

This is a repository copy of *Quasifree (p, 2p) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/126821/>

Version: Published Version

Article:

Atar, Leyla, Paschalis, Stefanos orcid.org/0000-0002-9113-3778, Barbieri, C. et al. (98 more authors) (2018) Quasifree (p, 2p) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength. *Physical Review Letters*. 052501. ISSN 1079-7114

<https://doi.org/10.1103/PhysRevLett.120.052501>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Quasifree ($p, 2p$) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength

L. Atar,^{1,2*} S. Paschalis,^{3,1} C. Barbieri,⁴ C. A. Bertulani,⁵ P. Díaz Fernández,⁶ M. Holl,¹ M. A. Najafi,⁷ V. Panin,^{1,8} H. Alvarez-Pol,⁶ T. Aumann,^{1,2,†} V. Avdeichikov,⁹ S. Beceiro-Novo,⁶ D. Bemmerer,¹⁰ J. Benlliure,⁶ J. M. Boillos,^{6,2} K. Boretzky,² M. J. G. Borge,¹¹ M. Caamaño,⁶ C. Caesar,^{2,1} E. Casarejos,¹² W. Catford,⁴ J. Cederkall,⁹ M. Chartier,¹³ L. Chulkov,¹⁴ D. Cortina-Gil,⁶ E. Cravo,¹⁵ R. Crespo,¹⁶ I. Dillmann,^{17,2} Z. Elekes,¹⁸ J. Enders,¹ O. Ershova,² A. Estrade,¹⁹ F. Farinon,¹ L. M. Fraile,²⁰ M. Freer,²¹ D. Galaviz Redondo,²² H. Geissel,^{2,17} R. Gernhäuser,²³ P. Golubev,⁹ K. Göbel,²⁴ J. Hagdahl,²⁵ T. Heftrich,²⁴ M. Heil,² M. Heine,²⁶ A. Heinz,²⁵ A. Henriques,²² A. Hufnagel,¹ A. Ignatov,¹ H. T. Johansson,²⁵ B. Jonson,²⁵ J. Kahlbow,¹ N. Kalantar-Nayestanaki,⁷ R. Kanungo,²⁷ A. Kelic-Heil,² A. Knyazev,⁹ T. Kröll,¹ N. Kurz,² M. Labiche,²⁸ C. Langer,²⁴ T. Le Bleis,²³ R. Lemmon,²⁸ S. Lindberg,²⁵ J. Machado,²² J. Marganiec-Gałązka,^{1,29,2} A. Movsesyan,¹ E. Nacher,¹¹ E. Y. Nikolskii,¹⁴ T. Nilsson,²⁵ C. Nociforo,² A. Perea,¹¹ M. Petri,³ S. Pietri,² R. Plag,² R. Reifarth,²⁴ G. Ribeiro,¹¹ C. Rigollet,⁷ D. M. Rossi,^{1,2} M. Röder,^{10,30} D. Savran,²⁹ H. Scheit,¹ H. Simon,² O. Sorlin,³¹ I. Syndikus,¹ J. T. Taylor,¹⁵ O. Tengblad,¹¹ R. Thies,²⁵ Y. Togano,⁸ M. Vandebrouck,³¹ P. Velho,²² V. Volkov,¹⁴ A. Wagner,¹⁰ F. Wamers,^{2,1} H. Weick,² C. Wheldon,²¹ G. L. Wilson,³² J. S. Winfield,^{2,17} P. Woods,¹⁹ D. Yakorev,¹⁰ M. Zhukov,²⁵ A. Zilges,³³ and K. Zuber³⁰

(R³B Collaboration)

¹Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

²GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

³Department of Physics, University of York, York YO10 5DD, United Kingdom

⁴Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

⁵Texas A&M University-Commerce, 75428 Commerce, Texas, United States of America

⁶Departamento de Física de Partículas, Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Spain

⁷KVI-CART, University of Groningen, Zernikelaan 25, 9747 AA Groningen, Netherlands

⁸RIKEN, Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, 351-0198 Wako, Saitama, Japan

⁹Department of Physics, Lund University, 22100 Lund, Sweden

¹⁰Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiation Physics, P.O.B. 510119, 01314 Dresden, Germany

¹¹Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain

¹²Universidad de Vigo, 36310 Vigo, Spain

¹³University of Liverpool, L69 3BX Liverpool, United Kingdom

¹⁴NRC Kurchatov Institute, place Akademika Kurchatova, Moscow 123182, Russia

¹⁵Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

¹⁶Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal

¹⁷Justus-Liebig-Universität Gießen, 35392 Gießen, Germany

¹⁸ATOMKI Debrecen, Bem tér 18/c, 4026 Debrecen, Hungary

¹⁹University of Edinburgh, EH8 9YL Edinburgh, United Kingdom

²⁰Grupo de Física Nuclear & IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain

