

## Quenching of Single-Particle Strength in $A = 15$ Nuclei

B. P. Kay<sup>1,\*</sup>, T. L. Tang<sup>1,†</sup>, I. A. Tolstukhin<sup>1</sup>, G. B. Roderick<sup>2</sup>, A. J. Mitchell<sup>2</sup>, Y. Ayyad<sup>3,‡</sup>, S. A. Bennett<sup>4</sup>, J. Chen<sup>3,§</sup>, K. A. Chipps<sup>5,6</sup>, H. L. Crawford<sup>7</sup>, S. J. Freeman<sup>4</sup>, K. Garrett<sup>4</sup>, M. D. Gott<sup>1</sup>, M. R. Hall<sup>5</sup>, C. R. Hoffman<sup>1</sup>, H. Jayatissa<sup>1</sup>, A. O. Macchiavelli<sup>7</sup>, P. T. MacGregor<sup>4</sup>, D. K. Sharp<sup>4</sup>, and G. L. Wilson<sup>8,1</sup>

<sup>1</sup>Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA

<sup>2</sup>Department of Nuclear Physics and Accelerator Applications, Research School of Physics, The Australian National University, Canberra ACT 2601, Australia

<sup>3</sup>Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA

<sup>4</sup>Schuster Laboratory, The University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

<sup>5</sup>Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

<sup>6</sup>Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA

<sup>7</sup>Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

<sup>8</sup>Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA

Ⓜ (Received 6 February 2022; revised 5 July 2022; accepted 29 August 2022; published 3 October 2022)

Absolute cross sections for the addition of  $s$ - and  $d$ -wave neutrons to  $^{14}\text{C}$  and  $^{14}\text{N}$  have been determined simultaneously via the  $(d,p)$  reaction at 10 MeV/u. The difference between the neutron and proton separation energies,  $\Delta S$ , is around  $-20$  MeV for the  $^{14}\text{C} + n$  system and  $+8$  MeV for  $^{14}\text{N} + n$ . The population of the  $1s_{1/2}$  and  $0d_{5/2}$  orbitals for *both* systems is reduced by a factor of approximately 0.5 compared with the independent single-particle model, or about 0.6 when compared with the shell model. This finding strongly contrasts with results deduced from intermediate-energy knockout reactions between similar nuclei on targets of  $^9\text{Be}$  and  $^{12}\text{C}$ . The simultaneous technique used removes many systematic uncertainties.

DOI: 10.1103/PhysRevLett.129.152501

**Introduction.**—Single-particle motion of nucleons in the nuclear mean field is quenched by correlations, the understanding of which has relevance to the study of nuclear structure, neutron stars, and beyond [1,2]. For stable nuclei, the degree of quenching is around 0.6 and appears to be reasonably independent of the reaction mechanism that is used to probe it, the mass of the nucleus, the orbital-angular momentum of the nucleon probed, and nucleon separation energy, and it is the same within uncertainties for both protons and neutrons [3–6].

Stable nuclei have differences between their proton ( $S_p$ ) and neutron ( $S_n$ ) separation energies,  $\Delta S$ , of about  $\pm 10$  MeV; for proton-adding or -removing reactions,  $\Delta S = S_p^* - S_n$  and for neutrons  $S_n^* - S_p$  (the asterisk denotes corrections for excited states where relevant). Information from intermediate-energy heavy-ion knockout reactions on  $^9\text{Be}$  and  $^{12}\text{C}$  targets using radioactive-ion beams (referred to as “HI knockout” here) has revealed a strong dependence between the degree of quenching (or reduction factor  $R$ , defined as the ratio of the experimental and theoretical inclusive cross sections) and  $\Delta S$ , especially at extreme values of  $|\Delta S| > 10$  MeV [5]. This trend, shown in Fig. 1(a), has been the topic of much discussion [6].

There are limited data on nucleon-removal reactions from such exotic nuclei with different reaction probes, such as transfer and proton knockout, and they appear to disagree with the results of Ref. [5], for example, the blue points in Fig. 1(b) [7,8].

