The observation of long-range three-body Coulomb effects in the decay of $^{16}$Ne

K.W. Brown, 1 R.J. Charity, 1 L.G. Sobotka, 1 Z. Chajecki, 2 L.V. Grigorenko, 3, 4 I.A. Egorova, 5 Yu.L. Parfenova, 6, 7 M.V. Zhukov, 8 S. Bedoer, 9 W.W. Buhro, 2 J.M. Elson, 1 W.G. Lynch, 2 J. Manfredi, 2 D.G. McNeel, 9 W. Reviol, 1 R. Shane, 2 R.H. Showalter, 2 M.B. Tsang, 2 J.R. Winkelbauer, 2 and A.H. Wuosmaa 9

1Departments of Chemistry and Physics, Washington University, St. Louis, Missouri 63130, USA.
2National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA.
3Flerov Laboratory of Nuclear Reactions, JINR, Dubna, RU-141980, Russia.
4Russian Research Center “The Kurchatov Institute”, Kurchatov sq. 1, RU-123182 Moscow, Russia.
5Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, 141980, Russia.
6Flerov Laboratory of Nuclear Reactions, JINR, Dubna, RU-141980 Russia.
7Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia.
8Fundamental Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden.
9Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA.

The interaction of an $E/A = 57.6$-MeV $^{17}$Ne beam with a Be target was used to populate levels in $^{16}$Ne following neutron knockout reactions. The decay of $^{16}$Ne states into the three-body $^{14}$O+$p$+$p$ continuum was observed in the High Resolution Array (HIRA). For the first time for a $2p$ emitter, correlations between the momenta of the three decay products were measured with sufficient resolution and statistics to allow for an unambiguous demonstration of their dependence on the long-range nature of the Coulomb interaction. Contrary to previous experiments, the intrinsic decay width of the $^{16}$Ne ground state was found to be narrow ($\Gamma < 60$ keV), consistent with theoretical estimates.

PACS numbers: 25.10.+s, 23.50.+z, 21.60.Gx, 27.20.+n

Introduction — Two-proton ($2p$) radioactivity [1] is the most recently discovered type of radioactive decay. It is a facet of a broader three-body decay phenomenon actively investigated within the last decade [2]. In binary decay, the correlations between the momenta of the two decay products are entirely constrained by energy and momentum conservation. In contrast for three-body decay, the corresponding correlations are also sensitive to the internal nuclear structure and decay dynamics providing another way to constrain this information from experiment. In $2p$ decay, as the separation between the decay products becomes greater than the range of the nuclear interaction, the subsequent modification of the initial correlations is determined solely by the Coulomb interaction between the decay products. As the range of the Coulomb force is infinite, this contribution to the correlations can be quite substantial in heavy $2p$ emitters.

Prompt $2p$ decay is a subset of a more general phenomenon of three-body Coulomb decay (TCD) which exists in mathematical physics (as a formal solution of the $3 \rightarrow 3$ scattering of charged particles), in atomic physics (as a solution of the $e \rightarrow 3e$ process), and in molecular physics (as exotic molecules composed from three charged constituents) [3–8]. The theoretical treatment of TCD is one of the oldest and most complicated problems in physics because of the difficulty associated with the boundary conditions due the the infinite range of the Coulomb force. The exact analytical boundary conditions for this problem are unknown and different approximation schemes have been applied. In nuclear physics, the TCD problem has not attracted much attention, however the three-body Coulomb aspect of $2p$ decay becomes increasingly important as interest moves to heavier prospective $2p$ emitters [9].

Detailed experimental studies of the correlations have been made for the lightest $2p$ emitter $^8$Be [10, 11]. However in this $p$-shell nucleus, the Coulomb interactions are minute and their effects are easily masked by the dynamics of the nuclear interactions [12]. The Coulomb effects should be more prominent for the heaviest observed $2p$ emitters, however experimentally, these cases are limited by poor statistics; e.g. the latest results for the $2p$-emitter $^{54}$Zn is based on just 7 events [13] and the best available statistics for the $pf$ shell have been obtained for $^{45}$Fe where 75 events were detected [14]. Due to these limitations, previous work dedicated to the long-range treatment of the three-body Coulomb interaction in $2p$ decays [15], found consistency with the data, but no more.