²¹University of Birmingham, B15 2TT Birmingham, United Kingdom

²²Nuclear Physics Center, University of Lisbon, 1649-003 Lisboa, Portugal

²³Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

²⁴Goethe-Universität Frankfurt, Max-von-Laue Straße 1, 60438 Frankfurt am Main, Germany

²⁵Chalmers University of Technology, Kemivägen 9, 412 96 Göteborg, Sweden

²⁶IPHC-CNRS/Université de Strasbourg, 67037 Strasbourg, France

²⁷Saint Mary's University, 923 Robie Street, B3H 3C3 Halifax, Nova Scotia, Canada

²⁸Science and Technology Facilities Council-Daresbury Laboratory, WA4 4AD Warrington, United Kingdom

²⁹Extreme Matter Institute, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

³⁰Technische Universität Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, 01069 Dresden, Germany

³¹GANIL, Boulevard Henri Becquerel, 14076 Caen, France³²University of Surrey, GU2 7XH Surrey, United Kingdom³³Universität zu Köln, Institut für Kernphysik, Zùlpicher Straße 77, 50937 Köln, Germany

(Received 14 August 2017; revised manuscript received 8 November 2017)

Quasifree one-proton knockout reactions have been employed in inverse kinematics for a systematic study of the structure of stable and exotic oxygen isotopes at the R³B/LAND setup with incident beam energies in the range of 300–450 MeV/u. The oxygen isotopic chain offers a large variation of separation energies that allows for a quantitative understanding of single-particle strength with changing isospin asymmetry. Quasifree knockout reactions provide a complementary approach to intermediate-energy one-nucleon removal reactions. Inclusive cross sections for quasifree knockout reactions of the type $^A\text{O}(p, 2p)^{A-1}\text{N}$ have been determined and compared to calculations based on the eikonal reaction theory. The reduction factors for the single-particle strength with respect to the independent-particle model were obtained and compared to state-of-the-art *ab initio* predictions. The results do not show any significant dependence on proton-neutron asymmetry.

DOI:

States near the Fermi surface of closed-shell nuclei display single-particle (SP) behavior [1,2]. This fact underpins the success of the nuclear shell model (SM) [3] and motivates a simplified description of nuclei in terms of an independent-particle model (IPM), in which nucleons move freely in an average potential. Deviations from the simple IPM description have been quantified by ($e, e'p$) measurements on stable nuclei, for instance, at the NIKHEF facility, evidencing that the strength of dominant SP states, the so-called spectroscopic factor (SF), is reduced by about 30%–40% in comparison to predictions based on the IPM [4,5]. This deviation can be understood as a consequence of correlations among nucleons leading to a fragmentation of the SP strength and a partial occupation of states above the Fermi energy.

Correlations among the nucleons are taken into account in the SM, which reproduces the resulting configuration mixing and SP strength distribution close to the Fermi surface reasonably well. Still, an overall reduction of SF compared to the SM has been reported, which is usually quantified by a reduction factor R , defined as the ratio of the experimental cross section to theoretical predictions (based on either the IPM or SM). These remaining deviations are often attributed to correlations beyond those taken into account in the SM such as short-range correlations (SRC), including those induced by the short-range tensor interaction [6–8]. We note that signatures of SRC in momentum distributions [9] and strong proton-neutron correlations [10,11] have been observed in high-energy electron scattering.

The first systematic studies on SFs for unstable isotopes have been undertaken by evaluating one-nucleon removal cross sections at intermediate energies close to 100 MeV/u

[12] [One-nucleon removal encompasses any process producing an $A-1$ nucleus in the final state including different reaction mechanisms such as individual nucleon-nucleon collisions or inelastic excitation and decay. Still, this process is sometimes referred to as (heavy-ion induced) knockout in the literature.]. A recent compilation of the existing data by Tostevin and Gade [13] reports reduction factors relative to the SM description for a large number of isotopes. While the residual interactions in SM calculations can account for the spread of the SP strength near the Fermi surface, the data of Ref. [13] suggest a very strong dependance of SFs on the isospin asymmetry of nuclei, quantified by the difference between one-proton and one-neutron separation energies $\pm(S_p - S_n)$. In contrast, more recent results from transfer reactions at lower beam energies suggest a constant quenching of SFs and do not indicate such a pronounced isospin dependance [14–16]. *Ab initio* calculations, such as the self-consistent Green's function (SCGF) [17,18] or coupled-cluster theory [19], suggest indeed a reduction of SFs due to correlations but with a weak asymmetry dependance.

The isospin dependance is still heavily debated and it is unsettled whether this is an indication of correlation effects missing in SM calculations [20] or deficiencies in the reaction model, which is based on the sudden and eikonal approximations [21]. In particular, an asymmetric momentum distribution with a very large tail towards low momenta was observed in Ref. [21] after removing a tightly bound nucleon, indicating strong deviations from the approximations made. An additional potential issue lies in the fact that the sensitivity of the one-nucleon removal reaction induced by light composite nuclear targets, e.g., Be or C, at intermediate beam energies of around 100 MeV/u is concentrated strongly at the nuclear surface [22,23], probing only the outer part of the projectile wave function, which limits the access to deeply bound states.

