Investigation of two-proton emission from excited states of the odd-Z nucleus ^{28}P by complete-kinematics measurements

X. X. Xu,[1,*] C. J. Lin,[1] H. M. Jia,[1] F. Yang,[1] F. Jia,[1] Z. D. Wu,[1] S. T. Zhang,[1] Z. H. Liu,[1] H. Q. Zhang,[1] H. S. Xu,[2] Z. Y. Sun,[2] J. S. Wang,[2] Z. G. Hu,[2] M. Wang,[2] R. F. Chen,[2] X. Y. Zhang,[2] C. Li,[2] X. G. Lei,[2] Z. G. Xu,[2] G. Q. Xiao,[2] and W. L. Zhan[2]

[1]*China Institute of Atomic Energy, Beijing 102413, People's Republic of China*

[2]*Institute of Modern Physics, The Chinese Academy of Science, Lanzhou 73000, People's Republic of China*

(Received 20 January 2010; revised manuscript received 22 March 2010; published 25 May 2010)

An experiment to study exotic two-proton emission from excited levels of the odd-Z nucleus ^{28}P was performed at the National Laboratory of Heavy Ion Research-Radioactive Ion Beam Line (HIRFL-RIBLL) facility. The projectile ^{28}P at the energy of 46.5 MeV/u was bombarding a ^{197}Au target to populate the excited states via Coulomb excitation. Complete-kinematics measurements were realized by the array of silicon strip detectors and the CsI + PIN telescope. Two-proton events were selected and the relativistic-kinematics reconstruction was carried out. The spectrum of relative momentum and opening angle between two protons was deduced from Monte Carlo simulations. Experimental results show that two-proton emission from ^{28}P excited states less than 17.0 MeV is mainly two-body sequential emission or three-body simultaneous decay in phase space. The present simulations cannot distinguish these two decay modes. No obvious diproton emission was found.

DOI: 10.1103/PhysRevC.81.054317 PACS number(s): 23.50.+z, 25.60.−t, 25.70.−z, 27.30.+t

I. INTRODUCTION

Notable progress has been made in the study of two-proton ($2p$) decay within the last few years. The $2p$ radioactivity from ^{45}Fe [1–4], ^{54}Zn [5], and possibly ^{48}Ni [6] was observed experimentally. In addition, the $2p$ decay from the very shorted-lived ground states of ^{19}Mg [7,8] and ^{16}Ne [8] was measured by using a tracking technique with microstrip detectors and described as the three-body decay. The study of $2p$ emission from excited states was primarily focused on the even-Z nuclei owing to the existence of the pairing force, such as ^{10}C [9,10], ^{14}O [11], ^{17}Ne [12–14], ^{18}Ne [15,16], and ^{29}S [17]. For the odd-Z nucleus, it was claimed that direct $2p$ emission [18] was observed during the decay of the long-lived isomer ^{94}Ag^m. However, recent analysis [19] casts doubt on the detection technique and the results of this experiment. In a new experiment [20], no evidence was found to support $2p$ radioactivity of the isomer ^{94}Ag^m ($T_{1/2} = 0.4$ s, $E^* = 6.7$ MeV, $I^\pi = 21^+$).

The nature of $2p$ emission from high-lying excited states, for instance, in the cases of ^{17}Ne [14] and ^{29}S [17], is still an open question. It may be related to the $2p$ halo structure or the large deformed orbit [21]. To answer this question, it is helpful to investigate $2p$ emission from the odd-Z nucleus. In some high-lying excited states of the odd-Z nucleus that are not $2p$ halos, it is expected that large deformations will occur and dynamical correlations between emitted protons resulting from the strong anisotropy of the Coulomb barrier will be observed. If not, the relevance of $2p$ emission to the existence of proton halos should be studied further.

