD02 global optical potential.[12)] From the deformation lengths a matter deformation parameter $\beta_2(p,p')$ was obtained and compared with previously measured charge deformations, β_2(EM). For the Ni isotopes $\beta_2(p,p')$ is slightly higher than β_2(EM), consistent with a previous measurement on ^{74}Ni[13)] and with the conservation of the $Z = 28$ gap for neutron-rich Ni isotopes. The opposite effect is observed for ^{80}Zn, thus suggesting that the shell closure for $N = 50$ is conserved when approaching $Z = 28$. This work represents a step towards a consistent interpretation of the (p,p') data and will be beneficial for the extraction of useful physics parameters linked to nuclear structure calculations.

References
1) O. Sorlin *et al.*, Prog. Part. Nucl. Phys. **61**, 602 (2008).
2) F. Wienholtz *et al.*, Nature **498**, 346 (2013).
3) D. Steppenbeck *et al.*, Nature **502**, 207 (2013).
4) O. Perru *et al.*, Phys. Rev. Lett. **96**, 232501 (2006).
5) K. Kolos *et al.*, Phys. Rev. Lett. **116**, 122502 (2016).
6) T. Marchi *et al.*, Phys. Rev. Lett. **113**, 182501 (2014).
7) T. Kubo *et al.*, Prog. Theor. Exp. Phys. **2012** (2012).
8) A. Obertelli *et al.*, Eur. Phys. J. A **50**, 8 (2014).
9) S. Takeuchi *et al.*, Nucl. Instrum. Methods Phys. Res. A **763**, 596 (2014).
10) J.-P. Jeukenne *et al.*, Phys. Rev. C **16**, 80 (1977).
11) J. Raynal, Phys. Rev. C **23**, 2571 (1981).
12) A. Koning *et al.*, Nucl. Phys. A **713**, 231 (2003).
13) N. Aoi *et al.*, Phys. Lett. B **692**, 302 (2010).

† Condensed from the article in Phys. Rev. C **97**, 044315 (2018)
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