

Multifaceted Decay of ^{116}Cs

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The multifaceted decay properties of ^{116}Cs near the proton drip line have been studied at ISOLDE, CERN. More than six new unbound states of ^{116}Xe have been identified. A novel phenomenon of low energy isoscalar octupole resonance has been observed. After proton decay, that state populates both $11/2^+$ and $11/2^-$ states of ^{115}I . First observation of delayed two protons is reported in the medium heavy region and this exotic decay mode is 3 orders of magnitude lower than the delayed single proton events. The fingerprint of long-range proton-proton correlation has been evidenced in the relative momentum of two protons. An indication of rare event, heavy cluster emission (^{12}C) in medium heavy nucleus is reported.

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Introduction—A renaissance in nuclear physics has been catalyzed in this century by the discovery of novel nuclear phenomena and properties found around the limits of nuclear existence [1–3]. Key observed features are the disappearance of traditional magic shell gaps [4–8], the emergence of new magic numbers, and the presence of exotic shapes, cluster structures [9–11], new excitation modes [12–15], and unusual decay processes [16–23]. Collectively, these phenomena open a new window for a comprehensive understanding of the strong and weak interactions that define the atomic nucleus. Investigating the multifaceted decay properties of nuclei near the proton drip line constitutes a critical

pathway for elucidating nuclear structure and the fundamental nucleon-nucleon interaction. Specifically, examining the nuclear properties of doubly magic heavy nuclei near the proton drip line provides invaluable insights into how neutrons and protons interact at the very boundaries of nuclear existence [24–27]. Recently, there has been much excitement regarding understanding the phenomena of direct and delayed two proton emission [18–22]. In heavier $N = Z$ nuclei (^{100}Sn), enhanced proton-neutron pairing interactions lead to a stronger tendency for α -cluster formation. The heavy cluster emission was predicted [11] in this region of nuclei but experimental observation remains inconclusive [28–30]. Nevertheless, the cluster radioactivity is well established in heavier nuclei [31,32]. Another intriguing aspect of this mass region is rapid proton capture process [33,34], which is responsible for synthesizing nuclei around proton drip line. For the end point of this process, the competition between (p, γ) and α decay plays an important role. But the data in the trans-tin region [22,35–37] are limited. New data on multifaceted decay can further enrich

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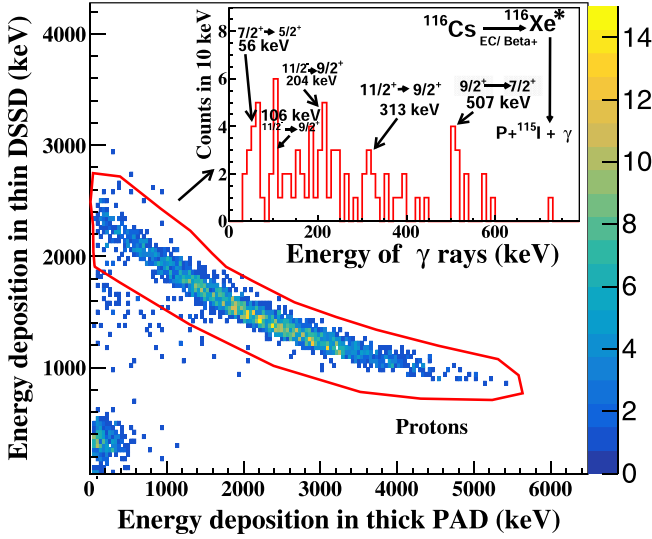


FIG. 1. ΔE -E coincidence spectrum for one of the thin DSSDs (65 μm) along with consecutive PAD detector. Inset: contoured proton gated γ -ray spectrum.

the quantum mechanics for solving the problem of open quantum systems by studying the evolution of nucleon wave function from nuclear potential to continuum or asymptotic region.