The relativistic mean-field theory predicted that there are one-proton ($1p$) halos in ^{26,27,28}P and two-proton halos in ^{27,28,29}S [22]. A series of experiments [17,23–27] was performed to study proton halos and proton emission from nuclei in the $A = 30$ mass region. It was found that $2p$ emission from excited states of the even-Z nucleus ^{29}S presents a feature of ^{2}He decay [17,26]. For the odd-Z nucleus, experiments on ^{27,28}P + ^{28}Si [24] showed enhancement of the total cross sections of these reactions, which indicates that $1p$ proton halos probably occur in these nuclei. With the aim to investigate $1p$ and $2p$ emission from the excited states of ^{28}P, a new experiment was performed. This work presents the first experimental studies of these exotic decays for nuclei in the $A = 30$ region.

II. EXPERIMENTAL PROCEDURE

The experiment was performed with a primary beam ^{32}S^{16+} at an intensity of 100 enA and an energy of 80.4 MeV/u, which was extracted from the Separate Sector Cyclotron (SSC) at the National Laboratory of Heavy Ion Research (HIRFL) of the Institute of Modern Physics (Lanzhou, China) and then impinged on a ^{9}Be target with a thickness of 1588 μm. A radioactive ion beam (RIB) of $E/A = 46.5$ MeV ^{28}P was produced by projectile fragmentation, then separated and purified by the RIB line (RIBLL) spectrometer [28] using the combined $B\rho$-ΔE-$B\rho$ method. Secondary ions, with a purity of ^{28}P at 6.8% and an intensity of 10^4 ions/s RIB mixture, bombarded on a secondary target, ^{197}Au, with a thickness of 100 μm and a diameter of 30 mm.

Complete-kinematics measurements of all the reaction products were obtained by the cascaded silicon-strip detectors, large-area silicon detectors, and CsI + PIN array, as shown in Fig. 1. The interaction point of each fragment incident on the secondary target was reconstructed with two parallel-plate avalanche counters. The time of flight (ToF) of the secondary beams was measured by two plastic scintillators placed on the second and fourth focus planes of the RIBLL spectrometer. The energy loss (ΔE) of RIBs in a large-area silicon detector (SD1; 325 μm thick) combined with ToF measurements was

*xuxinxing@ciae.ac.cn

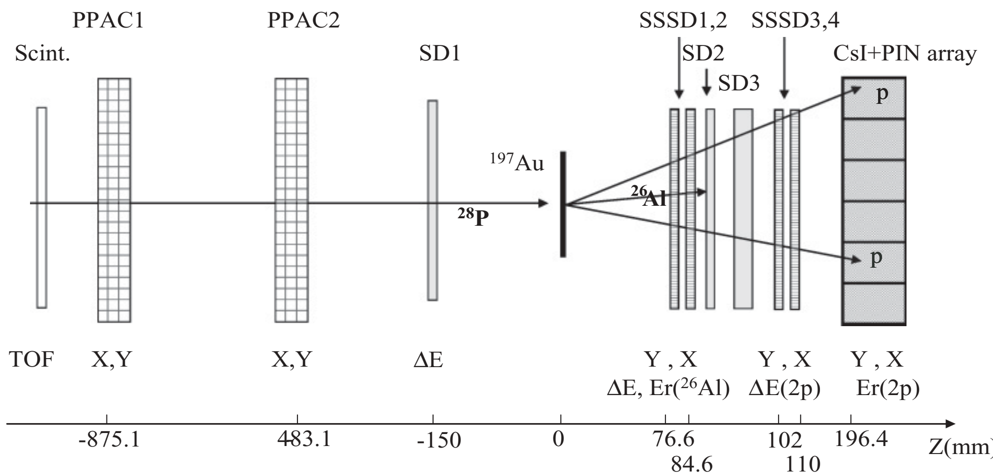

FIG. 1. Schematic of the detection setup designed for the study of exotic emission of ^{28}P by complete-kinematics measurement.

used for the particle identification of secondary ions. Figure 2 displays the ΔE versus ToF matrix for particle identification of secondary ions. A total of 1.5×10^7 ^{28}P events were accumulated in the experiment.

