Democratic Decay of ^{6}Be Exposed by Correlations

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Democratic decay of ^{6}Be exposed by correlations

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The interaction of an E/A=70-MeV ^{7}Be beam with a Be target was used to populate levels in ^{6}Be following neutron knockout reactions. The three-body decay of the ground and first excited states into the α+p+p exit channel were detected in the High Resolution Array (HiRA). Precise three-body correlations extracted from the experimental data allowed us to obtain an insight into the mechanism of the three-body democratic decay. The correlation data are in a nice agreement with a three-cluster-model calculation and thus validate this theoretical approach over a broad energy range.

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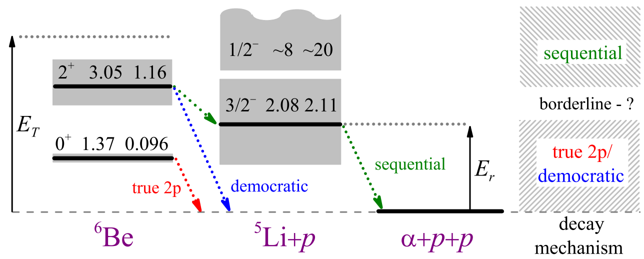

FIG. 1. (Color online) The level and decay scheme for ^{6}Be and illustrations of possible decay mechanisms. The continuum states are labeled $\{J^\pi, E_r, \Gamma\}$

Introduction. — The ^{6}Be system is located beyond the proton dripline and its ground and excited states all belong to the three-body α+p+p continuum. Moreover, the ^{6}Be ground state might be considered a so-called "true two-proton emitters"; systems for which one-proton decay is energetically prohibited and thus the two protons should be emitted simultaneously, as most of the strength of the ^{5}Li intermediate state is inaccessible (Fig. 1). However, at large excitation energies, one expects the decay mechanism in the 3-body continuum should eventually evolve to a sequential decay process through such intermediate states. In light two-proton emitters these intermediate states are often quite broad and hence the concept of "democratic decay" was proposed [1, 2]. "Democracy" in this case means that no strong focusing in kinematical space is produced even if the intermediate states are accessible for decay; the decay mechanism remains essentially three-body in nature. The 3-body decay of the ^{6}Be ground state may thus be classified as both a "true" and a "democratic" two-proton decay. The interplay and transition between the different decay mechanisms in three-body systems have been strongly debated and it is still not completely understood [2–8]. The location of the borderline between the three-body decay dynamics (true 2p or democratic) and two-body dynamics (sequential decay) is not known.

In the recent years there has been a revival of interest in the ^{6}Be system [7–11] with comparative studies to two-proton radioactive decay in ^{45}Fe [7], precise studies of correlations for the ground state [8], and the discovery of an "isovector soft dipole mode" in a charge-exchange reaction [11]. ^{6}Be is the lightest two-proton-ground-state emitter and, being relatively easily accessible in experiments, could become a benchmark system for studies of two-proton emission (two-proton radioactivity in heavier nuclei). In addition, because of isopin symmetry, the two-proton correlations can shed light on the structure of the mirror neutron-halo nucleus ^{6}He [8].

In this Letter we report on studies of the ^{6}Be continuous spectrum up to a decay energy of $E_T \sim 10$ MeV (E_T is energy above the α+p+p threshold). The high-statistics and high-resolution data provide a very detailed view of the evolution of the correlation patterns with excitation energy. This allows us to obtain insights into the mechanism of two-proton decay. The result is a demonstration of the counterintuitive character of the evolution of the decay mechanism with excitation energy.

Experiment. — A primary beam of E/A=150-MeV ^{16}O was extracted from the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University with an intensity of 125 pnA. This beam bombarded a ^{9}Be target and ^{7}Be projectile-fragmentation products were selected by the A1900 separator with a momentum acceptance of $\pm$0.5%. This ^{7}Be secondary beam had an intensity of 4×10^7 s^{-1} with a purity of $\sim$ 90%. It impinged on a 1-mm-thick target of ^{9}Be creating ^{6}Be projectile-like fragments via neutron knockout reactions.