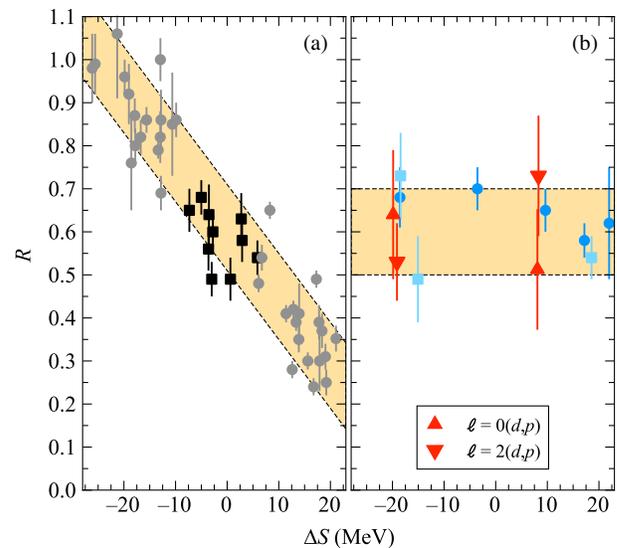


FIG. 1. (a) Degree of quenching  $R$ , as a function of  $\Delta S$  deduced from  $(e,e'p)$  reactions [3] (black squares) and from knockout reactions on  $^9\text{Be}$  and  $^{12}\text{C}$  targets (gray circles)—data and shaded band from Ref. [5], compared with (b) results from the current measurement (red triangles) and previous neutron- and proton-removing transfer reaction study of Ref. [7] (blue squares) and the  $(p,2p)$  study [8] (blue circles). The shaded band,  $R = 0.6(1)$ , in (b) is to guide the eye. The  $(e,e'p)$  and  $(p,2p)$  measurements are compared to the independent single-particle model and the rest, including the present Letter, to the shell model.

Here, we report on new data, also shown in Fig. 1(b), from a simultaneous determination of quenching factors for different momentum transfer in the nucleon-adding  $^{14}\text{N}(d,p)^{15}\text{N}$  and  $^{14}\text{C}(d,p)^{15}\text{C}$  transfer reactions at energies just above the Coulomb barrier, spanning 28 MeV in  $\Delta S$ . The  $(d,p)$  reaction is well understood, and the simultaneous measurement using these two isobars eliminates many uncertainties. Our result supports the hypothesis that the strong dependence of  $R$  on  $\Delta S$  seen in the HI-knockout data is unique to that probe.

Some nucleon-removal reaction techniques, such as the  $(p,2p)$  reaction and nucleon-transfer reactions do not yield evidence for this trend in  $\Delta S$ , but the body of work is very scarce. The neutron-removing  $^{34,36,46}\text{Ar}(p,d)^{33,35,45}\text{Ar}$  reactions [9,10] (covering a range of  $-10 \lesssim \Delta S \lesssim +12$  MeV, similar to stable nuclei) and  $^{14}\text{O}(d,^3\text{He}/t)^{13}\text{N}/^{13}\text{O}$  reactions [7] [ $\Delta S$  approximately  $-18$  MeV and  $+18$  MeV, see Fig. 1(b)] give results that are not necessarily conclusive, but consistent with  $R$  being almost constant with  $\Delta S$ . More recently, two works using the  $(p,2p)$  knockout reaction on isotopes of oxygen spanning  $-20 \lesssim \Delta S \lesssim +23$  MeV were published [8,11] and were also consistent with  $R$  being fairly constant with  $\Delta S$  [see Fig. 1(b) for the results from Ref. [8]].

From a theoretical perspective, no clear picture has yet emerged concerning the behavior of  $R$  as a function of  $\Delta S$  in HI knockout, with various efforts made to explore this via nuclear structure and reaction theory (see, for example, Refs. [6,12–18]).

To provide additional insights, we took advantage of the weak binding of the  $s$  and  $d$  states in  $^{15}\text{C}$ , which results in a large, negative value of  $\Delta S$ . We measured the *neutron-adding*  $(d,p)$  reaction at beam energies where the reaction models used are well validated. In early HI-knockout work, Terry *et al.* [19] showed that removal of the  $s_{1/2}$  neutron from  $^{15}\text{C}$ , when impinging on a  $^9\text{Be}$  target, had a quenching factor of 0.96(4), in contrast to results for well-bound states near stability.

In order to reduce systematic uncertainties in both the experimental and reaction theory sides, we studied the same reaction simultaneously on two isobars,  $^{14}\text{N}(d,p)^{15}\text{N}$  and  $^{14}\text{C}(d,p)^{15}\text{C}$ , under identical conditions, giving an assessment of  $R$  at  $\Delta S$  of approximately  $-20$  MeV and  $+8$  MeV (when considering the energy of the excited states populated), and for both  $1s_{1/2}$  and  $0d_{5/2}$  strength.

Both reactions have been studied before in normal kinematics. Previous results for the  $^{14}\text{C}(d,p)^{15}\text{C}$  reaction [20–24] are somewhat at odds with each other [25], with values of  $R$  ranging from  $\approx 0.6$  to 1.0 for both  $1s_{1/2}$  and  $0d_{5/2}$  transfer. Several of these measurements suffer from significant contamination present in the  $^{14}\text{C}$  targets and from difficulty in estimating their thickness. Previous measurements of the  $^{14}\text{N}(d,p)^{15}\text{N}$  reaction [26,27] are in better agreement with each other; those of Ref. [27] provide