The present work fills a gap between these studies by investigating the correlations in the $2p$ ground-state (g.s.) decay in the sd-shell nucleus $^{16}$Ne where the Coulombic effects are already strong enough to be important. Known experimentally for several decades [16], the $^{16}$Ne system has remained poorly investigated with just a few dedicated experimental works [17–20]. However, interest has returned recently with the decay of $^{16}$Ne measured in relativistic neutron-knockout reactions from a $^{17}$Ne beam [21, 22]. In this work we study the same reaction, but at an “intermediate” beam energy and obtain data with better resolution and smaller statistical uncertainty. Combined with state-of-the-art calculations, we find unambiguous evidence for the role of the long-range Coulomb interactions in the measured correlations.

Experiment — A primary beam of $E/A = 170$ MeV $^{20}$Ne was extracted from the Coupled Cyclotron Facility at the National Superconducting Cyclotron Labora-
hoty at Michigan State University and bombarded a $^9$Be target. The $^{17}$Ne projectile-fragmentation products were selected by the A1900 separator with a momentum acceptance of $\pm 1.0\%$. The $^{17}$Ne secondary beam had an intensity of $\sim 1.5 \times 10^5 \text{ s}^{-1}$ and a purity of $11\%$ (the largest component was $^{15}$O). This secondary beam impinged on a 1-mm-thick $^9$Be target and $^{16}$Ne nuclei were produced by neutron knockout reactions. The average $^{17}$Ne kinetic energy in the center of the target was $E/A = 57.6$ MeV.

The $^{16}$Ne decay products were detected in the High Resolution Array (HiRA) [23] in an arrangement with 14 $E - E$ [Si-CsI(Tl)] telescopes located at a distance 85 cm downstream from the target subtending zenith angles from $2^\circ$ to $13.9^\circ$. This arrangement is similar to our other $2p$ experiments [10, 24]. Detector energy calibrations were achieved using beams of 55 and 75 MeV protons and $E/A=73$ and 93 MeV $^{14}$O.

**Theoretical model** — The model used in this work is similar to that applied to $^{16}$Ne in Ref. [25], but, with improvements concerning basis convergence [26], TCD [15], and the treatment of the reaction mechanism [10].

The dynamics of the three-body $^{14}$O+$p$+$p$ continuum of $^{16}$Ne is described by solving the inhomogeneous three-body Schrödinger equation for wave functions (WF) $\Psi(+)$ with the outgoing asymptotic

$$\langle \hat{H}_3 - E_T \rangle \Psi(+) = \Phi_q, \quad j = \langle \Psi(+) | j | \Psi(+) \rangle \bigg|_{S},$$

corresponding to an approximate boundary condition of the three-body Coulomb problem. The three-body part of the model is described in detail in [26]. The differential cross section is expressed via the flux $j$ (1) induced by the WF $\Psi(+)$ on the remote surface $S$. When comparing to the experimental data, the predicted differential cross sections were used in Monte-Carlo (MC) simulations of the experiment, similar to those in [10, 24], to take into account the apparatus bias and resolution.

The source function $\Phi_q$ for the $0^+$ continuum was approximated assuming the sudden removal of a neutron from the $^{15}$O core of the $^{17}$Ne nucleus,

$$\Phi_q = \int d^3r_n e^{i\mathbf{q} \cdot \mathbf{r}_n} \langle \Psi_{14O} | \Psi_{17Ne} \rangle .$$

The $^{17}$Ne g.s. WF $\Psi_{17Ne}$ was obtained in a three-body model of $^{15}$O+$p$+$p$ and broadly tested against various observables [27]. Similar ideas had previously been applied to two different direct reactions populating the three-body continuum of the $^9$Be [10–12]. The $^{14}$O-$p$ potential sets were taken from [25], which were found consistent with the more recent results from [28]. We used the potential of [29] for the $p$-$p$ channel.

The three-body Coulomb treatment in our model consists of two steps. (i) We are able to impose approximate boundary conditions of the TCD problem on the hypersphere of very large (up to $\rho_{\text{max}} \sim 4000$ fm) hypersurface. This is made by diagonalizing the Coulomb interaction on the finite hyperspherical basis [30]. Within this limitation the procedure is exact, however it breaks down at larger radii as the accessible basis sizes become insufficient. (ii) Classical trajectories are generated by a MC procedure at the hypersphere $\rho_{\text{max}}$ and propagated out to distances $\rho_{\text{ext}} \gg \rho_{\text{max}}$. The asymptotic momentum distributions are reconstructed from the set of trajectories after the radial convergence is achieved.