The protons and α-particles created following ^{6}Be decay were detected in the HiRA array [12]. For this experiment, the array consisted of 14 ΔE-E [Si-CsI(Tl)] telescopes located at a distance 90 cm downstream from the target and subtended zenith angles from 1.4° to 13°. Each telescope consisted of a 1.5-mm thick, double-sided Si strip ΔE detector followed by a 4-cm thick, CsI(Tl) E detector. The ΔE detectors are 6.4 cm×6.4 cm in area with each of the faces divided into 32 strips. Each E detector consisted of four separate CsI(Tl) elements each spanning a quadrant of the preceding Si detector. Signals produced in the 896 Si strips were processed with the HINP16C chip electronics [13].

The energy calibration of the Si detectors was obtained with a ^{228}Th α-particle source. The particle-dependent energy calibrations of the CsI(Tl) detectors were achieved with E/A=60 and 80 MeV beams of protons and α particles selected with the A1900 separator. An experimental ^{6}Be decay energy E_T was determined from the invariant mass of each detected α+2p event minus the rest masses of the three decay products.

Theoretical model. — The dynamics of the three-body α+p+p continuum of ^{6}Be is described by solving the inhomogeneous three-body Schrödingier equation for wavefunctions (WF) with the outgoing asymptotic

$$(\hat{H}_3 - E_T)\Psi^{(+)} = \Phi_{\mathbf{q}}, \qquad (1)$$

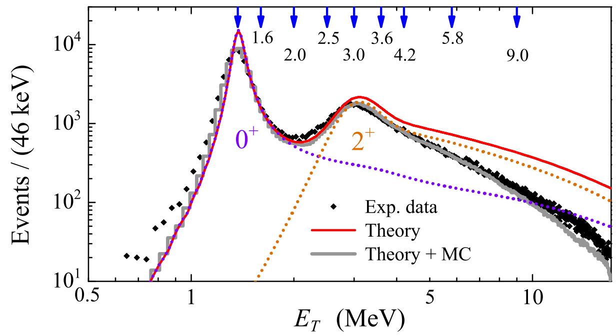

FIG. 2. (Color online) Experimental invariant-mass spectrum of ^{6}Be and the fitted theoretical result. Within this work the data points show experimental data, solid curve – the theoretical result, and gray histogram – the Monte Carlo simulation which takes into account the bias introduced by experimetal setup. To the extent that Monte Carlo simulation reproduces the experiment result, the theoretical curve can be interpreted as the reconstructed distribution. The dotted curves show the contributions of 0^+ and 2^+ states to the theoretical spectrum. The arrows indicate the boundaries of the energy bins used in this work.

corresponding to an approximate boundary condition of the three-body Coulomb problem. The differential cross section is expressed via the flux induced by the WF $\Psi^{(+)}$ on the remote surface S

$$\frac{d\sigma}{d^3k_\alpha d^3k_{p_1} d^3k_{p_2}} \sim \left. \langle \Psi^{(+)} | \hat{j} | \Psi^{(+)} \rangle \right|_S . \tag{2}$$

To compare to experimental data, the calculated sevenfold-differential cross sections were used in Monte-Carlo (MC) simulations of the experiment, taking into account the apparatus bias and resolution. The model is described in detail in [8] and applied in different ways in [7, 11].

The source function $\Phi_{\mathbf{q}}$ for the reaction considered in this work is constructed in the approximation of a sudden removal of a neutron from ^{7}Be (transparent limit of the Serber model),

$$\Phi_{\mathbf{q}} = \int d^3r_n e^{i\mathbf{q}\mathbf{r}_n} \langle \Psi_{^4\mathrm{He}} | \Psi_{^7\mathrm{Be}} \rangle , \tag{3}$$

where $\mathbf{r}_n$ is the radius-vector of the removed neutron and $\mathbf{q}$ is the transferred momentum. The ^{7}Be WF is constructed in the spirit of COSM approximation (e.g., [14]) as an "inert" α-core plus a neutron and two protons occupying $p_{3/2}$ and $p_{1/2}$ configurations with coupling $[l_j(\nu)[l_j(\pi_1)l_j(\pi_2)]_J]_{J_{^7\mathrm{Be}}}$:

$$\begin{aligned} \Psi_{^7\mathrm{Be}} = \Psi_{^4\mathrm{He}} \big(& \alpha[p_{3/2}[p^2_{3/2}]_0]_{3/2} + \beta[p_{3/2}[p^2_{1/2}]_0]_{3/2} \\ & + \gamma[p_{3/2}[p^2_{3/2}]_2]_{3/2} + \delta[p_{3/2}[p_{3/2}p_{1/2}]_2]_{3/2} \big) . \end{aligned} \tag{4}$$