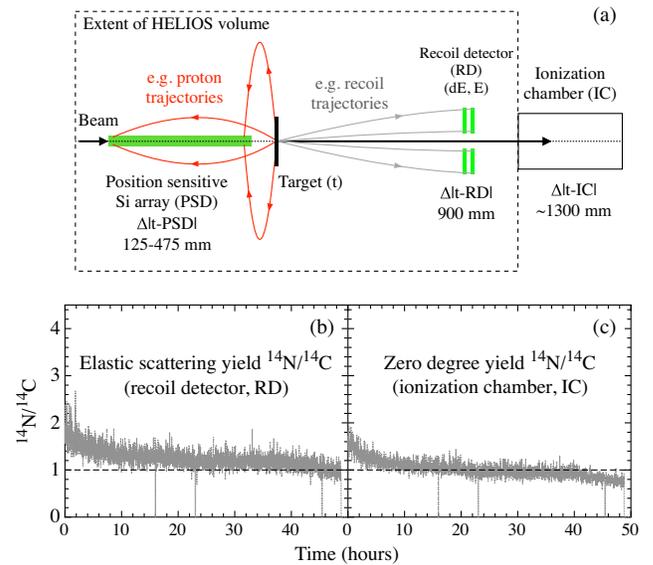


FIG. 2. (a) A schematic of the experimental setup and (b) the ratio  $^{14}\text{N}/^{14}\text{C}$  determined from elastic scattering (raw counts) in the recoil detectors sampled throughout the experiment at a rate of approximately 15 Hz. (c) The same ratio determined from the ionization chamber at the same frequency.

detailed information on the spin and parity using polarized beams. The goal of the current work is to provide an accurate comparison of the degree of quenching between these two systems lying  $\approx 28$  MeV apart in  $\Delta S$ .

*Experiment.*—The measurement was carried out in inverse kinematics using the HELIOS spectrometer [28] at the ATLAS facility at Argonne National Laboratory. A cocktail beam of  $^{14}\text{C}$  and  $^{14}\text{N}$  was accelerated to 10 MeV/u at a total intensity ( $^{14}\text{C} + ^{14}\text{N}$ ) of approximately 300 000 particles per second. A  $124(7)\text{-}\mu\text{g}/\text{cm}^2$  thick deuterated-polyethylene target was used (with an estimated hydrogen content of around 6%). The thickness was determined offline in five measurements across its surface of  $\alpha$ -particle energy-loss characteristics, before and after the experiment; the uncertainty is represented by their rms spread. A schematic of the experimental setup, discussed below, is shown in Fig. 2.

The total beam rate was determined by a fast-counting ionization chamber [29] located  $\approx 1300$  mm downstream of the target, where the discriminator rate was used as a scaler to count the total incident ions. The beam composition was sampled at a rate of 15 times per second, triggered (dominantly) by an  $\alpha$  source which illuminated the position-sensitive silicon detector array, itself the trigger for the data acquisition. The two different beam species were clearly separated by energy and energy-loss determined measurements in two segments of the ionization chamber. The beam ratio, determined by this method, was corroborated by Rutherford elastic scattering in the recoil detectors, placed 900 mm downstream from the target; a hole in the center allowed the unreacted beam to enter the

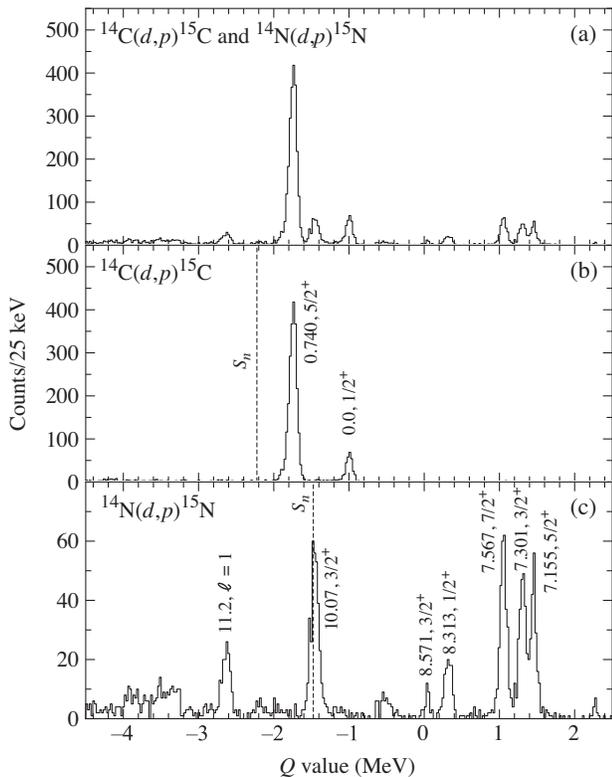


FIG. 3. (a) Simultaneously determined  $Q$ -value spectrum for the  $^{14}\text{C}(d,p)^{15}\text{C}$  and  $^{14}\text{N}(d,p)^{15}\text{N}$  reactions at 10 MeV/u. The recoil-gated reaction yields are shown in (b) and (c). States are labeled by their excitation energy in MeV, and spin and/or transferred orbital-angular momentum.

ionization chamber. Both beam-ratio determinations are shown in Fig. 2, where the ratio determined from the recoil detectors is  $\approx 10\%$  higher in favor of  $^{14}\text{N}$  due to the difference in the elastic-scattering cross sections. From the accumulated yields of  $^{14}\text{N}$  and  $^{14}\text{C}$ , a time-averaged ratio of 1:1 was determined within 3%, or approximately  $1.5 \times 10^5$  particles per second of both  $^{14}\text{C}$  and  $^{14}\text{N}$  on average.