Particle identification and tracking of reaction products, including heavy fragments and light particles (mainly protons), were achieved by a multiple-stack telescope of particles. Two 300-μm-thick single-sided silicon strip detectors (SSSDs), orthogonally placed in front of a 325-μm-thick silicon detector (SD2) that stopped all the heavy fragments, were used for construction of the particle trajectories. There were 24 strips 2 mm wide, with a 0.1-mm interval for each SSSD. SSSD1 (y axis; ΔE signal detector) and the combination of SSSD2 (x axis) and SD2 (Er signal detectors) composed the first telescope for heavy particles of decay products, such as ^{27}Si and ^{26}Al. Figure 3 shows the identification of heavy ions after the target. The timing signals derived from SSSD1 combined with one of the scintillator detectors as the ToF window were used for selection of the daughter nucleus. The light particles passed through a quadrant silicon detector (SD3) with a thickness of 1000 μm and SSSD3 and -4, with the same configuration as SSSD1 and -2, and were finally stopped in the 6×6 CsI detector array ($15 \times 15 \times 20$ mm) coupled with PIN photodiodes. SSSD3 and -4 were used for tracking of the emitted light particles and measurement of the energy loss with ΔE detectors. The residual energy of protons was measured by the CsI + PIN array. With this arrangement, the opening angle covered by the detectors array was $\pm 13^\circ$.

At the beginning of the experiment, the particle telescope for heavy fragments was calibrated using secondary beams produced by the primary beam ^{32}S at several energies. This was achieved by using different targets with thicknesses of 1588 and 2634 μm. The ^{27}Al degrader after the target was removed in order to provide more isotopes and the energy loss of these heavy ions could cover the entire energy range of interest. Calibration of the telescope for light particles was achieved by proton beams at energies of 26, 46, 66, and

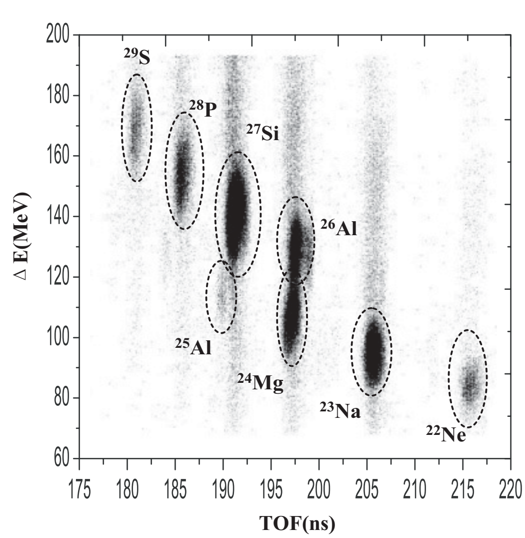

FIG. 2. Particle identification spectrum of energy loss from SD1 versus time of flight between the two plastic scintillators for RIBs.

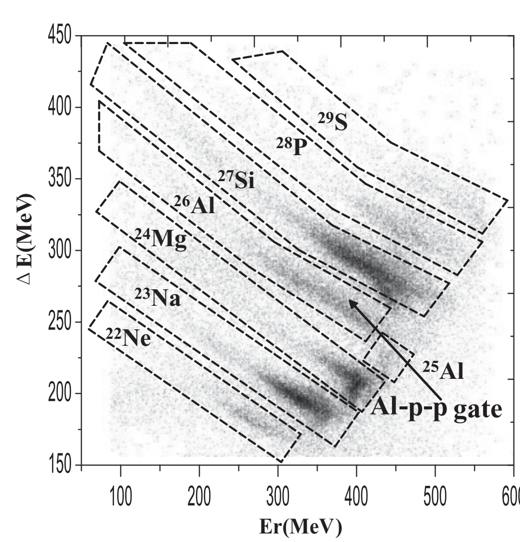

FIG. 3. Two-dimensional matrix for identification of heavy fragments after the target. The energy loss in SSSD1 (ΔE) is plotted versus the sum of the residual energy loss (E_r) in SSSD2 and SD2.