Neutron removal populates the 0^+ state in ^{6}Be for terms with coefficients $\{\alpha, \beta\}$ and populates the 2^+ state for terms with coefficients $\{\gamma, \delta\}$. The ratios α/β and γ/δ control the spin contents of the source terms in Eq. (1). From the fit of the experimental E_T distribution in Fig. 2 we obtain $\{\alpha, \beta, \gamma, \delta\} = \{0.42, 0.3, 0.94, 0.7\}$. The sensitivity of the reaction to the structure of ^{7}Be is an interesting question by itself that will be discussed elsewhere.

Complete energy-angular correlations. — Two-body decays are described by just two quantities – energy and width. For three-body decays one also needs at least two extra continuous degrees of freedom that in this work are the energy distribution parameter ε and the angle θ_k between the Jacobi momenta $\mathbf{k}_x$, $\mathbf{k}_y$:

$$\begin{gathered} \varepsilon = E_x/E_T , \qquad \cos(\theta_k) = (\mathbf{k}_x \cdot \mathbf{k}_y)/(k_x\, k_y) , \\ \mathbf{k}_x = \frac{A_2\mathbf{k}_1 - A_1\mathbf{k}_2}{A_1 + A_2} , \;\; \mathbf{k}_y = \frac{A_3(\mathbf{k}_1 + \mathbf{k}_2) - (A_1 + A_2)\mathbf{k}_3}{A_1 + A_2 + A_3} , \\ E_T = E_x + E_y = k_x^2/2M_x + k_y^2/2M_y , \end{gathered} \tag{5}$$

where M_x and M_y are the reduced masses of the X and Y subsystems (see, e.g. Ref. [8] for details). If we put $k_3 \to k_\alpha$, then the correlations are obtained in the "T" Jacobi system where ε describes the energy correlation in the p-p channel. However, if we put $k_3 \to k_p$, then the correlations are obtained in one of the "Y" Jacobi systems where ε describes the energy correlation in the α-p channel.

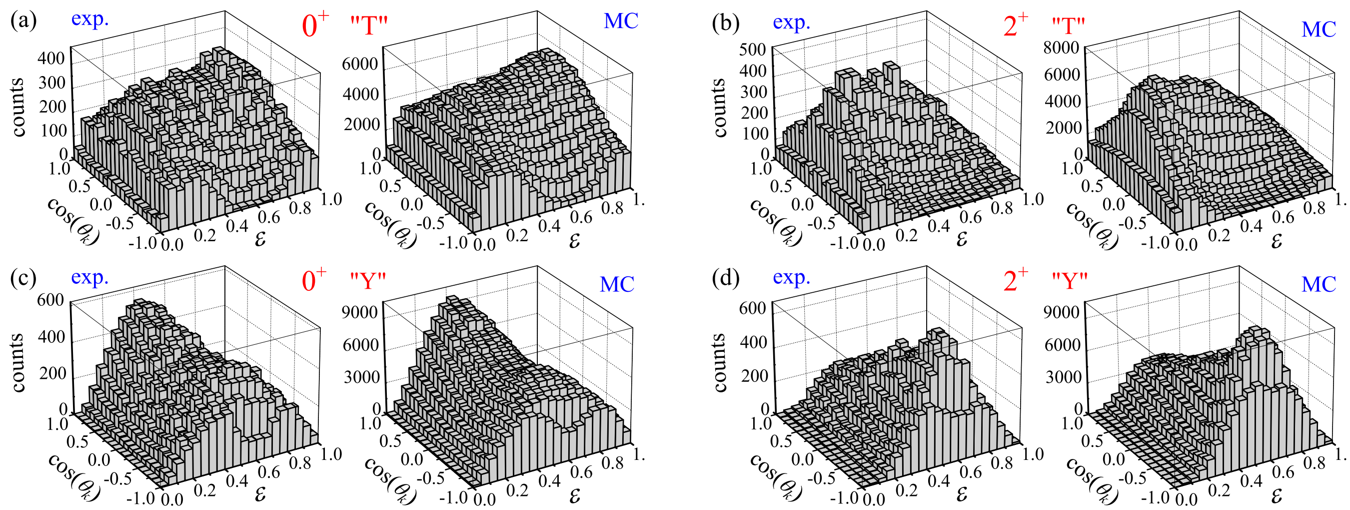

FIG. 3. (Color online) Complete energy-angular correlations for 0^+ (a,c) and 2^+ (b,d) states of ^{6}Be. Comparison of experiment and MC simulations for Jacobi "T" and "Y" systems (upper and lower rows, respectively). The data are taken for 0.5 and 1 MeV wide bins centered on the 0^+ and 2^+ resonance peaks, respectively.