The accuracy of this approach has been tested in calculations with simplified three-body Hamiltonians allowing exact semi-analytical solutions [15].

**Excitation spectrum** — The spectrum of the total decay energy $E_T$ constructed from the invariant mass of detected $^{14}$O+$p$+$p$ events, plotted in Fig. 1, is dominated by the peak at $E_T = 1.476(20)$ MeV associated with g.s. decay. This decay energy is consistent with the value of 1.466(45) MeV measured in [19] and almost consistent with, but slightly larger than, other experimental values of 1.34(8) MeV [17], 1.399(24) MeV [18], and 1.35(8) MeV [21].

The predictions of the $^{16}$Ne excitation spectrum in Fig. 1 provide a guidance for possible spin-parity identification of the other observed structures. These predictions suggest that the peak at $E_T = 3.16(2)$ MeV and the broader peak structure at $E_T = 7.60(4)$ MeV are both $2^+$ excited states. These peaks were also observed in [21, 22]. The broad structure at $E_T \sim 5.0(5)$ MeV is well described as a $1^-$ “soft” excitation. However in the mirror $^{16}$C system, there are also $J = 2^+$, $3^+$, and $4^+$ contributions in this energy range, but for neutron-knockout from $p_{1/2}$, $p_{3/2}$, an $s_{1/2}$ orbitals in $^{17}$Ne, we should only expect strong population for $0^+$, $2^+$, and $1^-$ configurations. The small peak at $E_T \sim 1$ MeV is a contaminant from $^{17}$Ne decay produced by $^{16}$O fragments leaking into the $^{14}$O gate. We will concentrate on the g.s. data for the remainder of this work.

**Three-body energy-angular correlations** — The complete information about three-body decays of narrow, long-lived states can be described by two correlation parameters: an energy distribution parameter $\varepsilon$ and an un-
and then discussed theoretically many times for reproducing the large experimental g.s. widths measured for $^{16}$Ne. Experimental and predicted (MC simulations) correlations for Jacobi “T” and “Y” systems are compared.

\[
\cos(\theta_k) = \frac{(k_x \cdot k_y)}{|k_x| |k_y|},
\]

\[
k_x = \frac{A_2 k_1 - A_1 k_2}{A_1 + A_2}, \quad k_y = \frac{A_3 (k_1 + k_2) - (A_1 + A_2) k_3}{A_1 + A_2 + A_3},
\]

\[
E_T = E_x + E_y = \frac{k_x^2}{2M_x} + \frac{k_y^2}{2M_y},
\]

where $M_x$ and $M_y$ are the reduced masses of the $X$ and $Y$ subsystems (see [26] for details). With the assignment $k_3 \rightarrow k_{3O}$, the correlations are obtained in the “T” Jacobi system where $\varepsilon$ describes the relative energy $E_{pp}$ in the $p$-$p$ channel. For $k_3 \rightarrow k_p$, the correlations are obtained in one of the “Y” Jacobi systems where $\varepsilon$ describes the relative energy $E_{core-p}$ in the $^{14}$O-$p$ channel.

The experimental and predicted (MC simulations) energy-angular distributions, in both Jacobi representations for the $^{16}$Ne g.s. decay, are compared in Fig. 2 and found to be similar. A more detailed comparison will be made with the projected energy distributions.

The convergence of three-body calculations is quite slow for some observables (see $^6$Be and $^{17}$Ne examples in Refs. [26, 31]). Figure 3 demonstrates the convergence, with increasing maximum generalized angular momentum $K_{\text{max}}$ for two observables for which the slowest convergence is expected. This work provides considerable improvement compared to the calculations of [25] which were limited by $K_{\text{max}} = 20$.