In this Letter, we introduce a complementary experimental approach based on quasifree scattering (QFS)

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

138 reactions in inverse and complete kinematics using a proton
 139 target bombarded by a high-energy beam of radioactive and
 140 stable nuclei. The oxygen isotopic chain provides thereby a
 141 large selection of nuclei with different nucleon separation
 142 energies that are suitable for a systematic study of the
 143 asymmetry dependence of the SP strength.

144 The usage of proton targets increases the sensitivity to
 145 deeply bound states, which in turn allows for a more
 146 complete investigation of the SP wave function [24].
 147 Since the nucleon-nucleon (NN) total cross section has a
 148 minimum at around 300 MeV, final-state interactions, such as
 149 rescattering and absorption effects, are minimized at beam
 150 energies of around 400 MeV/u, where the energies of the
 151 outgoing nucleons amount to 200 MeV in average. At these
 152 energies, the picture of a localized reaction is supported,
 153 which can be described as an elementary QFS process
 154 between the struck nucleon and the target proton, where
 155 both nucleons are scattered at large angles centered around
 156 45° [25]. Below 100 MeV, the NN cross section rises steeply
 157 and causes a strong distortion of the outgoing nucleon wave
 158 functions; i.e., the nucleus becomes opaque and the reaction
 159 thus probes only the surface at lower beam energies.

160 The theoretical description of QFS used here is based on
 161 the eikonal reaction model where the effect of multiple
 162 scattering is treated by use of the distorted wave impulse
 163 approximation with a complex optical potential [24]. The
 164 internal momentum of the knocked-out nucleon is related
 165 directly to the recoil momentum of the residual fragment,
 166 which is measured experimentally, and can be interpreted in
 167 terms of the angular momentum of the corresponding
 168 SP state.

169 The experiment was performed at the R³B/LAND setup at
 170 GSI Helmholtzzentrum für Schwerionenforschung in
 171 Darmstadt, Germany. A primary ⁴⁰Ar beam was accelerated
 172 up to 500 MeV/u and directed onto a Be target. The heavy
 173 reaction fragments were selected in the fragment separator
 174 FRS according to their magnetic rigidity [26] and transported
 175 to the experimental hall. The secondary beam was delivered
 176 as a cocktail beam containing different isotopes around a
 177 certain nominal rigidity. The incoming ions were identified
 178 on an event-by-event basis. The solid reaction targets were
 179 located at the center of the Crystal Ball detector array (CB)
 180 [27] and surrounded by double-sided silicon strip detectors
 181 (DSSSD) [28] for energy-loss and position measurements.
 182 The CB covers a solid angle of close to 4π and was used for
 183 the detection of γ rays and high-energy nucleons from the
 184 knockout reactions. The heavy reaction products were
 185 deflected by the dipole magnet ALADIN and charges and
 186 masses were reconstructed by several tracking detectors. A
 187 detailed description of the setup can be found in
 188 Refs. [25,29–32]. The experiment was performed with
 189 CH₂ (459, 922 mg/cm²) and C (559, 935 mg/cm²) targets
 190 as well as with an empty target frame. The C target was used
 191 to estimate and subtract C-induced reactions in the CH₂
 192 target, while measurements without target were made to
 193 estimate background contributions.

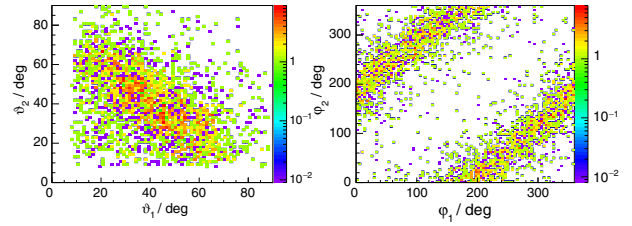


FIG. 1. Correlations of polar (ϑ) and azimuthal (φ) angles of
 two protons detected in the CB for the reaction $^{16}\text{O}(p, 2p)^{15}\text{N}$
 measured in coincidence with the ^{15}N fragment.

The angular correlations of the knocked-out projectile
 nucleon and the recoiled target proton shown in Fig. 1 for
 the reaction $^{16}\text{O}(p, 2p)^{15}\text{N}$ exhibit the characteristics of
 QFS indicating a nearly coplanar back-to-back scattering.
 Slight modifications compared to free NN scattering are
 caused by the binding energy and the internal motion of the
 nucleons in the nucleus [25]. A coincident measurement of
 the knocked-out and recoiled nucleons as well as of the
 residual fragment allows an unambiguous and practically
 background-free reconstruction of QFS channels.

