Studies of Two Proton Radioactivity

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In the last decade, impressive progress has been made in the production and study of exotic short-lived nuclei by reactions with radioactive ion beams produced at large-scale accelerators. Nevertheless, nuclear structure beyond the proton drip line, where nuclei are unbound and exist only as resonances in the continuum, is still a rather unexplored topic despite the experimental advance. The recently discovered two-proton (2p) radioactivity, the spontaneous break-up of an atomic nucleus by the 2p emission, exhibits unexpectedly long half-lives of all reported 2p precursors, ^{45}Fe, ^{54}Zn,^{48}Ni, ^{19}Mg, ^{94m}Ag [1–6]. The main features of the studied nuclei and the corresponding experiments are listed in Table 1.

TABLE 1. Two-proton emitters studied experimentally.

Isotope	*E* keV	Γ or $T_{1/2}$	Fragment correlation	Experimental method, reference
^{6}Be	1371(5)	92(6) keV	*No*	Missing mass, [13]
			$E_{p\text{-}p}$	Kinematically complete, [14]
			three-body	Invariant-mass, [15]
^{12}O	1820(120)	400(250) keV	no	Missing mass, [16]
	1790(40)	580(200) keV	no	Missing mass, [17]
	1800(400)	600(500) keV	three-body	Kinematically complete, [18]
^{16}Ne	1350(80)	200(100) keV	no	Missing mass, [16]
	1400(20)	110(40) keV	no	Missing mass, [19]
	1350(80)	<200 keV	three-body	Tracking decay-in-flight, [20]
^{19}Mg	750(50)	4.0(1.5) ps	three-body	Tracking decay-in-flight, [5]
^{45}Fe	1100(100)	$3.2(^{+2.6}_{-1.0})$ ms	no	Implantation-decay, [1]
	1140(50)	$5.7(^{+2.7}_{-1.4})$ ms	no	Implantation-decay, [2]
	1154(16)	$2.8(^{+1.0}_{-0.7})$ ms	three-body	Kinematically complete, [21]
	–	3.7(0.4) ms	three-body	Kinematically complete, [22]
^{48}Ni	1350(20)	$8.4(^{+12.8}_{-7.0})$ ms	no	Implantation-decay, [3]
^{54}Zn	1480(20)	$3.2(^{+1.8}_{-2.8})$ ms	no	Implantation-decay, [4]
^{94m}Ag(21+)	1900(100)	390(40) ms	$E_{p\text{-}p}$	ISOL implantation-decay, [6]

The time scales of nuclear decay by proton emission, accessible by experiment, spans from 10^{-2} s (for the longer lifetimes, weak decays prevail) to 10^{-21} s (for the shorter lifetimes, continuum dynamics are important). Such a broad range can be accessed only by different experimental techniques. In the case of nuclear 1p and 2p decays with lifetimes larger than a few microseconds, one can implant the radioactive atoms and subsequently detect their decay. The first 2p radioactivity experiments were performed with such technique [1-4]. For much shorter half lives, the conventional in-flight-decay method aims at detecting all fragments of a proton precursor in missing-mass or invariant-mass measurements [13-19]. A novel experimental technique for measuring in-flight decays of proton-unbound nuclei with lifetimes in the intermediate time range of 10^{-7}–10^{-12} s was suggested and discussed in Ref. [13-15]. In such a measurement, the trajectories of all decay products are tracked. The decay vertexes as well as the angular correlations of the decay products can be deduced from the measured trajectories, in analogy to the methods of high-energy physics. The observations of previously-unknown isotope ^{19}Mg and its 2p radioactivity [5], p-p correlations from 2p decays of ^{19}Mg and ^{16}Ne [16], and new resonances in ^{15}F populated by 1p decay of excited states in ^{16}Ne [17] were reported. The tracking technique was verified by reproducing the properties of the previously known 1p and 2p unbound states in the isotopes ^{15}F, ^{16}Ne, ^{19}Na , which was described in detail in Ref. [18], the key article for understanding the method. This tracking technique is very powerful in studies of the extremely exotic nuclei. The method is ideally suited for low-intensity beams of exotic nuclei. Thick targets (up to several g/cm^2) and large-emittance radioactive beams can be used without losing precision in the derived resonance energies and widths. Since such measurements require only a rather simple setup and can be applied to proton-unbound isotopes with very small production yields, many more unexplored nuclei may be studied with this method in the future. Novel 2p-detection techniques are also gaseous implantation detectors, based on the principle of the time projection chamber (TPC), and being developed to directly record emitted protons and to establish the correlations between them. The first direct observation of two protons ejected by ^{45}Fe was achieved in [24] when projections of protons' tracks on the anode plane of the TPC were recorded. Later, this detector was used to directly demonstrate 2p in decay of ^{54}Zn [25]. A novel type of a detector, utilizing the optical readout of the TPC signals [22], was applied to the detailed study of ^{45}Fe 2p-decays with reconstruction of tracks of two emitted protons in three dimensions. The full correlation picture for the 2*p* decay of ^{45}Fe established in this experiment is shown in Fig. 1(g,h).