The odd-odd nucleus ^{116}Cs is loosely proton bound ($S_p = 680$ keV) but alpha unbound (2.0 MeV). After decay ($Q_{EC} = 11$ MeV), several excited states of daughter nucleus ^{116}Xe were populated above the thresholds of one and two protons or α cluster, etc. Thus a large number of decay channels are possible decay channels are possible as discussed earlier [22]. The delayed proton [37], alpha [38], and γ -ray [39] spectra of the nucleus ^{116}Cs were reported by different groups. Two long-lived isomers were identified in the nucleus: one with $I^\pi = (1^+)$, $T_{1/2} = 0.70(4)$ s, and one with $I^\pi = (4^+, 5, 6)$, $T_{1/2} = 3.85(13)$ s [37,40]. Recently, the spin of the longer isomer has been confirmed as 6^+ with the configuration $\pi g_{9/2} \otimes \nu g_{7/2}$ [41]. In this Letter, multifaceted decay properties of ^{116}Cs are presented. The present measurement is in agreement within error with previous reported works on half-life [37], delayed higher energy proton [37], and alpha spectrum [38]. For the first time we report the observation of novel exotic phenomena of delayed two proton (2p) and emission of ^{12}C in this medium heavy mass nucleus near the proton drip line.

Experimental setup—The experiment was conducted at ISOLDE, CERN. The beam ^{116}Cs produced using LaC_2 target was separated by a mass spectrometer and transferred to the experimental hall, where it was implanted on a carbon foil. Details of the setup, events validation, and analysis procedure are mentioned in [22,23]. Thin (U4 and U6) (67 μm) and thick (U2 and U5) double-sided silicon strip detectors (DSSDs) and unsegmented silicon-pad

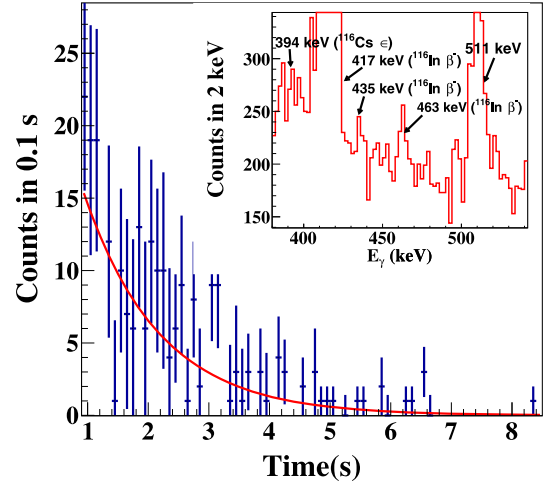


FIG. 2. Time distribution of delayed γ -ray of 394 keV. The solid line represents the fitted half-life ($t_{1/2}$) of ^{116}Cs as 0.86 (15) s. Inset: β -gated γ -ray spectrum. The γ -ray energies and correspondence to parent nuclei are mentioned.

detectors were used for detecting charge particles. Four Clover arrays were placed for detecting delayed γ -rays.

Data analysis and research discussion—The raw data were unpacked. The energy calibration of the detectors and data analysis were performed using the ROOT framework [22,23]. The ΔE -E spectrum provides easy distinction between proton and beta events. The high-energy proton events were marked in Fig. 1. Figure 2 [inset] shows β -gated γ -ray spectrum. As evident from Fig. 2 [inset], ^{116}In was contaminated with ^{116}Cs beam. From the time distribution of the delayed γ -ray of 394 keV ($2^+ \rightarrow 0^+$) of the daughter nucleus, the half-life of ^{116}Cs has been obtained by fitting with the exponential decay function $N = N_0 e^{-\lambda t}$ via χ^2 minimization, as shown in Fig. 2.

The measured $t_{1/2}$ is 0.86(15) s, in agreement with previously reported value [37,42,43]. The population of high spin isomer ($6^+; 3.85$ s) compared to low spin [$1^+; 0.86(15)$ s] in the spallation-fragmentation reaction by proton beam is around 2(1)%.