It is emphasized that all reaction channels were selected
 requiring the simultaneous detection of two protons and a
 bound residual N fragment ($A-1$) in the final state. The
 inclusive cross sections thus contain the population of the
 ground and bound excited states of the fragment. In order to
 extract the exclusive cross sections for the population of
 excited states below the particle threshold, the measure-
 ment of γ rays in coincidence has been analyzed for all
 reaction channels. In the following paragraphs, the reaction
 $^{16}\text{O}(p, 2p)^{15}\text{N}$ will be presented in detail and the results of
 the other reaction channels will be summarized later.
 Additional results including γ spectra and momentum
 distributions for the other isotopes will be presented
 together with a more detailed description of the analysis
 procedure in a forthcoming article.

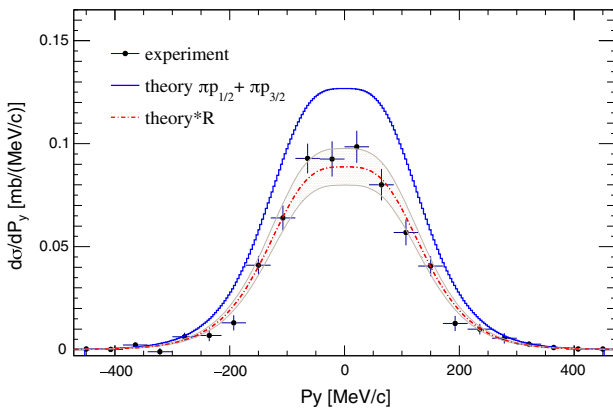
The measured cross sections were subject to various
 corrections such as for the $2p$ detection efficiency, which
 was crucial since its uncertainty dominates the systematic
 uncertainty of the deduced cross sections. This efficiency
 has been obtained from simulations of $(p, 2p)$ events
 according to the QFS kinematics at the various beam
 energies listed in Table I. The simulation of the experiment
 was performed within the R3Broot framework [33,34] based
 on the GEANT4 toolkit [35] and using different physics
 models [36–38] for the treatment of reactions in the
 detector material. The observed 6% variation of the
 deduced detection efficiency of 63% with the different
 model inputs was treated as a systemic uncertainty. For the
 reaction $^{16}\text{O}(p, 2p)^{15}\text{N}$, for instance, an inclusive cross
 section of $26.8(9)[1.7]$ mb was deduced, where the sys-
 tematic uncertainty is given in square brackets (see Table I).
 This cross section includes proton knockout from the $0p_{1/2}$
 orbit to the ground state (g. s.) of ^{15}N and from the $0p_{3/2}$

TABLE I. Measured and calculated ($p, 2p$) cross sections for the reactions given in the first column. The second and third columns give neutron and proton separation energies of the residual $A-1\text{N}$, respectively [39,40]. In the fourth column, the mean beam energy in the middle of the CH_2 target is given. In the fifth column, inclusive cross sections for all bound states are listed along with statistical (round brackets) and systematic uncertainties (square brackets). The predictions from eikonal theory (sixth column) are shown for the knockout of $0p_{1/2}$ protons except for ^{16}O , where the sum of $0p_{1/2}$ and $0p_{3/2}$ contributions is given. The last column gives the resulting reduction factor R relative to the IPM with its total uncertainty.

Reaction	$S_n(^{A-1}\text{N})$ [MeV]	$S_p(^{A-1}\text{N})$ [MeV]	E_{beam} [MeV/u]	σ_{exp} [mb]	σ_{theory} [mb]	R
$^{13}\text{O}(p, 2p)^{12}\text{N}$	15.0	0.60	401	5.78(0.91)[0.37]	18.96	...
$^{14}\text{O}(p, 2p)^{13}\text{N}$	20.1	1.94	351	10.23(0.80)[0.65]	15.09	0.68(7)
$^{15}\text{O}(p, 2p)^{14}\text{N}$	10.6	7.55	310	18.92(1.82)[1.20]	12.19	...
$^{16}\text{O}(p, 2p)^{15}\text{N}$	10.9	10.2	451	26.84(0.90)[1.70]	38.34	0.70(5)
$^{17}\text{O}(p, 2p)^{16}\text{N}$	2.49	11.5	406	7.90(0.26)[0.50]	12.23	0.65(5)
$^{18}\text{O}(p, 2p)^{17}\text{N}$	5.89	13.1	368	17.80(1.04)[1.13]	9.95	...
$^{21}\text{O}(p, 2p)^{20}\text{N}$	2.16	17.9	449	5.31(0.23)[0.34]	9.16	0.58(4)
$^{22}\text{O}(p, 2p)^{21}\text{N}$	4.59	19.6	415	5.93(0.39)[0.40]	8.54	...
$^{23}\text{O}(p, 2p)^{22}\text{N}$	1.28	21.2	448	5.01(0.97)[0.33]	8.06	0.62(13)

237 orbit to bound excited states (see discussion below). The
 238 removal of a proton from the $0s_{1/2}$ orbit can only populate
 239 unbound states of ^{15}N and is thus not considered.