The calculated energy-angular distributions are in excellent agreement with the experimental data for both the 0^+ and 2^+ resonances, see Fig. 3. These correlation data for the two resonance states are also in agreement with the recent results from [7–9, 11] and with the older data of [1, 15]. Only the data of [10] were found to be inconsistent. However, compared to all these other data sets, the present data have the highest statistical significance and thus provide the best validation of the theoretical model. In addition with the present high-statistics data, we are able to explore the evolution of the correlations on and off resonance.

Evolution of energy distribution between two protons. — Fig. 4 shows the evolution of the distribution of relative energy between two protons with E_T. There is a qualitative difference between the distributions for the 0^+ [Figs. 4 (a,b)] and 2^+ [Figs. 4 (d,e)] states. In addition, the small-E_{pp} region for p-p motion becomes enhanced with increasing E_T for 0^+ state. This result is unexpected as the p-p final-state interaction (FSI) is generally considered to be a predominantly low-energy phenomenon, but this trend is also confirmed in the calculations. For the first time we can see the evolution of distributions in the transition-energy region [Fig. 4 (c)] characterized by strong $0^+/2^+$ state mixing. For the energy region covering the 2^+ state and beyond [Fig. 4 (d)-(f)], the energy distributions demonstrate stable shapes far beyond the 2^+ peak [Fig. 4 (f)] a result again confirmed in the calculations.

Evolution of energy distribution between alpha and proton. — There is a wide spread belief that as soon as the intermediate state becomes energetically accessible, the decay mechanism changes over from three-body decay to a sequential decay through this resonance. To see what happens in reality, let us consider the energy correlation in the α-p channel, which should reflect the ^{5}Li ground-state resonance in the case of sequential decay.

We can see in Fig. 5 (a,b) that at low E_T, the shapes of the energy distribution in the Jacobi "Y" system have a relatively broad bell-like profile typical for true $2p$ decay [2]. However as E_T increases the profile first becomes significantly narrower. This narrowing happens exactly when the ^{5}Li ground-state resonance enters the decay window, Fig. 5 (c). The location of sequential-decay strength to the centroid of the ^{5}Li resonance, $E_{\alpha p} = E_r(^5\text{Li})$ and $E_{\alpha p} \approx E_T - E_r(^5\text{Li})$, where the concentration of strength might intuitively be expected, is indicated in Fig. 5 by large blue and small green arrows, respectively. It seems that for $E_T < 2E_r(^5\text{Li})$, the availability of the two-body α-p resonance for sequential decay does not lead to correlation patterns that one might consider typical of sequential decay with two peaks or a peak plus a shoulder. Significant evidence for such sequential correlations are only observed when $E_T \gtrsim 2E_r(^5\text{Li}) + \Gamma(^5\text{Li})$.

Let us now turn to the energy correlation at high E_T values ($5.8 < E_T < 9.0$ MeV), Fig. 5 (f). The ^{5}Li energy correlation is very evident here with peaks located at the energies indicated by the two arrows. However, if sequential decay is the only process here, then the *angular* correlations should be completely defined by angular-momentum coupling. The predicted angular distribution corresponding to sequential decay via $[p_{3/2} \otimes p_{3/2}]_2$ coupling (dotted curve) is compared to the corresponding experimental data in Fig. 6. In contrast to this prediction, the experimental distribution has a strong asymmetry with a focusing of the two protons at small relative angles. Technically such asymmetry cannot exist for pure sequential decay and must be connected with an interference between odd/even parity configurations (say of $[p^2]$ with $[sd]$ configurations in ^{6}Be). Physically it is clear that the peak at $\cos(\theta_k) \sim -1$