Proton unbound states of ^{116}Xe : The deposited energies by delayed protons in coincidence in the thin DSSD and PAD detectors were summed to obtain the delayed proton spectrum for higher energies. To obtain that spectrum, a gated condition of graphical cut of proton events, as shown in Fig. 1 was considered. The low-energy delayed protons (less than 2.5 MeV) were fully stopped in the thin DSSD, as observed from the thin DSSD (U4 and U6) spectrum in anticoincidence with the PAD detector. After adding both the low energy and the high energy spectrum, the proton binding energy was added following the transformation from laboratory to projectile frame for obtaining the spectrum of the proton unbound states of ^{116}Xe . The delayed proton spectrum was fitted with multiple peaks via

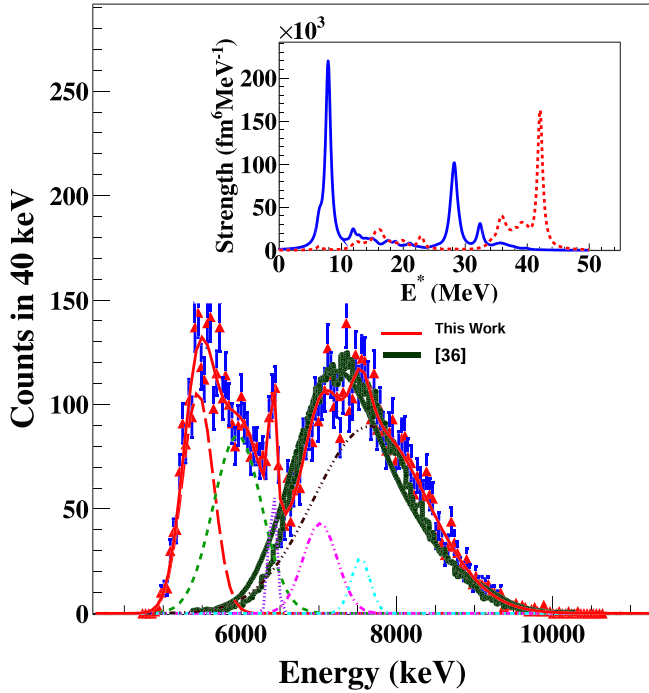


FIG. 3. The energy of proton unbound states of ^{116}Xe (keV). Inset: isoscalar and isovector octupole resonance of ^{116}Xe , obtained using density-dependent point coupling interaction.

χ^2 minimization and an approach based on Bayes' theorem [44] used to extract the properties of particle unbound excited states of ^{116}Xe . Six peaks have been obtained at 5.45(2), 5.95(6), 6.4(1), 7.02(3), 7.53(4), and 7.66(8) MeV. Figure 3 shows various excited states of ^{116}Xe , populated after ^{116}Cs decay. The detailed properties of those proton unbound states of the daughter nucleus and the branching ratios of populating those states are mentioned in Table I. In both methods of analysis, the peak positions are in agreement within errors, but the widths of the peaks are slightly different, as shown in the second column of Table I. The widths within square brackets are from the Bayesian approach. The width of all states range from 100 to 800 keV except one, which is 1.720(76) MeV wide, peaked at 7.66(8) MeV. The ratio of electron capture and positron emission is highly sensitive to the type of forbidden transition. Using the experimental values of half-life of parent and daughter nucleus, the excitation energy of both the nucleus and branching ratio, the ratio of electron capture to positron emission and logFT values were obtained considering various types of transitions following the prescription by [45]. For the first and second unique forbidden transitions, the calculated EC/β^+ , logFT [45] are 2.02(35), 6.17(14) and 4.68(90), 7.70(14) respectively. The measured EC/β^+ is 2.5(5), which is in agreement to first unique forbidden transition. Thus, the structure represented by three dots and dash in Fig. 3 can be assigned as 3^- , octupole resonance state. The calculated strength for isoscalar and isovector giant octupole resonance using a

TABLE I. Various particle unbound states of ^{116}Xe , populated after decay of ^{116}Cs , obtained by fitting the delayed p spectrum via χ^2 minimization and the Bayesian method (mentioned in the square bracket).

