# Prominence of Pairing in Inclusive $(p,2p)$ and $(p,pn)$ Cross Sections from Neutron-Rich Nuclei

N. Paul,[1,2,*] A. Obertelli,[3,1,2] C. A. Bertulani,[4] A. Corsi,[1] P. Doornenbal,[2] J. L. Rodriguez-Sanchez,[1,5] G. Authelet,[1] H. Baba,[2] D. Calvet,[1] F. Château,[1] S. Chen,[6,2] A. Delbart,[1] J.-M. Gheller,[1] A. Giganon,[1] A. Gillibert,[1] T. Isobe,[2] V. Lapoux,[1] M. Matsushita,[7] S. Momiyama,[2,8] T. Motobayashi,[2] M. Niikura,[8] H. Otsu,[2] C. Péron,[1] A. Peyaud,[1] E. C. Pollacco,[1] J.-Y. Roussé,[1] H. Sakurai,[2,8] C. Santamaria,[1,2,9] M. Sasano,[2] Y. Shiga,[10] D. Steppenbeck,[2] S. Takeuchi,[2] R. Taniuchi,[2,8] T. Uesaka,[2] H. Wang,[2] K. Yoneda,[2] T. Ando,[2,8] T. Arici,[5,11] A. Blazhev,[12] F. Browne,[13] A. M. Bruce,[13] R. Carroll,[14] L. X. Chung,[15] M. L. Cortés,[3,5,2] M. Dewald,[12] B. Ding,[16] Zs. Dombradi,[17] F. Flavigny,[18] S. Franchoo,[18] F. Giacoppo,[19] M. Górska,[5] A. Gottardo,[18] K. Hadynska-Klek,[19] Z. Korkulu,[17] S. Koyama,[2,8] Y. Kubota,[2,7] A. Jungclaus,[20] J. Lee,[21] M. Lettmann,[3] B. D. Linh,[15] J. Liu,[21] Z. Liu,[16] C. Lizarazo,[5,3] C. Louchart,[3] R. Lozeva,[22,23] K. Matsui,[2,8] T. Miyazaki,[2,8] K. Moschner,[12] S. Nagamine,[8,2] N. Nakatsuka,[24] C. Nita,[25] S. Nishimura,[2] C. R. Nobs,[13] L. Olivier,[18] S. Ota,[7] Z. Patel,[14] Zs. Podolyák,[14] M. Rudigier,[14] E. Sahin,[19] T. Y. Saito,[8,2] C. Shand,[14] P.-A. Söderström,[2,26] I. G. Stefan,[18] T. Sumikama,[27] D. Suzuki,[18] R. Orlandi,[28] V. Vaquero,[20] Zs. Vajta,[17] V. Werner,[3] K. Wimmer,[8] J. Wu,[2,6] and Z. Xu[21]

[1]*IRFU, CEA, Université Paris–Saclay, F-91191 Gif-sur-Yvette, France*
[2]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[4]*Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA*
[5]*GSI Helmholtzzentrum für Schwerionenforschung, GmbH, D-64291 Darmstadt, Germany*
[6]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China*
[7]*Center for Nuclear Study, The University of Tokyo, RIKEN campus, Wako, Saitama 351-0198, Japan*
[8]*Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*
[9]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[10]*Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 172-8501, Japan*
[11]*Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany*
[12]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[13]*School of Computing Engineering and Mathematics, University of Brighton, Brighton, England BN2 4GJ, United Kingdom*
[14]*Department of Physics, University of Surrey, Guildford, England GU2 7XH, United Kingdom*
[15]*Institute for Nuclear Science and Technology, VINATOM, P.O. Box 5T-160, Nghia Do, Hanoi, Vietnam*
[16]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[17]*MTA Atomki, P.O. Box 51, Debrecen H-4001, Hungary*
[18]*Institut de Physique Nucléaire, CNRS-IN2P3, Université Paris–Sud, Université Paris–Saclay, F-91406 Orsay Cedex, France*
[19]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[20]*Instituto de Estructura de la Materia, CSIC, 28006 Madrid, Spain*
[21]*Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong*
[22]*IPHC, CNRS/IN2P3, Université de Strasbourg, F-67037 Strasbourg, France*
[23]*CSNSM, CNRS/IN2P3, Université Paris–Sud, F-91405 Orsay Campus, France*
[24]*Department of Physics, Faculty of Science, Kyoto University, Kyoto 606-8502, Japan*
[25]*Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), RO-077125 Bucharest, Romania*
[26]*Extreme Light Infrastructure-Nuclear Physics (ELI-NP), 077125 Bucharest-Măgurele, Romania*
[27]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[28]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

Fifty-five inclusive single nucleon-removal cross sections from medium mass neutron-rich nuclei impinging on a hydrogen target at ~250 MeV/nucleon are measured at the RIKEN Radioactive Isotope Beam Factory. Systematically higher cross sections are found for proton removal from nuclei with an even number of protons as compared to odd-proton number projectiles for a given neutron separation energy. Neutron removal cross sections display no even-odd splitting, contrary to nuclear cascade model predictions. Both effects are understood through simple considerations of neutron separation energies and bound state level densities originating in pairing correlations in the daughter nuclei. These conclusions are supported by comparison with semimicroscopic model predictions, highlighting the enhanced role of low-lying level densities in nucleon-removal cross sections from loosely bound nuclei.