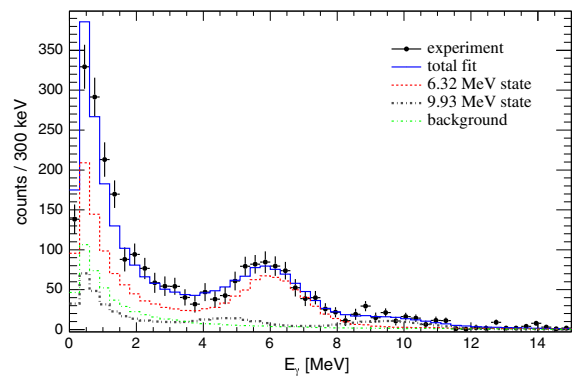
240 Figure 2 shows the projection of the transverse momen-
 241 tum distribution of ^{15}N on the y axis (symbols). Since this
 242 includes proton knockout from the $0p_{1/2}$ and $0p_{3/2}$ orbits,
 243 it is compared to the sum of the theoretical distributions for
 244 both orbits. The theoretical cross sections were calculated
 245 with the eikonal theory of Ref. [24] and amount to 13.3 and
 246 25.3 mb assuming knockout from completely filled $0p_{1/2}$
 247 and $0p_{3/2}$ orbits, respectively. The reduction factor R
 248 amounts to $R = 0.70(5)$ and agrees well with the result
 249 $R = 0.65(5)$ from ($e, e'p$) data [5]. The dash-dotted curve
 250 in Fig. 2 shows the distribution of the total spectrum (solid)
 251 scaled by R . The scaled distribution describes the



F2:1 FIG. 2. Projection P_y of the momentum distribution of ^{15}N after
 F2:2 one-proton removal from ^{16}O , compared to the sum of theoretical
 F2:3 distributions for the $0p_{1/2}$ and $0p_{3/2}$ orbits (solid curve) and
 F2:4 the one scaled to the experimental cross section (dashed-dotted curve
 F2:5 with shaded 2σ uncertainty range).

252 experimental data well, confirming our assumption that
 253 the data is dominated by proton knockout from orbits
 254 of $\ell = 1$.

255 Exclusive cross sections were extracted from a fit to the
 256 coincident γ spectrum as shown in Fig. 3 for the
 257 $^{16}\text{O}(p, 2p)^{15}\text{N}$ reaction. Besides the simulated two tran-
 258 sitions from the excited $3/2^-$ states at 6.63 and 9.93 MeV, a
 259 background contribution arising from ($p, 2p$) reactions
 260 without γ -ray emission was included in the fit. The
 261 population of the g. s. was obtained by subtracting the
 262 contribution of the excited states from the total cross
 263 section resulting in SF values of 1.60(39), 2.01(23), and
 264 0.58(13) for populating the g. s. and the $3/2^-$ states at 6.63
 265 and 9.93 MeV, respectively. Note that the measured SF for
 266 the $1/2^-$ g. s. amounts to 80% of the IPM, while the $0p_{3/2}$
 267 strength adds up to 65%, whereas the SCGF calculation
 268 discussed below predicts 78% and 80%, respectively.
 269 However, theory does not reproduce the observed



F3:1 FIG. 3. Doppler-corrected single- γ spectrum measured in
 F3:2 coincidence with ^{15}N and two protons in CB. The simulated
 F3:3 decays of the $3/2^-$ states at 6.32 and 9.93 MeV were fitted to the
 F3:4 experimental data together with the background contribution. The
 F3:5 total fit is displayed by the solid curve.

270 fragmentation of $3/2^-$ strength, which is collected in one
 271 single state. The experimental SF values for the states
 272 discussed above are consistent with the results from $(e, e'p)$
 273 data [41,42].

274 The measured inclusive cross sections for proton knock-
 275 out are listed in Table I. Since only bound states of the
 276 residual $A-1N$ are detected, the results fluctuate with
 277 changes of the separation energies along the isotopic chain
 278 as a consequence of the very different nucleon separation
 279 energies of the daughter nuclei. $^{16}\text{O}(p, 2p)^{15}\text{N}$ has the
 280 largest cross section since both knockout from $0p_{1/2}$ and
 281 $0p_{3/2}$ populate bound states in ^{15}N . For the $^{15}\text{O}(p, 2p)^{14}\text{N}$
 282 and $^{18}\text{O}(p, 2p)^{17}\text{N}$ reactions, the $0p_{1/2}$ protons contribute
 283 fully, but only part of the (fragmented) $0p_{3/2}$ strength is
 284 below the continuum threshold. The case is similar for the
 285 ^{22}O projectile, albeit with a larger contribution of the $0p_{3/2}$
 286 proton strength due to the relatively large neutron separa-
 287 tion energy of 4.59 MeV of the daughter nucleus ^{21}N [39].
 288 The case of $^{13}\text{O}(p, 2p)^{12}\text{N}$ is at the other extreme, since the
 289 knockout from the $0p_{1/2}$ orbit contributes only partially to
 290 the cross section due to the very weakly bound protons in
 291 ^{12}N ($S_p = 0.6$ MeV [39]). The rest of the reaction channels
 292 can be safely considered as arising from the full $0p_{1/2}$
 293 proton knockout alone. Table I also gives the corresponding
 294 theoretical cross sections, assuming the IPM occupation.