Protons from the  $(d,p)$  reaction emitted at forward center-of-mass angles (backwards in the laboratory) for both  $^{14}\text{C}$  and  $^{14}\text{N}$  were incident on the Si array, subtending  $10^\circ \lesssim \theta_{\text{c.m.}} \lesssim 40^\circ$  (the c.m. angle and the detected position along the axis are related to one another [30]). The solenoidal  $B$  field was 2 T. A  $Q$ -value resolution of  $\approx 125$  keV FWHM was achieved, sufficient to separate close-lying states in  $^{15}\text{N}$ . The spectra, shown in Fig. 3, were recorded simultaneously, and separated by gating on the different recoils. Absolute cross sections were determined from the known target thickness and integrated beam dose in the ionization chamber.

**Data reduction and results.**—In  $^{15}\text{C}$ , the  $1s_{1/2}$  and  $0d_{5/2}$  strength is carried by the ground state and first excited state, respectively, and to first order this represents the  $(2j+1)$  vacancy of each. Data from the  $^{14}\text{C}(d,p)^{13}\text{C}$  reaction [31]

show that about 3% of the  $0d_{5/2}$  strength, and a negligible ( $<1\%$ ) component of the  $1s_{1/2}$  strength, is seen in neutron removal (probing occupancy), validating this assumption, and broadly agreeing with shell-model calculations. These results can be readily compared to the inclusive cross sections determined in HI-knockout reactions.

To extract spectroscopic factors (SF) from the experimental data, the distorted-wave Born approximation (DWBA) is used, which has been well validated over many years [4,32]. A similar model, using the adiabatic wave approximation (ADWA) provides a comparison, although at these incident beam energies results are similar.

The DWBA calculations were done using the finite-range code PTOLEMY [33], and those for the ADWA calculations used the code TWOFNR [34]. In the DWBA case, the deuteron bound state was described by the Argonne  $\nu_{18}$  potential [35]. For ADWA, the Johnson-Tandy adiabatic model was used [36]. The beam species bound-state form factors were generated using a Woods-Saxon potential, defined by  $r_0 = 1.25$  fm,  $a = 0.65$  fm,  $V_{\text{so}} = 6$  MeV,  $r_{\text{so}0} = 1.1$  fm, and  $a_{\text{so}} = 0.65$  fm. The depth of the potential was varied to reproduce the binding energy of the transferred nucleon to the final state.

Different global optical-model parametrizations were explored in the incoming  $(d + ^{14}\text{C}/^{14}\text{N})$  and outgoing  $(p + ^{15}\text{C}/^{15}\text{N})$  channels. For deuterons, these included the parametrizations of Refs. [37–39]. Those of Ref. [38] were not explicitly derived from fits which included nuclei in this mass range, while those of Refs. [37,39] were. For protons, the parametrizations of Refs. [40,41] were used. Again, these are not explicitly derived from fits to nuclei in this mass range, but from systems close in mass. For the ADWA calculations, the proton and neutron potentials used are those derived from the nucleon-nucleus optical potentials [40]. Different combinations of parameter sets and modest variations in the bound-state radius parameter resulted in variations in spectroscopic factors of approximately 15%–30%, which is commensurate with other parameter sensitivity studies [42]. These variations were most significant for the  $s$  wave in  $^{15}\text{C}$  and are reflected in the quoted uncertainties. The parametrizations used gave satisfactory fits to previously determined  $^{14}\text{C}(d,p)^{15}\text{C}$  data at similar energies [21,23,24], further validating the choices made.

The spectroscopic factors were derived from fitting the experimental angular distributions, illustrated in Fig. 4. The deduced  $R$  values are given in Table I, derived by comparing the DWBA-derived spectroscopic factors with shell-model calculations carried out using OXBASH [43] and the WBP interaction [44].

For  $^{15}\text{C}$ ,  $R$  is determined to be 0.64(15) and 0.53(9) for the  $1s_{1/2}$  and  $0d_{5/2}$  strength, respectively. The uncertainties are estimated by the rms spread in the different DWBA and ADWA fits. This contrasts the value of 0.96(4) for the  $s$ -wave strength deduced in the HI-knockout study [19].