$^{16}$Ne g.s. width puzzle — The theoretical difficulty of reproducing the large experimental g.s. widths measured for $^{12}$O and $^{16}$Ne was originally pointed out 24 years ago [32] and then discussed theoretically many times [25, 33–35]. For $^{12}$O, this issue was resolved when a new measurement [36] gave a small upper bound to this width. For $^{16}$Ne, previous measurements of the intrinsic width of 200(100) keV [17] and 110(40) keV [18] were large compared to the theoretical predictions, e.g. 0.8 keV in Ref. [25]. With the present data, $\chi^2$ fits with Breit-Wigner line shapes and including the experimental resolution via MC simulations, give a 3-$\sigma$ upper limit of $\Gamma < 60$ keV. This value is consistent with the theoretical predicted value from the present calculations of $\Gamma = 3.1$ keV [Fig. 3(a)]. Therefore there is now no conflict between theory and experiment concerning the g.s. widths of the sd-shell, $2p$ emitters.

**Evolution of energy distribution between core and proton.** — To investigate the long-range nature of the TCD we terminated the Coulomb interaction at some hyperradius $\rho_{\text{cut}}$ and studied the effect on the predictions. The energy distribution in the “Y” Jacobi system is largely sensitive to just the TCD and the global properties of the system ($E_T$, charges, separation energies) [2]. This makes it most suitable for studying the sensitivity to $\rho_{\text{cut}}$ which is shown in Fig. 4(a). The comparison with the data in Fig. 4(b) demonstrates consistency with the theoretical calculations only if the considered range of the Coulomb interaction far exceeds $10^3$ fm (value $10^5$ fm guarantees fully converged result). This conclusion is only possible due to high quality of the present data. In contrast in the lower-resolution work of Ref. [22], where the experimental width of the g.s. peak is almost twice as large and its integrated yield is $\sim 3$ times smaller, the corresponding $\varepsilon$ distribution is broader with a FWHM of 0.41 compared to our value of 0.33. This difference in FWHM is similar to that obtained over the range of $\rho_{\text{cut}}$ considered in Fig. 4(d) demonstrating the need for high resolution to isolate these effects.

Our conclusions on the TCD are evidently dependent on the stability of the predicted correlations to the other inputs of the calculations. Figure 4(d) demonstrates the excellent stability of the core-$p$ energy distribution for a broad range $(\pm 200$ keV) of decay energy. The reason for this stability is that the maximum possible width for this
distribution is achieved for an $E_T$ value very close to the g.s. energy due to the competition between two trends: (i) the $\varepsilon$ distribution tends to $\delta(\varepsilon-0.5)$ in the limit $E_T \rightarrow 0$ (foreseen by Goldansky [1]), and (ii) some minimal width for the $\varepsilon$ distribution is expected at $E_T \sim 2 E_r$, where $E_r \sim 1.4$ MeV is the decay energy of the g.s. in the core+$p$ subsystem. The predictions of such a “narrowing” in Ref. [2] were recently proven experimentally [10].

The other important stability issue is with respect to the properties of the $^{15}$F subsystem where, experimentally, there is no agreement on the centroid $E_r$ and width of the g.s. [37, and Refs. therein]. Figure 4(c) shows predicted $\varepsilon$ distributions based on four different $^{14}$O+$p$ interactions which give the indicated $^{15}$F g.s. properties. Even if we use the data from [38], which differs the most from the other results ($E_r \sim 1.23$ MeV instead of typical $E_r \sim 1.4 - 1.5$ MeV), no drastic effect is seen.

The evolution of energy distribution between two protons with the cut-off hyperradius is shown in Fig. 4(e).

The observed evolution also cannot be easily related to the Coulombic effect only, as the spin-singlet interaction in the $p$-$p$ channel provides the virtual state (sometimes interpreted as “diproton”) which also can affect the long-range behavior of the momentum distributions. The theoretical prediction for $\rho_{cut} = 10^5$ fm in Fig. 4(f) reproduces experimental data quite well, however, the sensitivity to $\rho_{cut}$ is diminished compared to the core-$p$ energy distribution.

Limits on classical motion — In our model the very long distances are achieved by classical extrapolation. This approximation has been studied using calculations with simplified Hamiltonians in [15] where it was demonstrated that the classical extrapolation provides stable results if the starting distance $\rho_{max}$ exceeds some hundreds of fermis for a $\sim 1$ MeV decay energy (e.g. $\sim 300$ fm for $^{19}$Mg g.s. decay). At such distances, the typical ratio of the Coulomb potential to the kinetic energy of fragments is of the order $10^{-2} - 10^{-3}$. Figure 5 shows that for the $^{19}$Ne g.s., the predictions are consistent with the data only if the conversion from quantum to classical dynamics is made at or above 200 fm.