295 For the discussion of the reduction factor R , we concen-
 296 trate on the aforementioned isotopes, where it is reasonable
 297 to assume that the full $0p_{1/2}$ strength is collected in bound
 298 states, while the $0p_{3/2}$ strength is exclusively located in the
 299 continuum. We also include the one exception for ^{16}O , where
 300 also the $0p_{3/2}$ hole states are bound. We exclude cases where
 301 the $0p_{3/2}$ strength is located close to the particle separation
 302 threshold and is fragmented. Such a selection is possible
 303 since the structure of the produced nuclei is known and, in
 304 addition, the γ spectra of the final states were analyzed. For
 305 the selected cases, we can then compare the measured cross
 306 sections directly to the theoretical ones based on the IPM
 307 without the need for additional theoretical structure input,
 308 which would complicate the discussion on the asymmetry
 309 dependence.

310 The resulting R values are summarized in the last column
 311 of Table I and are displayed in Fig. 4 as a function of the
 312 difference of g. s. separation energies ($S_p - S_n$) as filled
 313 circles and as a square for ^{16}O , where the sum of $0p_{1/2}$ and
 314 $0p_{3/2}$ contributions is shown as discussed above. The error
 315 bars represent the statistical uncertainty while the horizon-
 316 tal square brackets indicate the total uncertainty including
 317 the systematic errors. This allows a direct comparison of R
 318 relative to each other without identical systematic uncer-
 319 tainties. The data from this work show a fluctuation of R
 320 around 0.66. The solid and dotted lines display fits with a
 321 linear function and with a constant value resulting in a
 322 reduced χ^2 of 1.29 and 1.91, respectively. We conclude that

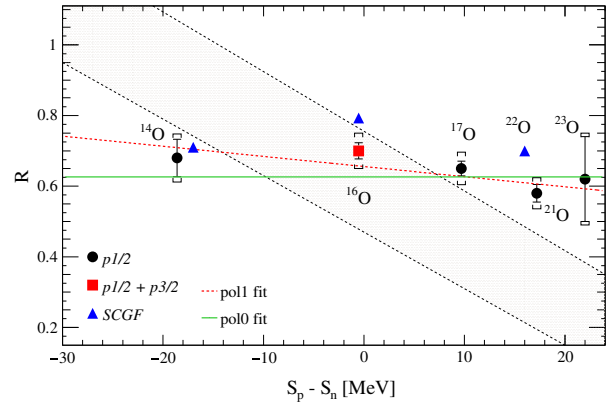


FIG. 4. Reduction factor R deduced from $(p, 2p)$ cross sections (circles and square) as a function of $S_p - S_n$ compared to theoretical SFs calculated with SCGF (triangles). The shaded area indicates the trend from an analysis of intermediate-energy one-nucleon removal cross sections.

the data are consistent with weak or even no dependance of the SP strength on the neutron-proton asymmetry. This trend differs drastically from the result of one-nucleon removal reactions at intermediate energies as compiled in Ref. [13]. Note that R is the ratio of the experimental cross section to the theoretical one based on the IPM, while the R values of Ref. [13] are given relative to a particular SM calculation. For the cases selected here, however, the fragmentation is small and the sum of the SM SF values reflects the sum-rule value given by the IPM. We estimated the uncertainties of the calculated cross sections related to possible variations of the input parameters within a reasonable range (NN cross sections, densities, and SP wave functions) to be less than 5%, i.e., significantly smaller than the experimental uncertainties. Our conclusion agrees with Ref. [16], where transfer data on ^{14}O have been analyzed. We note that our deduced reduction factor of 0.68(7) is in very good agreement with the one of 0.73(10)(10), derived from the $^{14}\text{O}(d, ^3\text{He})$ transfer [16].

Furthermore, we have performed state-of-the-art *ab initio* calculations of the proton-hole strength in $^{14,16,22}\text{O}$ based on the SCGF theory, using the third-order algebraic diagrammatic construction approach [ADC(3)] [18,43]. This is the method of choice for calculating the nuclear spectral function and yields the most accurate SF results near subshell closures. The theoretical SF can be sensitive to particle-hole gaps and the density of states at the Fermi surface [44]. Hence, we based our calculations on the saturating chiral interaction NNLO-sat [45], which guarantees the best possible predictions of radii and gaps in this region of the nuclear chart [46]. The resulting SF values shown as blue triangles in Fig. 4 for proton removal to the ground states of ^{13}N and ^{21}N and for summed p -shell states in ^{15}N are in reasonable agreement with the present measurements, although they seem to overestimate the

358 $3/2^-$ strength in ^{15}N , where theory does not reproduce the
 359 correct fragmentation as explained above. These results are
 360 also compatible with earlier microscopic studies [47] as
 361 well as $(e, e'p)$ data [5]. As was seen for other nuclear
 362 interactions [17,18], the SF from NNLO-sat depend little
 363 on isospin asymmetry. Note that continuum effects can
 364 further affect the quenching of SP strength in ^{22}O but not to
 365 the extent of altering this trend [19]. Thus, *ab initio* results
 366 do not support a significant dependence on isospin asym-
 367 metry, in agreement with the experimental results presented
 368 in this Letter.