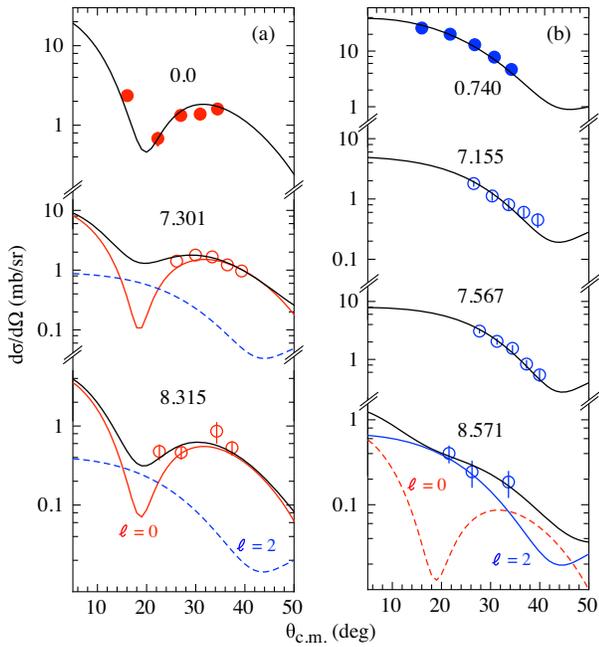


FIG. 4. Absolute differential cross sections, labeled by excitation energy in MeV, with fits (solid black lines) determined from a DWBA analysis (see text). The solid data points are for the  $^{14}\text{C}(d,p)^{15}\text{C}$  reaction and empty symbols for  $^{14}\text{N}(d,p)^{15}\text{N}$ . (a) States populated via (in the case of  $^{15}\text{N}$ , dominantly)  $\ell = 0$  transfer (red) and (b) for  $\ell = 2$  (blue). The colored solid (dashed) curves denote the dominant (subdominant)  $\ell$  transfer where relevant.

For  $^{15}\text{N}$ , the  $1s_{1/2}$  and  $0d_{5/2}$  strength is carried by two sets of multiplets, which were previously studied [26,27]. The majority of the strength ( $\approx 95\%$ ) is shared among five states between 7.155 and 8.571 MeV in excitation energy, naively arising from the coupling of a  $1s_{1/2}$  or  $0d_{5/2}$  neutron to the  $1^+$ ,  $T = 0$   $^{14}\text{N}$  ground state. A lower-lying, positive-parity doublet (5.270 and 5.299 MeV) carries the remaining  $< 5\%$  of the strength, with small spectroscopic factors seen in previous transfer-reaction studies [27]. In this measurement, they were not observed due to the detector acceptance. The omission of these states from the summed strength contributes to the overall uncertainty to a similar extent as other sources. There is no other  $1s_{1/2}$  or  $0d_{5/2}$  strength below the neutron-separation threshold. As for  $^{14}\text{C}$ , the  $1s_{1/2}$  and  $0d_{5/2}$  orbitals in  $^{14}\text{N}$  are approximately fully unoccupied, with no strength observed in neutron-removal reactions [45], corroborated by the shell-model calculations.

The  $^{15}\text{N}$   $0d_{5/2}$  strength is shared between two pure  $0d_{5/2}$  states and one mixed state, as was well established in previous studies (e.g., Ref. [27]). The  $J^\pi = 3/2^+$  state at 8.571 MeV has a strength that is approximately one third  $1s_{1/2}$  and two thirds  $0d_{5/2}$  in terms of  $S$  and, though weakly populated, represents about 10% of the total  $0d_{5/2}$  strength. The remaining strength is carried by the  $J^\pi = 5/2^+$  and

TABLE I. Values of  $\Delta S$ , DWBA (SF), and shell-model ( $\text{SF}_{\text{SM}}$ ) spectroscopic factors, and  $R$  for the  $1s_{1/2}$  and  $0d_{5/2}$  strength in  $^{15}\text{C}$  and  $^{15}\text{N}$ .

$^A X$	$nlj$	$\Delta S$ (MeV)	SF	$\text{SF}_{\text{SM}}$	$R$
$^{15}\text{C}$	$1s_{1/2}$	-19.86	0.51(12)	0.80	0.64(15)
	$0d_{5/2}$	-19.12	0.41(7)	0.78	0.53(9)
$^{15}\text{N}$	$1s_{1/2}$	+8.08	0.41(11)	0.80	0.51(14)
	$0d_{5/2}$	+8.29	0.61(12)	0.84	0.73(14)

$7/2^+$  states at 7.155 and 7.567 MeV. Most of the  $1s_{1/2}$  strength lies in the 7.301 MeV,  $J^\pi = 3/2^+$  state (which has small admixtures of  $0d_{5/2}$  strength) and the 8.313-MeV,  $J^\pi = 1/2^+$  state [mixed with a small fraction of  $\ell = 2$ ,  $0d_{3/2}$  strength as determined from a previous  $(d,p)$  study with polarized beams [27]]. The remaining  $1s_{1/2}$  strength is carried by the 8.571-MeV state mentioned above. The SF values for  $^{15}\text{N}$  (see Table I and in Fig. 1) represent the summed spectroscopic factors for the  $1s_{1/2}$  and  $0d_{5/2}$  orbitals. We note that the states discussed here account for all the  $1s_{1/2}$  and  $0d_{5/2}$  strength below the neutron-separation energy threshold and, as for  $^{15}\text{C}$ , can be readily compared to the inclusive cross sections determined in HI-knockout reactions. The larger uncertainties for  $^{15}\text{N}$  are a consequence of fitting the  $\ell = 0 + 2$  states.