Conclusions — The correlations between the momenta of the three decay products in two-proton decay are sensitive to the nuclear structure of the state. However, the short-range correlations produced in the initial phase of the decay can be significantly modified by final-state Coulomb interactions. Before such correlation measurements can be used to extract nuclear-structure information, these long-range three-body Coulomb effects must be accurately accounted for.

In this work, the continuum of $^{16}$Ne has been studied both experimentally and theoretically with particular emphasis on the ground state which decays by prompt two-proton emission. The measured decay correlations in this work were found to require a theoretical treatment in which the three-body Coulomb interaction is considered out to distances far beyond $10^5$ fm. This theoretical treatment is now validated for use in interpreting the re-
sults of future studies of heavier two-proton decay.

The previous inconsistency of the theoretical and experimental $^{16}$Ne ground-state widths, highlighted in Refs. [25, 32], is now resolved. The experimental upper limit from this work of $\Gamma < 60$ keV is consistent with the calculated value of $\Gamma = 3.1$ keV from this work. All conclusions of this work were only possible due to the high statistics and fidelity of the present measurements.

Acknowledgments — This work was supported by the U.S. Department of Energy, Division of Nuclear Physics under grants DE-FG02-87ER-40316 and DE-FG02-04ER41320 and the National Science Foundation under grants PHY-1102511 and PHY-9977707. I.A.E. is supported by the Helmholtz Association under grant agreement IK-RU-002 via FAIR-Russia Research Center and L.V.G. by the RFBR 14-02-00090 and Russian Ministry of Industry and Science NSh-932.2014.2 grants.

[1] V. I. Goldansky, Nucl. Phys. 19, 482 (1960).
[2] M. Pfitzner, M. Karny, L. V. Grigorenko, and K. Risager, Rev. Mod. Phys. 84, 567 (2012).
[3] S. Zaytsev and G. Gasaneo, J. At. Mol. Sci. 4, 302 (2013).
[4] C. W. McCurdy, M. Baertschy, and T. N. Rescigno, J. Phys. B: At. Mol. Opt. Phys. 37, R137 (2004).
[5] L. Hilico, B. Gremaud, T. Jonckheere, N. Bily, and D. Delande, Phys. Rev. A 66, 022101 (2002).
[6] S. Kilic, J.-P. Karr, and L. Hilico, Phys. Rev. A 70, 042506 (2004).
[7] J. Madronero, L. Helico, B. Gremaud, D. Delande, and A. Buchleitner, Math. Struct. in Comp. Science 17, 225 (2007).
[8] M. J. Ambrosio, L. U. Ancarani, M. M. Mitnik, F. D. Colavecchia, and G. Gasaneo, Few-Body Systems (2014), 10.1007/s00601-014-0831-5.
[9] E. Olsen, M. Pfitzner, N. Birge, M. Brown, W. Nazarewicz, and A. Perhac, Phys. Rev. Lett. 110, 222501 (2013).
[10] I. A. Egorova, R. J. Charity, L. V. Grigorenko, Z. Chajecki, D. Coupland, J. M. Elson, T. K. Ghosh, M. E. Howard, H. Iwasaki, M. Kilburn, J. Lee, W. G. Lynch, J. Manfredi, S. T. Marley, A. Sanetullaev, R. Shane, D. V. Shetty, L. G. Sobotka, M. B. Tsang, J. Winkelbauer, A. H. Wuosma, M. Youngs, and M. V. Zhukov, Phys. Rev. Lett. 109, 202502 (2012).
[11] A. Fomichev, V. Chudoba, I. Egorova, S. Ershov, M. Golovkov, A. Gorskikh, V. Gorskikh, L. Grigorenko, G. Kamiski, S. Krukpo, I. Mukha, Y. Parfenova, S. Sidorchuk, R. Slepinev, L. Standyo, S. Stepantsov, G. Ter-Akopian, R. Wolski, and M. Zhukov, Physics Letters B 708, 6 (2012).
[12] L. V. Grigorenko, I. A. Egorova, R. J. Charity, and M. V. Zhukov, Phys. Rev. C 86, 061602 (2012).
[13] P. Ascher, L. Audirac, N. Adimi, B. Blank, C. Borcea, B. A. Brown, I. Companis, F. Delaee, C. E. Demonchy, F. de Oliveira Santos, J. Giovinazzo, S. Grévy, L. V. Grigorenko, T. Kurtukian-Nieto, S. Leblanc, J.-L. Pedroza, L. Perrot, J. Pibernat, L. Serani, P. C. Srivastava, and J.-C. Thomas, Phys. Rev. Lett. 107, 102502 (2011).
[14] K. Miernik, W. Dominik, Z. Janas, M. Pfitzner, L. Grigorenko, C. R. Bingham, H. Czykowski, M. Cwiok, I. G. Darby, R. Dabrowski, T. Ginter, R. Grzywacz, M. Karny, A. Kozgul, W. Kusmierz, S. N. Liddick, M. Rajabali, K. Rylaczewski, and A. Stolz, Phys. Rev. Lett. 99, 192501 (2007).
[15] L. V. Grigorenko, I. A. Egorova, M. V. Zhukov, R. J. Charity, and K. Miernik, Phys. Rev. C 82, 014615 (2010).
[16] R. Holt, B. Zeidman, D. Malbrough, T. Marks, B. Preece, M. Baker, R. Burman, M. Cooper, R. Hefner, D. Lee, R. Redwine, and J. Spencer, Physics Letters B 69, 55 (1977).
H. Iwasaki, M. Kilburn, J. Lee, W. G. Lynch, A. Sane-tullaev, M. B. Tsang, J. Winkelbauer, M. Youngs, S. T. Marley, D. V. Shetty, A. H. Wuosmaa, T. K. Ghosh, and M. E. Howard, Phys. Rev. C 84, 014320 (2011).