Energy of unbound states (MeV)	Width keV	Lifetime (10^{-21} s)	Branching (%)	Delayed
5.45(2)	471(27)[523]	0.69(04)	0.051(8)	p
5.95(6)	732(88)[766]	0.45(05)	0.064(1)	p
6.4(1)	111(17)[111]	2.96(37)	0.007(2)	p
7.02(3)	520(98)[583]	0.63(06)	0.021(8)	p
7.53(4)	286(85)[136]	1.15 15)	0.008(3)	p
7.66(8)	1720(76)	0.19(02)	0.159(16)	p
	[1620]			
6.4(1)	2431(405)	0.14(02)	$2.8(2) \times 10^{-3}$	α
8.0(1)	689(227)	0.48(16)	$3.9(4) \times 10^{-4}$	2p

fully consistent microscopic approach with density-dependent point coupling interaction [46] with relativistic Hartree-Bogoliubov model and relativistic Quasiparticle random phase approximation approximation [47] is shown in Fig. 3 (inset) and represented by solid and dotted lines, respectively. The observed proton unbound state with 3^- at 7.66 MeV can be identified as isoscalar octupole resonance state, which is obtained from calculation at 7.89 MeV. The low energy octupole resonance was also observed in neutron deficient ^{92}Mo [48], ^{116}Sn [48,49]. To further investigate the properties of that state, the E- Δ E proton-gated γ spectrum has been obtained. The inset of Fig. 1 shows the p-gated γ spectrum. The characteristic γ -rays of ^{115}I [50] evidence the population of low-lying states with spin and parity as $11/2^-$, $11/2^+$, with comparable intensities. This observation provides additional support for the octupole resonance state. Similarly, giant dipole resonance was observed in the neutron-rich $^{136}\text{I} \rightarrow \beta^- ^{136}\text{Xe}$ nucleus [51]. We recently came across a study of pygmy dipole resonance with spin and parity of non- 1^- state in neutron-rich nuclei at $A = 80$ [52].

Identification of delayed two-protons from ^{116}Cs : The delayed two-proton events have been selected from thin DSSDs (U4 and U6) considering two multiplicity hits in strips of individual DSSDs with anticoincidence of corresponding PAD detectors (P4 and P6) and deposited energies for each hit should be more than 150 keV. However, to eliminate crosstalk, etc., the events with consecutive strips hitting have been discarded. To select valid events, further conditions have been imposed by prompt timing gate of the DSSD and equal energy deposition between front and back layers of individual DSSDs. The two-proton events have been also identified from a thick DSSD (U5) with all above conditions except the discarded events' energy deposition of less than 1.0 MeV considering β -energy deposition. Other

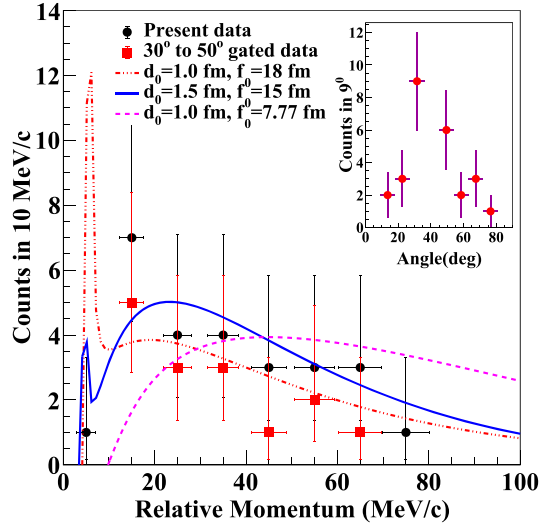


FIG. 4. Measured relative momentum of delayed two-proton system and the fitted correlation function with different scattering length. Inset: observed angles between the delayed two protons.

two-proton events, where two different DSSD hits have been considered, i.e., the DSSDs' multiplicities are one. To identify two-proton events, one occurring in the detector U4 or U6 (in anticoincidence with PAD4 or PAD6) and the other one may hit into thick DSSD (U5), similar criteria have been used. Higher energy protons in U4 and U6 along with PAD in coincidence with U5 have been searched. Here, DSSD events were selected based on coincidence with the corresponding PAD detectors, verified by the coincidence patch of the E- ΔE plot (see Fig. 1).