**Conclusions.**—In a measurement where many systematic errors are absent because of the ratio method, we show that, for two different nuclei separated by  $\approx 28$  MeV in  $\Delta S$ , a similar degree of quenching of the single-particle strength is observed for both the  $s$  and  $d$  excitations. This contrasts with the factor-of-two difference observed in HI-knockout over the same range in  $\Delta S$ . This Letter provides the first assessment of *neutron-adding*  $(d,p)$ -reaction data at extreme  $\Delta S$ , complementing a very limited number of datasets from nucleon-removing knockout and transfer reactions, adding to the growing evidence of a discrepancy between HI knockout and results using other probes.

There is an expectation that more data will become available as radioactive beams at energies above the Coulomb barrier become more widely available for transfer-reaction studies, for example, at the Facility for Rare Isotope Beams. With many of these facilities likely to provide isobarically *impure* beams, the simultaneous beams technique discussed in this Letter could be a convenient and useful approach for future studies. Developing a body of transfer-reaction data, using both adding and removing reactions, comparable in magnitude to that of the HI-knockout data is likely essential to guide theoretical insights into this discrepancy.

The authors recognize fruitful discussions with John Schiffer and would like to acknowledge Bob Scott and the ATLAS operations team for the delivery of the cocktail beam. This material is based upon work supported by the

U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contracts No. DE-AC02-06CH11357 (Argonne), No. DE-AC02-05CH11231 (Berkeley), No. DE-AC05-00OR22725 (Oak Ridge), and Grant No. DE-FG02-96ER40978 (Louisiana); the International Technology Center Pacific (ITC-PAC) under Contract No. FA520919PA138; the UK Science and Technology Facilities Council Grants No. ST/P004423/1 and No. ST/T004797/1; and the U.S. National Science Foundation (NSF) under Cooperative Agreement No. PHY-1565546. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility.

\*kay@anl.gov

†Present address: Department of Physics, Florida State University, Tallahassee, Florida 32306, USA.

‡Present address: Instituto Galego de Física de Altas Enerxías, University of Santiago de Compostela, E-15782 Santiago de Compostela, Spain.

§Present address: Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA.