[25] L. V. Grigorenko, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, Phys. Rev. Lett. 88, 042502 (2002).

[26] L. V. Grigorenko, T. D. Wiser, K. Mercurio, R. J. Charity, R. Shane, L. G. Sobotka, J. M. Elson, A. H. Wuosmaa, A. Banu, M. McCleskey, L. Trache, R. E. Tribble, and M. V. Zhukov, Phys. Rev. C 80, 034602 (2009).

[27] L. V. Grigorenko, Y. L. Parfenova, and M. V. Zhukov, Phys. Rev. C 71, 051604 (2005).

[28] V. Z. Goldberg, G. G. Chubarian, G. Tabacaru, L. Trache, R. E. Tribble, A. Aprahamian, G. V. Rogachev, B. B. Skorodumov, and X. D. Tang, Phys. Rev. C 69, 031302 (2004).

[29] D. Gogny, P. Pires, and R. D. Tourreil, Physics Letters B 32, 591 (1970).

[30] L. V. Grigorenko, R. C. Johnson, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, Phys. Rev. C 64, 054002 (2001).

[31] L. V. Grigorenko and M. V. Zhukov, Phys. Rev. C 76, 014008 (2007).

[32] A. A. Korsheninnikov, Sov. J. Nucl. Phys. (Yad. Fiz.) 52, 827 (1990).

[33] A. Azhari, R. A. Kryger, and M. Thoennessen, Phys. Rev. C 58, 2568 (1998).

[34] F. C. Barker, Phys. Rev. C 68, 054602 (2003).

[35] H. T. Fortune and R. Sherr, Phys. Rev. C 68, 034309 (2003).

[36] M. F. Jager, R. J. Charity, J. M. Elson, J. Manfredi, M. H. Mahzoon, L. G. Sobotka, M. McCleskey, R. G. Pizzone, B. T. Roeder, A. Spiridon, E. Simmons, L. Trache, and M. Kurokawa, Phys. Rev. C 86, 011304 (2012).

[37] H. T. Fortune, Phys. Rev. C 74, 054310 (2006).

[38] F. Q. Guo, J. Powell, D. W. Lee, D. Leitner, M. A. McMahan, D. M. Moltz, J. P. O’Neil, K. Perajarvi, L. Phair, C. A. Ramsey, X. J. Xu, and J. Cerny, Phys. Rev. C 72, 034312 (2005).