369 In summary, we have measured inclusive $(p, 2p)$ cross
 370 sections for stable and unstable oxygen isotopes using the
 371 quasifree scattering technique in inverse kinematics and
 372 extracted the single-particle reduction factor R from the
 373 comparison with eikonal theory. The reduction obtained
 374 from the reaction $^{16}\text{O}(p, 2p)^{15}\text{N}$ shows good agreement
 375 with the results obtained from $(e, e'p)$ measurements. The
 376 results for stable and exotic nuclei indicate a weak or even
 377 no dependence on the proton-neutron asymmetry. This
 378 finding is compatible with the *ab initio* Green's function
 379 and coupled cluster calculations but contradicts the trend
 380 derived from intermediate-energy one-nucleon removal
 381 cross section measurements. This disagreement calls for
 382 further investigations of the reaction mechanism of nucleon
 383 removal from deeply bound states at intermediate energies.
 384 In the future, quasifree knockout reactions in inverse
 385 kinematics will allow for a systematic investigation of
 386 proton and neutron knockout from exotic nuclei covering a
 387 wide range of neutron-to-proton asymmetry, which will be
 388 important to corroborate the observed trend and to improve
 389 our understanding on the evolution of the single-particle
 390 structure as a function of neutron-to-proton asymmetry.

391 This work was supported by the German Federal
 392 Ministry for Education and Research (BMBF project
 393 **5** 05P15RDFN1), and through the GSI-TU Darmstadt co-
 394 operation agreement. The work of C. B., W. C., and G. W.
 395 was supported by the United Kingdom Science and
 396 Technology Facilities Council (STFC) under Grant
 397 No. ST/L005816/1. SCGF calculations were performed
 398 at the DiRAC Complexity system of the University of
 399 Leicester (BIS National E-1023 infrastructure capital Grant
 400 No. ST/K000373/1 and STFC 1024 Grant No. ST/
 401 K0003259/1). C.A.B. acknowledges support by the
 402 U.S. DOE Grant No. DE-FG02-08ER41533 and the
 403 U.S. NSF Grant No. 1415656. L.M.F. acknowledges
 404 funding from MINECO FPA2015-65035-P project.

*L.Atar@gsi.de

Present address: Department of Physics, University of
 Guelph, Guelph, Ontario N1G 2W1, Canada.

†t.aumann@gsi.de

[1] M. G. Mayer, *Phys. Rev.* **75**, 1969 (1949).