Direct or simultaneous and sequential delayed two protons in heavy neutron deficient nucleus: It is important to know if the observed two protons were decaying in simultaneous or sequential mode. The opening angle is an important parameter in characterizing the two-proton decay process. Figure 4 (inset) shows the measured angles between delayed two protons in center-of-mass coordinate. The angle between delayed two-proton events is peaked around $39(3)^\circ$ with distribution of $13.4(44)^\circ$. These events are 27(11)% of the total delayed two-proton events. So, those events can be considered as simultaneous or direct decay of two protons. A very similar observation has been discussed in a lighter mass proton-rich nucleus [53]. To quantify the correlation in a two-proton system within the nucleus, the scattering length (f_0) and mean-square radius of emission point $d(d_0 * \sqrt{3})$ have been varied to fit the data of relative momentum with the correlation function [54]. It has been observed that the correlation function with larger d (2.6 fm) and f_0 as 15 fm shows better fit than that with the standard d (1.7 fm) and f_0 (7.8 fm) [54]. The result of fitted data is better with a larger value (18 fm) of f_0 with standard d , when an energy gate with 8 MeV considered. Figure 4 shows the data of relative momentum of a two-proton system overlaid with the fitted correlation function

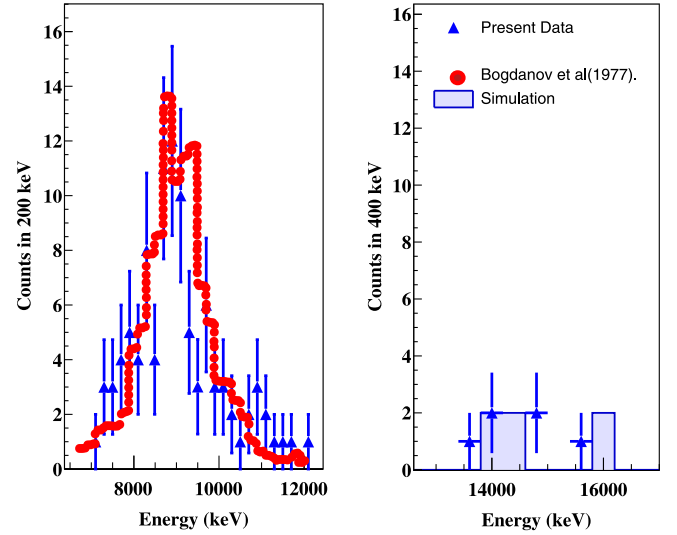


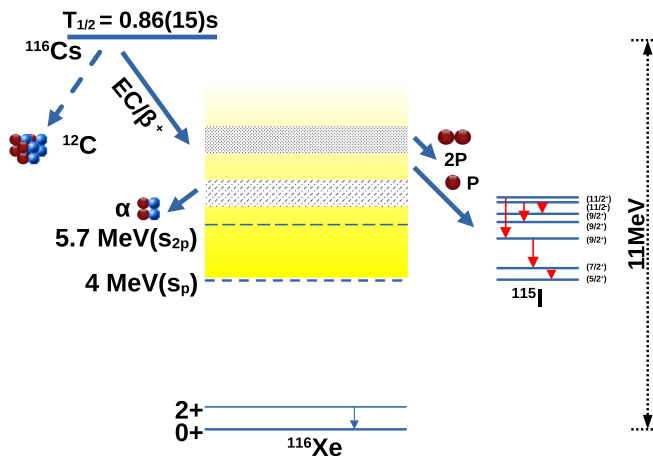
FIG. 5. Energy deposition at thick DSSD (1000 μm) by charge particle heavier than proton.

with various f_0 and d_0 . The filled circles and squares represent the total and partial data with angle between two-proton system from 30° to 50° , respectively. The dashed (pink online), dot-dashed (red online), solid (blue online) lines in Fig. 4 represent the correlation curve for standard d : f_0 , much larger f_0 (18 fm); standard d (1.7 fm), and larger f_0 (15 fm); d (2.6 fm), respectively. Thus, d as 2.6 fm with f_0 as 15 fm signifies enhanced long-range correlation of a delayed two-proton system. In the correlation function [54], s -wave scattering was considered. This is valid for low relative momentum and higher partial waves are negligible [54,55]. From one proton decay spectrum, the octupole resonance state at 7.66 MeV with distribution of 1.7 MeV (FWHM) is overlapping with the energy of two-proton decaying state at 8.0 MeV. A correlated two-proton system may be decaying from that state and could be useful for probing long-range density dependent nucleon-nucleon interaction using data with better statistics.