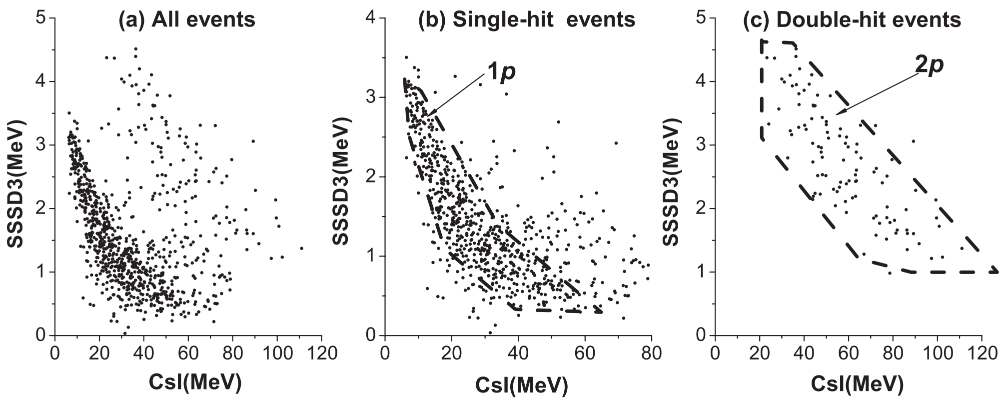

FIG. 4. Light particle identification spectrum from the detector array. Energy loss in SSSD3 is plotted as a function of the residual energy in the CsI + PIN detector array. In the construction of $2p$ emission from ^{28}P excited levels, a $2p$ gate for Al-p-p coincidence was selected.

80 MeV originating from the projectile fragmentation with the $B\rho$ setting for proton transmission.

III. DATA ANALYSIS AND DISCUSSION

A. Selection procedure for events of 1*p* and 2*p* emission

Coincidences of heavy fragments and light particles were carried out on an event-by-event basis for analyses of $1p$ and $2p$ emission from excited states. Selection of ^{28}P was accomplished on the two-dimensional RIB identification spectrum of ΔE versus ToF as already mentioned. Then light particles, such as a single proton or two protons emitted from the parent nucleus, were identified by the ΔE (SSSD3) versus Er (CsI) matrix (see Fig. 4). Finally, identification of the decay daughter nucleus, such as ^{26}Al, was achieved with the ΔE (SSSD1) versus Er (SSSD2 and SD2) spectrum and the ToF gate generated from SSSD1. Moreover, the reactions that did not take place in the target were rejected by the trajectory tracking methods. Details of the selection procedure are discussed in Ref. [17].

Figure 4 displays the identification spectrum of light particles emitted from the excited states of ^{28}P. Two obvious bands can be seen. One is the $1p$ emission, and the other is the $2p$ decay, which is located at values double the energy loss and residual energy of the single-proton band. This is an indication that there were few events from the reactions happening in the silicon detectors, because if the reactions took place in the SSSD, two protons with lower total kinetic energies would lead to higher values of energy loss and lower values of residual energy [29]. The deuteron band and triton band could hardly be detected. After additional purification by the identification of heavy fragments and tracking methods, about 80 two-proton and 1000 one-proton emission events were identified in the whole experiment, which clearly shows that one-proton emission from the odd-Z ^{28}P nucleus dominates.

B. Experimental results

Two-proton emission from the initial unbound state induced by Coulomb excitation can be described by three schematic pictures: (i) sequential two-body decay via an intermediate state of the daughter nucleus; (ii) three-body democratic decay in which the two protons have no correlations beyond phase-space constraints and final-state interactions; and (iii) diproton decay, which means a preformed ^{2}He cluster in the form of a resonance with the quasibound ^{1}S configuration in the parent nucleus that penetrates the Coulomb barrier and breaks up into two protons outside the barrier. To distinguish these three mechanisms, the proton-proton correlations, including the relative momentum ($q_{pp} = |\mathbf{p}_1 - \mathbf{p}_2|/2$), the opening angle ($\theta_{pp}^{\mathrm{c.m.}}$), the excited states ($E_{\mathrm{ex}}$), or the invariant mass of decay products in the center-of-mass system of the parent nucleus ^{28}P, have been reconstructed by relativistic-kinematics analyses.