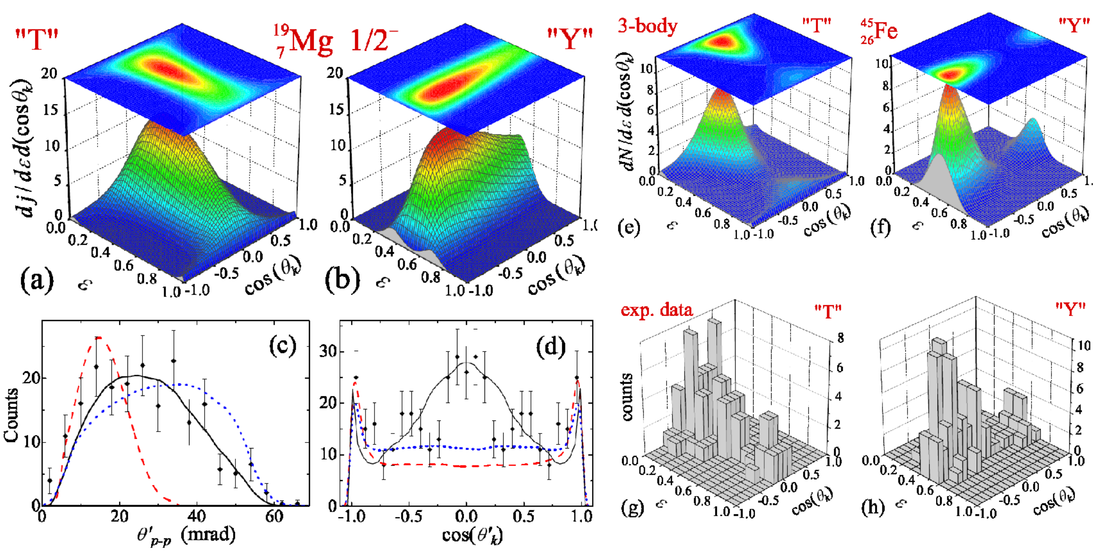

FIGURE 1. Experimental three-body correlations of two-proton radioactivity of ^{19}Mg shown in the panels (c,d) [20], and of ^{45}Fe, see the panels (g,h) [22]. The respective theoretical complete-correlations (a,b) and (c,f) are from the Ref. [23] where all observable are explained in detail. In panels (c,d), the

solid curves are the three-body model predictions, the dashed curves – the diproton model estimates, and the dotted curves – the phase-space calculations.

The theory of 2p decay was recently developed much comparing with the first simple quasi-classical estimates like the diproton model [26,27], or the model of direct three-body decay [28]. The first quantum-mechanical theory of 2p radioactivity (it is based on a 3-body model of 2p precursors by configurations p+p+“core”) explains their long half-lives as the result of a decay retardation due to a higher 3-body centrifugal barrier [7–9]. The theory predicts many long-lived 2p precursors beyond the proton drip line. Specific features of 2p radioactivity are three-body correlations of fragments. The 3-body model is the only theory explaining the observed correlation patterns, see the examples on ^{19}Mg and ^{45}Fe in Figure 1. One should also mention developments of the shell model embedded into continuum [29,30] applied to 2p radioactivity which though are not able to provide the correlation observables.

Properties of 2p-unbound nuclei are of interdisciplinary interest, in particuar for nuclear astrophysics. The inverse reaction to 2p decay, radiative 2p capture, may be important in the synthesis of elements in the universe by bridging bottlenecks in the rp process, so-called “waiting points” [10–12]. Measurements of 2p decays are the only way to study radiative 2p capture so far.

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