Heavy cluster decay: Cluster radioactivity is an important phenomenon that is established in the heavy nuclei when the daughters are closed shell ^{208}Pb or its neighbors. Theoreticians predicted similar cluster radioactivity in the trans-tin region. The cluster emission process is associated

TABLE II. Comparison between the experimental (Expt.) half-life of ^{12}C radioactivity and estimated ones by UDL, Horoi, formulas [11].

Parent Nucleus	Daughter Nucleus	Q (Expt.) MeV	$\log_{10} T_{1/2}(s)$		
			Expt.	Th-I UDL	Th-II Horoi
^{114}Ba	^{102}Sn	19	> 4.1 [29]	9.99	4.75
^{116}Cs	^{104}In	14.2	6.5(3)	21.3	19.0

FIG. 6. Multifaceted exotic decay of ^{116}Cs .

with high Q values, indicating a greater release of energy. Therefore, in modeling nuclear reactors for energy production, a comprehensive understanding of the complex decay processes is essential. Figure 5 shows the energy deposition spectrum ($E > 6.5$ MeV) in the thick detector (U5). The delayed alpha energy spectrum, measured earlier [38] is overlaid using filled circles. Unlike previous measurements, the present data show the energy deposition from 13.5 to 15.5 MeV. The possible energy deposition of delayed alpha can be up to a maximum of 13 MeV. Thus higher energy deposition could be due to spontaneous heavy cluster emission or delayed heavy cluster emission. The Q value for ^{12}C emission from ^{116}Cs is 14.2 MeV. Considering Poisson distribution for low statistics, simulated events of energy distribution of ^{12}C are shown in Fig. 5 by the shaded region. The branching ratio is $\sim 2.7(18) \times 10^{-5}\%$. The half-life of delayed heavy cluster emission, $(T_{1/2,^{12}\text{C}})$, is $3.2(22) \times 10^6$ s or $6.5(3)$ in $\log_{10} T_{1/2}$. This value is closer to previously reported value for that of ^{114}Ba . Recent calculations for cluster radioactivity using the liquid drop model with several sets of analytical formulas [11] are shown in Table II. As it is evident, the present data for emission of ^{12}C is more probable than theoretical prediction. For this purpose microscopic calculation may be important to understand the phenomena of quantum tunneling effect of macroscopic system in the nuclei. Figure 6 shows a schematic drawing of multifaceted exotic decay of ^{116}Cs , observed in present study. The results of delayed two-proton and heavy cluster emission may shed light on pp and np pairing correlation in this very neutron deficient environment. Moreover, the reconstructed particle unbound states of the daughter nucleus may be useful in obtaining p , α , $2p$, ^{12}C capture cross section and its impact on nucleosynthesis processes.

Summary—Multifaceted decay properties of the very neutron deficient ^{116}Cs (Fig. 6) was studied by measuring delayed charged particles and γ -rays using thin and thick

DSSDs, PAD detectors, and Clover arrays, respectively. Several new unbound states of ^{116}Xe have been identified. The higher energy proton spectrum, the α spectrum, and half-life are in agreement with previous measurements [37]. A broad distribution at 7.66 MeV has been identified as isoscalar octupole resonance that, after decaying proton, populates low-lying discrete states of ^{115}I with positive and negative parity. First observation of delayed two protons is reported. A large scattering length of 15 fm and larger mean-square radius of the emission point (2.6 fm) of two protons could be evidence for enhanced long-range proton-proton correlation near the proton drip line. A rare event of heavy cluster emission (^{12}C) has been evidenced. The present study demonstrates that the multifaceted decay properties of nuclei around drip lines is a very promising tool for exploring nucleon-nucleon interaction in unstable nuclear matter and its impact on fundamental and applied research.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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Correction: The Collaboration name was missing from the byline and has been added.