Generally speaking, the threshold of $2p$ emission for an odd-Z nucleus is higher than that for an even-Z one. For example, the emitting threshold is 9.53 MeV for ^{28}P but just 5.35 MeV for ^{29}S [30]. Figure 5 displays the excitation energy of ^{28}P reconstructed from ^{26}Al-p-p events on an event-by-event basis. Several resonance states are visible, with excitation energies of 11.5, 12.7, 13.5, 14.3, 15.1, and 15.9 MeV. The energy resolution of the experimental setup

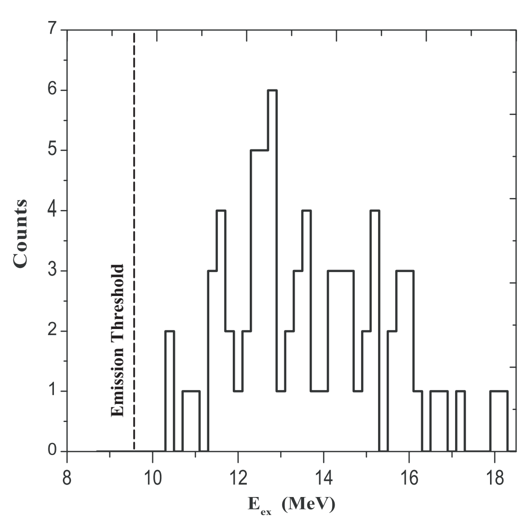

FIG. 5. Reconstructed excited energy spectrum for ^{28}P from three-body correlations of Al-p-p events.

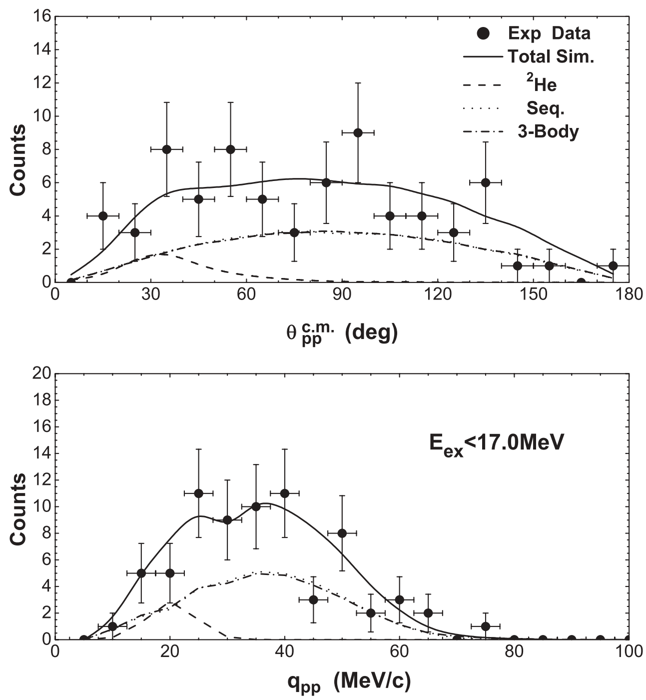

FIG. 6. Spectrum of the opening angle (top) and the relative momentum (bottom) of the two protons emitted from excited levels of ^{28}P less than 17.0 MeV, which shows two-body sequential emission or three-body simultaneous decay in phase space for the odd-Z nucleus ^{28}P.

is about 400 KeV, which includes the energy and position resolution of the detectors. Because of the limited statistics on $2p$ events, the spectrum of $2p$ correlations for each state could not be obtained. Figure 6 shows the relative momentum and the opening angle distribution for the events of $2p$ emission from excited states of ^{28}P less than 17.0 MeV. The experimental data show a nearly isotropic distribution for $\theta_{pp}^{\mathrm{c.m.}}$ and an enhancement in the region from 25 to 40 MeV/c for q_{pp}. In the case of ^{2}He cluster emission, the strong attractive nuclear interaction in the singlet ^{1}S state should result in an enhanced peak at $q_{pp} = 20$ MeV/c [31–33]. We did not observe obvious ^{2}He cluster emission in the present experiment.