- [1] J. Carlson, S. Gandolfi, F. Pederiva, Steven C. Pieper, R. Schiavilla, K. E. Schmidt, and R. B. Wiringa, Quantum Monte Carlo methods for nuclear physics, *Rev. Mod. Phys.* **87**, 1067 (2015).
- [2] O. Hen, G. A. Miller, E. Piasezky, and L. B. Weinstein, Nucleon-nucleon correlations, short-lived excitations, and the quarks within, *Rev. Mod. Phys.* **89**, 045002 (2017).
- [3] G. J. Kramer, H. P. Blok, and L. Lapikás, A consistent analysis of  $(e, e'p)$  and  $(d, ^3\text{He})$  experiments, *Nucl. Phys.* **A679**, 267 (2001).
- [4] B. P. Kay, J. P. Schiffer, and S. J. Freeman, Quenching of Cross Sections in Nucleon Transfer Reactions, *Phys. Rev. Lett.* **111**, 042502 (2013).
- [5] J. A. Tostevin and A. Gade, Systematics of intermediate-energy single-nucleon removal cross sections, *Phys. Rev. C* **90**, 057602 (2014).
- [6] T. Aumann, C. Barbieri, D. Bazin, C. A. Bertulani, A. Bonaccorso, W. H. Dickhoff, A. Gade, M. Gómez-Ramos, B. P. Kay, A. M. Moro *et al.*, Quenching of single-particle strength from direct reactions with stable and rare-isotope beams, *Prog. Part. Nucl. Phys.* **118**, 103847 (2021).
- [7] F. Flavigny, A. Gillibert, L. Nalpas, A. Obertelli, N. Keeley, C. Barbieri, D. Beaumel, S. Boissinot, G. Burgunder, A. Cipollone *et al.*, Limited Asymmetry Dependence of Correlations from Single Nucleon Transfer, *Phys. Rev. Lett.* **110**, 122503 (2013).
- [8] L. Atar, S. Paschalis, C. Barbieri, C. A. Bertulani, P. Díaz Fernández, M. Holl, M. A. Najafi, V. Panin, H. Alvarez-Pol, T. Aumann *et al.* (R<sup>3</sup>B Collaboration), Quasifree  $(p, 2p)$  Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength, *Phys. Rev. Lett.* **120**, 052501 (2018).
- [9] J. Lee, M. B. Tsang, D. Bazin, D. Coupland, V. Henzl, D. Henzlova, M. Kilburn, W. G. Lynch, A. M. Rogers, A. Sanetullaev *et al.*, Neutron-Proton Asymmetry Dependence of Spectroscopic Factors in Ar Isotopes, *Phys. Rev. Lett.* **104**, 112701 (2010).
- [10] J. Manfredi, J. Lee, A. M. Rogers, M. B. Tsang, W. G. Lynch, C. Anderson, J. Barney, K. W. Brown, B. Brophy, G. Cerizza *et al.*, Quenching of single-particle strengths in direct reactions, *Phys. Rev. C* **104**, 024608 (2021).
- [11] S. Kawase, T. Uesaka, T. L. Tang, D. Beaumel, M. Dozono, T. Fukunaga, T. Fujii, N. Fukuda, A. Galindo-Uribarri, S. Hwang *et al.*, Exclusive quasi-free proton knockout from oxygen isotopes at intermediate energies, *Prog. Theor. Exp. Phys.* **2018**, 021D01 (2018).
- [12] Ø. Jensen, G. Hagen, M. Hjorth-Jensen, B. A. Brown, and A. Gade, Quenching of Spectroscopic Factors for Proton Removal in Oxygen Isotopes, *Phys. Rev. Lett.* **107**, 032501 (2011).
- [13] J. Okołowicz, Y. Lam, M. Płoszajczak, A. Macchiavelli, and N. Smirnova, Consistent analysis of one-nucleon spectroscopic factors involving weakly- and strongly-bound nucleons, *Phys. Lett. B* **757**, 303 (2016).
- [14] S. Paschalis, M. Petri, A. O. Macchiavelli, O. Hen, and E. Piasezky, Nucleon-nucleon correlations and the single-particle strength in atomic nuclei, *Phys. Lett. B* **800**, 135110 (2020).
- [15] J. Wylie, J. Okołowicz, W. Nazarewicz, M. Płoszajczak, S. M. Wang, X. Mao, and N. Michel, Spectroscopic factors in dripline nuclei, *Phys. Rev. C* **104**, L061301 (2021).
- [16] F. Flavigny, A. Obertelli, A. Bonaccorso, G. F. Grinyer, C. Louchart, L. Nalpas, and A. Signoracci, Nonsudden Limits of Heavy-Ion Induced Knockout Reactions, *Phys. Rev. Lett.* **108**, 252501 (2012).
- [17] J. Lei and A. Bonaccorso, Comparison of semiclassical transfer to continuum model with Ichimura-Austern-Vincent model in medium energy knockout reactions, *Phys. Lett. B* **813**, 136032 (2021).
- [18] C. A. Bertulani, A. Idini, and C. Barbieri, Examination of the sensitivity of quasifree reactions to details of the bound-state overlap functions, *Phys. Rev. C* **104**, L061602 (2021).
- [19] J. R. Terry, D. Bazin, B. A. Brown, J. Enders, T. Glasmacher, P. G. Hansen, B. M. Sherrill, and J. A. Tostevin, Absolute spectroscopic factors from neutron knockout on the halo nucleus <sup>15</sup>C, *Phys. Rev. C* **69**, 054306 (2004).
- [20] F. E. Cecil, J. R. Shepard, R. E. Anderson, R. J. Peterson, and P. Kaczowski, Charged particle reaction studies on <sup>14</sup>C, *Nucl. Phys.* **A255**, 243 (1975).
- [21] J. D. Goss, P. L. Jolivet, C. P. Browne, S. E. Darden, H. R. Weller, and R. A. Blue, Angular distribution measurements for <sup>14</sup>C( $d, p$ )<sup>15</sup>C and the level structure of <sup>15</sup>C, *Phys. Rev. C* **12**, 1730 (1975).
- [22] G. Murillo, S. Sen, and S. E. Darden, A study of the reactions <sup>14</sup>C( $\vec{d}, \vec{d}'$ )<sup>14</sup>C and <sup>14</sup>C( $\vec{d}, p$ )<sup>15</sup>C at 16.0 MeV, *Nucl. Phys.* **A579**, 125 (1994).
- [23] A. M. Mukhamedzhanov, V. Burjan, M. Gulino, Z. Hons, V. Kroha, M. McCleskey, J. Mrázek, N. Nguyen, F. M. Nunes, Š. Piskoř *et al.*, Asymptotic normalization coefficients from the <sup>14</sup>C( $d, p$ )<sup>15</sup>C reaction, *Phys. Rev. C* **84**, 024616 (2011).
- [24] M. McCleskey, A. M. Mukhamedzhanov, L. Trache, R. E. Tribble, A. Banu, V. Eremenko, V. Z. Goldberg, Y.-W. Lui, E. McCleskey, B. T. Roeder *et al.*, Determination of the asymptotic normalization coefficients for <sup>14</sup>C +  $n \leftrightarrow$  <sup>15</sup>C, the <sup>14</sup>C( $n, \gamma$ )<sup>15</sup>C reaction rate, and evaluation of a new