- [2] O. Haxel, J. H. D. Jensen, and H. E. Suess, *Phys. Rev.* **75**, 1766 (1949). 413
414
- [3] E. Caurier, G. Martínez-Pinedo, F. Nowacki, A. Poves, and A. P. Zuker, *Rev. Mod. Phys.* **77**, 427 (2005). 415
416
- [4] I. Sick, *Prog. Part. Nucl. Phys.* **59**, 447 (2007). 417
- [5] L. Lapikás, *Nucl. Phys.* **A553**, 297 (1993). 418
- [6] C. Barbieri, *Phys. Rev. Lett.* **103**, 202502 (2009). 419
- [7] W. Dickhoff and C. Barbieri, *Prog. Part. Nucl. Phys.* **52**, 377 (2004). 420
421
- [8] V. R. Pandharipande, I. Sick, and P. K. A. d. Huberts, *Rev. Mod. Phys.* **69**, 981 (1997). 422
423
- [9] D. Rohe *et al.* (E97-006 Collaboration), *Phys. Rev. Lett.* **93**, 182501 (2004). 424
425
- [10] R. Subedi *et al.*, *Science* **320**, 1476 (2008). 426
- [11] O. Hen *et al.* (J. L. C. Collaboration), *Science* **346**, 614 (2014). 427
428
- [12] P. G. Hansen and J. A. Tostevin, *Annu. Rev. Nucl. Part. Sci.* **53**, 219 (2003). 429
430
- [13] J. A. Tostevin and A. Gade, *Phys. Rev. C* **90**, 057602 (2014). 431
432
- [14] J. Lee *et al.*, *Phys. Rev. Lett.* **104**, 112701 (2010). 433
- [15] B. P. Kay, J. P. Schiffer, and S. J. Freeman, *Phys. Rev. Lett.* **111**, 042502 (2013). 434
435
- [16] F. Flavigny *et al.*, *Phys. Rev. Lett.* **110**, 122503 (2013). 436
- [17] C. Barbieri and W. H. Dickhoff, *Int. J. Mod. Phys. A* **24**, 2060 (2009). 437
438
- [18] A. Cipollone, C. Barbieri, and P. Navrátil, *Phys. Rev. C* **92**, 014306 (2015). 439
440
- [19] O. Jensen, G. Hagen, M. Hjorth-Jensen, B. A. Brown, and A. Gade, *Phys. Rev. Lett.* **107**, 032501 (2011). 441
442
- [20] N. K. Timofeyuk, *Phys. Rev. C* **88**, 044315 (2013). 443
- [21] F. Flavigny, A. Obertelli, A. Bonaccorso, G. F. Grinyer, C. Louchart, L. Nalpas, and A. Signoracci, *Phys. Rev. Lett.* **108**, 252501 (2012). 444
445
446
- [22] A. Gade and T. Glasmacher, *Prog. Part. Nucl. Phys.* **60**, 161 (2008). 447
448
- [23] C. Bertulani and A. Gade, *Comput. Phys. Commun.* **175**, 372 (2006). 449
450
- [24] T. Aumann, C. A. Bertulani, and J. Ryckebusch, *Phys. Rev. C* **88**, 064610 (2013). 451
452
- [25] V. Panin *et al.*, *Phys. Lett. B* **753**, 204 (2016). 453
- [26] H. Geissel *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B* **70**, 286 (1992). 454
455
- [27] V. Metag *et al.*, *Nucl. Phys.* **A409**, 331 (1983). 456
- [28] J. Alcaraz *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **593**, 376 (2008). 457
458
- [29] C. Caesar *et al.* (R3B Collaboration), *Phys. Rev. C* **88**, 034313 (2013). 459
460
- [30] M. Röder *et al.* (R3B Collaboration), *Phys. Rev. C* **93**, 065807 (2016). 461
462
- [31] R. Thies *et al.* (R3B Collaboration), *Phys. Rev. C* **93**, 054601 (2016). 463
464
- [32] M. Heine *et al.* (R3B Collaboration), *Phys. Rev. C* **95**, 014613 (2017). 465
466
- [33] D. Bertini, *J. Phys. Conf. Ser.* **331**, 032036 (2011). 467
- [34] <http://fairroot.gsi.de>, accessed: 16.08. 2016. 468
- [35] S. Agostinelli, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003). 469
470
- [36] J. Apostolakis, G. Folger, V. Grichine, A. Heikkinen, A. Howard, V. Ivanchenko, P. Kaitaniemi, T. Koi, M. Kosov, 471
472

PHYSICAL REVIEW LETTERS

473	J. M. Quesada, A. Ribon, V. Uzhinskiy, and D. Wright, <i>J. Phys. Conf. Ser.</i> 160 , 012073 (2009).	[42] M. Bernheim, A. Bussiere, J. Mougey, D. Royer, D. Tarnowski <i>et al.</i> , <i>Nucl. Phys.</i> A375 , 381 (1982).	487
474			488
475	[37] D. Mancusi, A. Boudard, J. Cugnon, J.-C. David, P. Kaitaniemi, and S. Leray, <i>Phys. Rev. C</i> 90 , 054602 (2014).	[43] C. Barbieri and A. Carbone, <i>Lect. Notes Phys.</i> 936 , 571 (2017).	489
476			490
477	[38] D. H. Wright and M. H. Kelsey, <i>Nucl. Instrum. Methods Phys. Res., Sect. A</i> 804 , 175 (2015).	[44] C. Barbieri and M. Hjorth-Jensen, <i>Phys. Rev. C</i> 79 , 064313 (2009).	491
478			492
479	[39] B. Pritychenko, E. Běták, M. Kellett, B. Singh, and J. Totans, <i>Nucl. Instrum. Methods Phys. Res., Sect. A</i> 640 , 213 (2011).	[45] A. Ekström, G. R. Jansen, K. A. Wendt, G. Hagen, T. Papenbrock, B. D. Carlsson, C. Forssén, M. Hjorth-Jensen, P. Navrátil, and W. Nazarewicz, <i>Phys. Rev. C</i> 91 , 051301 (2015).	493
480			494
481			495
482	[40] D. Sohler <i>et al.</i> , <i>Phys. Rev. C</i> 77 , 044303 (2008).	[46] V. Lapoux, V. Somà, C. Barbieri, H. Hergert, J. D. Holt, and S. R. Stroberg, <i>Phys. Rev. Lett.</i> 117 , 052501 (2016).	496
483			497
484	[41] M. Leuschner, J. R. Calarco, F. W. Hersman, E. Jans, G. J. Kramer, L. Lapikás, G. van der Steenhoven, P. K. A. de Witt Huberts, H. P. Blok, N. Kalantar-Nayestanaki, and J. Friedrich, <i>Phys. Rev. C</i> 49 , 955 (1994).	[47] C. Barbieri and W. H. Dickhoff, <i>Phys. Rev. C</i> 65 , 064313 (2002).	498
485			499
486			500
			501