Experimental data were reproduced by a Monte Carlo (MC) simulation taking the arrangement and resolution of the detectors and the Coulomb deflections of heavy fragments in the target into account, which is similar to the simulation of $2p$ emission of ^{29}S [17]. As the energies, spins, and parities of the high-lying initial levels, as well as the intermediate and final ones, for exotic decay are still unknown, accurate calculation of the mechanism of $2p$ emission could not be achieved. Therefore, three extreme decay modes, ^{2}He emission, sequential decay, and three-body democratic decay without final-state interactions, as mentioned previously, were taken into consideration in the MC simulation. The fitting yields only $(7 \pm 5)\%$ ^{2}He emission by chi-square analysis and other sequential or three-body simultaneous decay, in which the last two mechanisms cannot be distinguished because of the existence of lots of intermediate states of ^{27}Si and final states of ^{26}Al. The MC simulation results are shown in Fig. 6; the dashed, dotted, and dash-dotted curves represent the ^{2}He cluster, sequential, and three-body simultaneous decay, respectively.

C. Discussion of two-proton emission relevant to proton halos

Two-proton emission from the excited states between 9.6 and 10.4 MeV in the even-Z nucleus ^{29}S [17], which is a $2p$ halo nucleus, shows ^{2}He cluster emission with a branching ratio of $29^{+10}_{-11}\%$. However, for the neighboring, odd-Z nucleus ^{28}P, which is considered to be a $1p$ halo nucleus, the experimental results exhibit basically the phase-space distribution of three-body simultaneous decay or sequential emission of two protons. No obvious ^{2}He emission from the high-lying excited states was found. These results indicate that the large deformations are not responsible for the $2p$ emission from excited states, as they should occur in the high-lying excited states and cause dynamical correlations between emitted protons in both the ^{29}S and the ^{28}P cases. On the contrary, it was suggested that the wave functions of some excited states such as $2p$ halos in the parent nucleus have a small overlap with the wave functions of excited states in the $1p$ daughter nucleus, resulting in a much large spectroscopic factor for direct $2p$ decay [34,35]. In other words, the $2p$ halo structure in some high-lying excited states leads to the anisotropy of the opening angle between two protons.

IV. CONCLUSION

Exotic $2p$ emission of the odd-Z ^{28}P nucleus excited via Coulomb excitation has been studied experimentally by means of complete-kinematics measurements. The results primarily show two-body sequential emission or a phase-space distribution of three-body simultaneous decay for two protons emitted from excited states of less than 17.0 MeV of the odd-Z nucleus ^{28}P. No obvious dirproton emission was discovered. Compared with the results of the experiment on ^{29}S [17], this indicates that the $2p$ halo structure rather than the large deformation is responsible for the anisotropy of the opening angle between two protons emitted from the high-lying excited states.

To compare the mechanisms of $2p$ emission from $1p$ and $2p$ halo nuclei, more statistics for ^{28}P would be required to reach a definite conclusion. Also, further experiments on odd-Z and even-Z nuclei, such as ^{28}S and ^{27}P, are strongly called for. In addition, for the purpose of understanding the decay dynamics of $2p$ emission, information on strict theoretical calculations, such as the three-body Faddeev equations with core excitation [36], should be taken into consideration in the MC simulation in future.

ACKNOWLEDGMENTS

We thank the HIRFL-RIBLL operators for supplying good-quality beams, ensuring compatibility of the electronics and the data acquisition system. This work was supported by the National Natural Science Foundation of China under Grant Nos. 10675169, 10735100, and 10727505 and the Major State Basic Research Developing Program under Grant No. 2007CB815003.