- method to determine spectroscopic factors, *Phys. Rev. C* **89**, 044605 (2014).
- [25] J. Lee, M. B. Tsang, and W. G. Lynch, Neutron spectroscopic factors from transfer reactions, *Phys. Rev. C* **75**, 064320 (2007).
- [26] G. W. Philips and W. W. Jacobs, Structure of  $^{15}\text{N}$  and the  $^{14}\text{N}(d,p)^{15}\text{N}$  Reaction, *Phys. Rev.* **184**, 1052 (1969).
- [27] W. Kretschmer, G. Pröbstle, and W. Stach, Investigation of low-lying states of  $^{15}\text{N}$  via  $^{14}\text{N}(d,p)^{15}\text{N}$  reactions with vector polarized deuterons, *Nucl. Phys.* **A333**, 13 (1980).
- [28] J. C. Lighthall, B. B. Back, S. I. Baker, S. J. Freeman, H. Y. Lee, B. P. Kay, S. T. Marley, K. E. Rehm, J. E. Roher, J. P. Schiffer *et al.*, Commissioning of the HELIOS spectrometer, *Nucl. Instrum. Methods Phys. Res., Sect. A* **622**, 97 (2010).
- [29] J. Lai, L. Afanasieva, J. C. Blackmon, C. M. Deibel, H. E. Gardiner, A. Lauer, L. E. Linhardt, K. T. Macon, B. C. Rasco, C. Williams *et al.*, Position-sensitive, fast ionization chambers, *Nucl. Instrum. Methods Phys. Res., Sect. A* **890**, 119 (2018).
- [30] For a given beam energy ( $E_{\text{beam}}$ ) and outgoing ion of mass  $A$  and charge  $q$ , the position ( $z$ ) and laboratory angle ( $\theta$ ) are proportional such that  $z \propto \sqrt{AE_{\text{beam}}} \cos \theta / qB$ , as shown in A. H. Wuosmaa, J. P. Schiffer, B. B. Back, C. J. Lister, and K. E. Rehm, A solenoidal spectrometer for reactions in inverse kinematics, *Nucl. Instrum. Methods Phys. Res., Sect. A* **580**, 1290 (2007).
- [31] M. Yasue, M. H. Tanaka, T. Hasegawa, K. Nisimura, H. Ohnuma, H. Shimizu, K. Ieki, H. Toyokawa, M. Iwase, J. Imura *et al.*, Structure of  $^{14}\text{C}$  studied by the  $^{14}\text{C}(p,d)^{13}\text{C}$  reaction, *Nucl. Phys.* **A509**, 141 (1990).
- [32] J. P. Schiffer, C. R. Hoffman, B. P. Kay, J. A. Clark, C. M. Deibel, S. J. Freeman, A. M. Howard, A. J. Mitchell, P. D. Parker, D. K. Sharp *et al.*, Test of Sum Rules in Nucleon Transfer Reactions, *Phys. Rev. Lett.* **108**, 022501 (2012).
- [33] M. H. Macfarlane and S. C. Pieper, ANL-76-11 Rev. 1, Argonne National Laboratory, 1978.
- [34] J. A. Tostevin, University of Surrey version of the code TWOFNR (of M. Toyama, M. Igarashi, and N. Kishida) and code FRONT (private communication).
- [35] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Accurate nucleon-nucleon potential with charge-independence breaking, *Phys. Rev. C* **51**, 38 (1995).
- [36] R. C. Johnson and P. C. Tandy, An approximate three-body theory of deuteron stripping, *Nucl. Phys.* **A235**, 56 (1974).
- [37] H. An and C. Cai, Global deuteron optical model potential for the energy range up to 183 MeV, *Phys. Rev. C* **73**, 054605 (2006).
- [38] W. W. Daehnick, J. D. Childs, and Z. Vrcelj, Global optical model potential for elastic deuteron scattering from 12 to 90 MeV, *Phys. Rev. C* **21**, 2253 (1980).
- [39] Y. Zhang, D. Y. Pang, and J. L. Lou, Optical model potential for deuteron elastic scattering with 1p-shell nuclei, *Phys. Rev. C* **94**, 014619 (2016).
- [40] A. J. Koning and J. P. Delaroche, Local and global nucleon optical models from 1 keV to 200 MeV, *Nucl. Phys.* **A713**, 231 (2003).
- [41] R. L. Varner, W. J. Thompson, T. L. McAbee, E. J. Ludwig, and T. B. Clegg, A global nucleon optical model potential, *Phys. Rep.* **201**, 57 (1991).
- [42] F. Flavigny, N. Keeley, A. Gillibert, and A. Obertelli, Single-particle strength from nucleon transfer in oxygen isotopes: Sensitivity to model parameters, *Phys. Rev. C* **97**, 034601 (2018).
- [43] B. A. Brown, A. Etchegoyen, N. S. Godwin, W. D. M. Rae, W. A. Richter, W. E. Ormand, E. K. Warburton, J. S. Winfield, L. Zhao, and C. H. Zimmerman, MSU-NSCL Report No. 1289.
- [44] E. K. Warburton and B. A. Brown, Effective interactions for the  $0p1s0d$  nuclear shell-model space, *Phys. Rev. C* **46**, 923 (1992). The configuration space is *spsdpf*, and up to  $4 \hbar\omega$  excitations are allowed.
- [45] F. Hinterberger, G. Mairle, U. Schmidt-Rohr, P. Turek, and G. J. Wagner, Single nucleon pick-up from  $^{12}\text{C}$  and  $^{14}\text{N}$  with 52 MeV deuterons, *Nucl. Phys.* **A106**, 161 (1967).