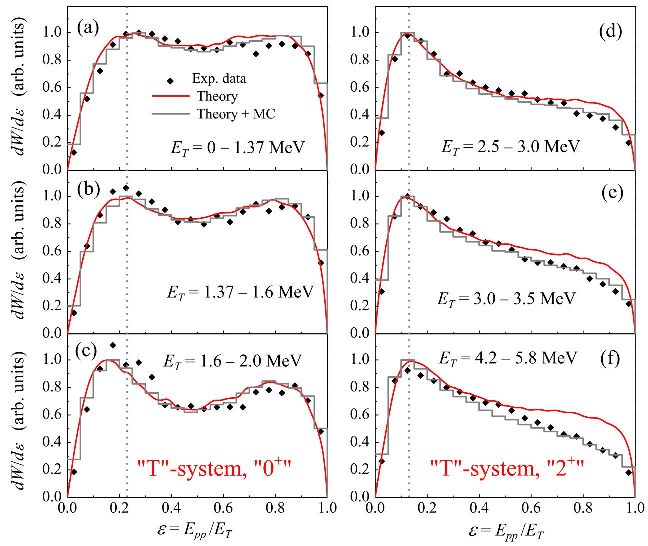

FIG. 4. (Color online) Evolution of energy distribution in the Jacobi "T" system (between two-protons) with the decay energy. The left and right columns show the energy ranges where the 0^+ and 2^+ states dominate. Vertical dotted lines are shown to help one evalute the shift, or lack of shift, in the peak location between different pannels. See caption Fig. 2 for explanation of symbols and curves.

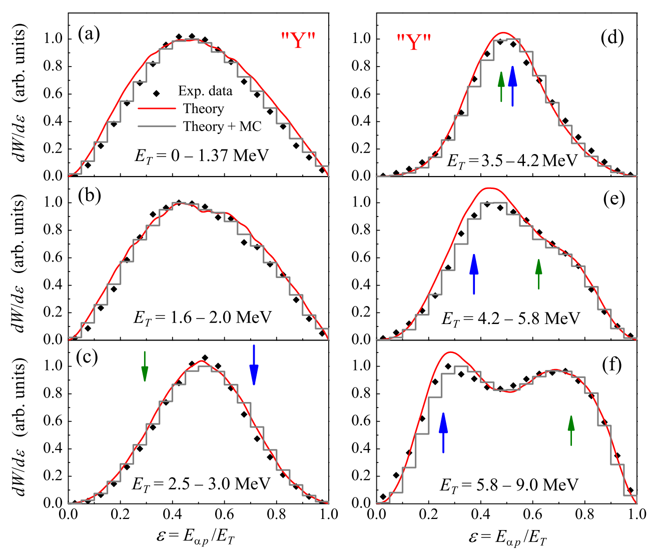

FIG. 5. (Color online) Evolution of the energy distribution in the Jacobi "Y" system (relative energy between alpha and one of the protons) with energy E_T. Arrows indicate the positions of the ^{5}Li g.s. resonance in the three-body energy window. See caption Fig. 2 for explanation of symbols and curves.

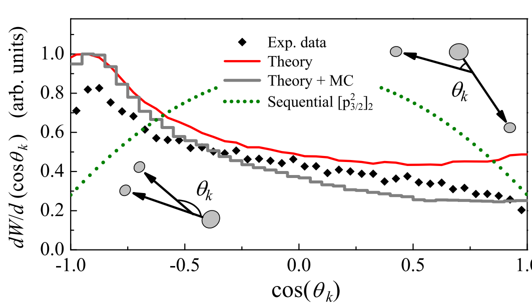

FIG. 6. (Color online) Angular distribution in the Jacobi "Y" system for the $E_T = 5.8 - 9$ MeV bin.

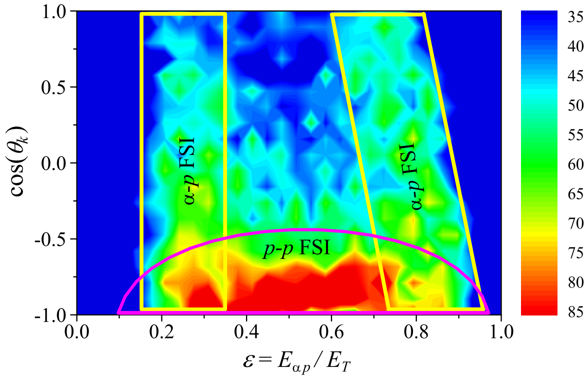

FIG. 7. (Color online) Experimental joint energy-angular distributions in the Jacobi "Y" system for the $E_T = 5.8 - 9$ MeV bin. The legend shows number of events for the used 30×20 grid.

is connected with p-p FSI present in realistic Hamiltonian [Eq. (1)].