[1] J. Giovinazzo *et al.*, Phys. Rev. Lett. **89**, 102501 (2002).
[2] M. Pfützner *et al.*, Eur. Phys. J. A **14**, 279 (2002).
[3] J. Giovinazzo *et al.*, Phys. Rev. Lett. **99**, 102501 (2007).
[4] K. Miernik *et al.*, Phys. Rev. Lett. **99**, 192501 (2007).
[5] B. Blank *et al.*, Phys. Rev. Lett. **94**, 232501 (2005).
[6] C. Dossat *et al.*, Phys. Rev. C **72**, 054315 (2005).
[7] I. Mukha *et al.*, Phys. Rev. Lett. **99**, 182501 (2007).
[8] I. Mukha *et al.*, Phys. Rev. C **77**, 061303(R) (2008).
[9] R. J. Charity, K. Mercurio, L. G. Sobotka, J. M. Elson, M. Famiano, A. Banu, C. Fu, L. Trache, and R. E. Tribble, Phys. Rev. C **75**, 051304(R) (2007).
[10] K. Mercurio *et al.*, Phys. Rev. C **78**, 031602(R) (2008).
[11] C. R. Bain *et al.*, Phys. Lett. B **373**, 35 (1996).
[12] M. J. Chromik, B. A. Brown, M. Fauerbach, T. Glasmacher, R. Ibbotson, H. Scheit, M. Thoennessen, and P. G. Thirolf, Phys. Rev. C **55**, 1676 (1997).
[13] M. J. Chromik *et al.*, Phys. Rev. C **66**, 024313 (2002).
[14] T. Zerguerras *et al.*, Eur. Phys. J. A **20**, 389 (2004).
[15] J. Gómez del Campo *et al.*, Phys. Rev. Lett. **86**, 43 (2001).
[16] G. Raciti, G. Cardella, M. De Napoli, E. Rapisarda, F. Amorini, and C. Sfienti, Phys. Rev. Lett. **100**, 192503 (2008).
[17] C. J. Lin *et al.*, Phys. Rev. C **80**, 014310 (2009).
[18] I. Mukha *et al.*, Nature (London) **439**, 298 (2006).
[19] D. G. Jenkins, Phys. Rev. C **80**, 054303 (2009).
[20] J. Cerny, D. M. Moltz, D. W. Lee, K. Peräjärvi, B. R. Barquest, L. E. Grossman, W. Jeong, and C. C. Jewett, Phys. Rev. Lett. **103**, 152502 (2009).
[21] B. Blank and M. Ploszajczak, Rep. Prog. Phys. **71**, 046301 (2008).
[22] B. Q. Chen, Z. Y. Ma, F. Grümmer, and S. Krewald, J. Phys. G **24**, 97 (1998).
[23] Z. H. Liu *et al.*, Chin. Phys. Lett. **21**, 1711 (2004).
[24] Z. H. Liu *et al.*, Phys. Rev. C **69**, 034326 (2004).
[25] C. J. Lin *et al.*, AIP Conf. Proc. **961**, 117 (2007).
[26] X. X. Xu *et al.*, AIP Conf. Proc. **1165**, 106 (2009).
[27] C. J. Lin *et al.*, Nucl. Phys. A **834**, 450c (2010).
[28] Z. Sun, W.-L. Zhan, Z.-Y. Guo, G. Xiao, and J.-X. Li, Nucl. Instrum. Methods Phys. Res. A **503**, 496 (2003).
[29] M. J. Chromik, Ph.D. thesis, University of Munich, 2001.
[30] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
[31] S. E. Koonin, Phys. Lett. B **70**, 43 (1977).
[32] W. G. Lynch *et al.*, Phys. Rev. Lett. **51**, 1850 (1983).
[33] M. A. Bernstein *et al.*, Phys. Rev. Lett. **54**, 402 (1985).
[34] R. Kanungo *et al.*, Phys. Lett. B **571**, 21 (2003).
[35] L. V. Grigorenko, Yu. L. Parfenova, and M. V. Zhukov, Phys. Rev. C **71**, 051604(R) (2005).
[36] I. J. Thompson, F. M. Nunes, and B. V. Danilin, Comput. Phys. Commun. **161**, 87 (2004).