Pairing correlations, which lower the energy of an atomic nucleus by coupling nucleons into spin-zero pairs, play a prominent role in nuclear structure [1,2]. They are responsible, for example, for the odd-even mass and nucleon separation energy staggering along isotopic chains and the reduced level density in the low-energy spectra of even-even nuclei. In the case of even-even neutron-rich nuclei, where the separation energy is very low, the ground state is often the only bound state. In the present Letter, we evidence that pairing correlations significantly drive the systematics of inclusive one-nucleon hydrogen-induced knockout cross sections for neutron-rich nuclei.

Nucleon-removal cross sections result from the interplay between nuclear structure and the reaction mechanism. In particular, nucleon-removal reactions at intermediate energies are used to evidence new structure effects far from stability, such as changes in the nuclear mass surface [3] or neutron skins [4]. Observed odd-even staggering in fragmentation cross sections has been understood as originating from the low particle separation energy and level density of the daughter nucleus [5–7]. One-nucleon knockout reactions are a tool of choice for spectroscopic studies, and exclusive cross sections between individual excited states may characterize the overlap between the initial and final wave functions [8,9]. Despite the pervasiveness of these methods, the relevant quantities that drive single nucleon-removal cross sections are still actively studied [10–15].

Here, we provide 55 new inclusive single nucleon-removal cross sections from medium-mass neutron-rich nuclei. The dataset is remarkable due to its size, the range of masses covered, and the low neutron separation energy ($S_n$) of produced nuclei from 3 to 8 MeV.

The measurements were performed at the Radioactive Isotope Beam Factory operated by the RIKEN Nishina Center for Accelerator-Based Science and the Center for Nuclear Study of the University of Tokyo. The data were collected in six different spectrometer settings over two experimental campaigns, comprising settings 1–3 and 4–6, respectively. Figure 1 shows the secondary beams exploited for this analysis, which extend over a region heretofore unexplored by single nucleon-removal inclusive cross section studies. A $^{238}$U primary beam accelerated to 345 MeV/nucleon impinged upon a 3-mm-thick $^{9}$Be production target, creating a cocktail of radioactive isotopes through in-flight fission at the entrance of the BigRIPS spectrometer [16]. The mean primary beam intensity was 12 pnA for settings 1–3 and 30 pnA for settings 4–6. Beam tracking and magnetic rigidity ($B\rho$) were provided by parallel-plate avalanche counters (PPACs) at each focal plane [17], energy loss was measured by ionization chambers [18], and plastic scintillators provided time-of-flight information. The nuclides of interest were selected via the $B\rho$-$\Delta E$-$B\rho$ method and identified via the $B\rho$-$\Delta E$-TOF method in the BigRIPS spectrometer [16]. The radioactive fragments then passed through a 38-mm-diameter cryogenic liquid hydrogen target [19] with 110 $\mu$m entrance and 150 $\mu$m exit Mylar windows located at the object focal point of the downstream ZeroDegree spectrometer [20]. The target length was 102(1) mm for settings 1–3 and 99(1) mm for settings 4–6. The energy at the entrance of the target was ~250 MeV/nucleon. A cut commensurate with the target diameter was applied to the beam spot image at the entrance of the liquid hydrogen target, as reconstructed with the PPAC detectors. Daughter nuclei were created through one nucleon removal in the target, with an energy loss ranging from 79 to 110 MeV/nucleon. The daughter nuclei were identified via the TOF-$B\rho$-$\Delta E$ method in the ZeroDegree spectrometer, which was operated in a large acceptance achromatic mode with a momentum acceptance of $\pm 3\%$. Details about the experimental campaigns can be found in [21–27].

Inclusive cross sections were determined based on events that triggered the beam detector according to

$$\sigma_{\text{inc}} = \frac{N_d}{N_p}\frac{1}{T\eta}(1-\gamma), \tag{1}$$

where $N_d/N_p$ is the ratio of daughter to parent nuclei for a given channel, $T$ is a transmission factor explained below, $\eta$ is the density of the liquid hydrogen target in atoms per square centimeter, and $\gamma$ is the percentage contribution of daughter nuclides from the empty target and beam line elements. $\gamma$ was measured from high statistics channels in empty target runs to be 12(2)% for $(p, pn)$ in settings 1–3,

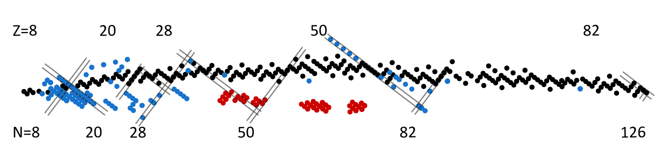


FIG. 1. Chart of the nuclides showing existing data (blue) for inclusive single nucleon-removal cross sections from exotic nuclei near 200 MeV/nucleon (see [12,15,28–55]) and data from this work (red). Parent nuclei are indicated. Stable nuclides are shown in black, and major proton and neutron shell closures are indicated by gray lines.

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