A more complete picture of the decay is obtained by studying the joint energy-angular distribution of Fig. 7. This distribution contains regions clearly identifiable with p-p and α-p FSIs and, in addition, a broad transition region. Each of these regions is responsible for roughly 1/3 of the events and are also present in the theoretical distribution. This agreement with the theoretical distribution strongly suggests that these features do not originate from a background of α+p+p events which are not associated with ^{6}Be decay. Even at such a high excitation energy, the decay is therefore not purely sequential and the contributions of the different decay mechanisms cannot be completely disentangled. The "democracy" of the decay is preserved in the sense that different parts of the kinematical space have comparable populations.

Discussion. — The mechanism of the three-body decays in nuclei is often discussed in terms of either the "diproton" or "sequential" decay mechanisms. The present data demonstrate two results which can be seen as paradoxical and reflect the complexity of the problem.

(i) It is now well established that the pure "diproton" decay mechanism is not a good picture for the 2p decay [2, and Refs. therein]. However, this does not mean that p-p final-state interaction is absolutely not important for formation of correlation patterns in such decays. In such a context then, "diprotons" are expected to be important for the lowest energies. However, in ^{6}Be decay there is a very clear indication that formation of the low-energy p-p correlation is enhanced as the decay energy increases. It is also more pronounced in the excited 2^+ state compared to the ground 0^+ state.

(ii) In ^{6}Be the accessibility of the broad intermediate states in the energy window of the three-body decay first leads to what appears as a *suppression of the sequential decay mechanism* in favor of three-body democratic dynamics. Only at decay energies $E_T \gtrsim 2E_r(^5\text{Li})+\Gamma(^5\text{Li})$ do the signs of sequential decay become visible in the correlation patterns. However even at such energies, the actual mechanism is a complex mixture of contributions of core-p and p-p final-state interactions which cannot be disentangled. Some indications for this decay complexity were found in [2] based on simplified theoretical models. Now we have a strong confirmation of this finding. This establishes the validity of democratic decay as an apropriate description of the decay mechanism in a much broader energy range than ever expected.

Conclusions. — High-statistics and high-resolution three-body correlation data were obtained for ^{6}Be decay over a broad range of decay energies. These experimental results are reproduced by the three-cluster model. The data elucidate the mechanism of democratic decay and emphasize the paradoxical and rather complex nature of 3-body decay. They completely devalue the simplistic ideas of "sequential" and "diproton" decay in favor of complex three-body dynamics.

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[1] O.V. Bochkarev *et al.*, Nucl. Phys. **A505** 215, (1989).
[2] M. Pfützner, L.V. Grigorenko, M. Karny, K. Riisager Rev. Mod. Phys. **84**, 567 (2012).
[3] B.V. Danilin *et al.*, Sov. J. Nucl. Phys. **46**, 225 (1987).
[4] F.C. Barker, Phys. Rev. C **68**, 054602 (2003).
[5] B. Blank, M. Ploszajczak, Rep. Prog. Phys. **71**, 046301 (2008).
[6] R. Alvarez-Rodriguez, H.O.U. Fynbo, A.S. Jensen, E. Garrido, Phys. Rev. Lett. **100**, 192501 (2008).
[7] L.V. Grigorenko *et al.*, Phys. Lett. **B677**, 30 (2009).
[8] L.V. Grigorenko *et al.*, Phys. Rev. C **80**, 034602 (2009).
[9] R.J. Charity *et al.*, Phys. Rev. C **82**, 041304 (2010).
[10] P. Papka *et al.*, Phys. Rev. C **81**, 054308 (2010).
[11] A.S. Fomichev *et al.*, Phys. Lett. **B708** 6, (2012).
[12] M.S. Wallace *et al.*, Nucl. Instr. Meth. **A583**, 302 (2007).
[13] G.L. Engel *et al.*, Nucl. Instr. Meth. **A573**, 418 (2007).
[14] M.V. Zhukov, A.A. Korsheninnikov, M.H. Smedberg, Phys. Rev. C **50**, R1 (1994).
[15] D.F. Geesaman *et al.*, Phys. Rev. C **15**, 1835 (1977).