Chapter 11
Fusion-Evaporation Reactions

11.1 Heavy Ions

In the quest for superheavy transuranium elements after the Second World War it soon became clear that neutron capture reactions followed by subsequent β-decay would not be able to reach elements beyond fermium (Z = 100). At the time, nuclear reactions were limited to light-particle induced reactions which again were not suitable to produce new elements. By 1950, the heaviest element produced in light-particle reactions was berkelium. Thompson, Ghiorso, and Seaborg had discovered ^{243}Bk by irradiating ^{241}Am with α-particles [1]. If, however, it was possible to accelerate heavier ions, fusion reactions of these heavy ions with heavy targets could lead to new heavier elements. The first acceleration of a heavy-ion beam was achieved by Miller et al. at the Crocker Laboratory of the University of California at Berkeley in 1950. The intensity of the accelerated ^{12}C and ^{16}O nuclei was not sufficient to induce a detectable number of fusion reactions [2]. However, only a couple of months later, Ghiorso et al. succeeded in identifying ^{246}Cf by irradiating ^{238}U with ^{12}C ions. The compound nucleus ^{250}Cf evaporated four neutrons to populate ^{246}Cf which then subsequently was identified by its α-radioactivity [3].

Soon thereafter it was realized that heavy-ion fusion-evaporation reactions were not only an excellent tool to produce new elements but that they also could be used to populate light neutron-deficient nuclides. Since these early attempts fusion-evaporation reactions have become one of the most productive reaction mechanisms to discover new nuclides. In addition to the almost 200 transuranium and superheavy nuclei well over 500 neutron-deficient nuclides were first identified in heavy-ion fusion-evaporation reactions.

The present chapter discusses the discovery of proton-bound neutron-deficient nuclides with Z < 92. The discovery of isotopes of transuranium ($92 \leq Z \leq 100$) and superheavy (Z > 100) elements using fusion-evaporation reactions are described in Chaps. 5 and 12, respectively. Nuclides beyond the proton drip-line are discussed in Chap. 16. In the present chapter the nuclides are arranged according to their

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decay mechanism; β^+-emitters in Sects. 11.2 and 11.3, α-emitters in Sect. 11.4, and β-delayed proton emitters in Sect. 11.5.

Initially, the detection and identification techniques were the same as for light-particle induced and spallation reactions. The element identification was somewhat easier at least for the dominant decay channels because charged-particle evaporation is suppressed relative to neutron evaporation for isotopes located not too far from the line of stability. Thus the most probable element of the residues was identical to the compound nucleus. Nevertheless chemical separation was important to discriminate against nuclei populated by other reaction mechanisms like inelastic scattering or incomplete fusion.

The mass identification was quite uncertain as the incident beam energy was not well known. In addition, the energy could not easily be changed so that excitation functions were measured by inserting different absorber foils into the beam.

A major breakthrough occurred when it was realized that the incoming heavy-ion beam imparted significant recoil velocities to the residues which was sufficient to knock them out of the target. The recoils were caught on catcher foils which were then chemically analyzed or placed directly in front of detectors. Later helium-jets were developed where the fragments recoiled into flowing helium gas which then transported them to catcher foils.

11.2 Beta-Decay

Neutron-deficient isotopes that decay by β^+ emission and that have been discovered in fusion-evaporation reactions are listed in Tables 11.1, 11.2 and 11.3. New isotopes populated by fusion-evaporation typically did not decay back to stable nuclei but to radioactive nuclei that had previously been populated by different methods. Thus the observation of the subsequent known daughter decay could be used to help in the identification of the new isotope.

Table 11.1 lists isotopes that were identified following chemical separation. The first non-transuranium isotope populated in a fusion-evaporation reaction was ^{74}Br in 1953. Hollander irradiated enriched ^{63}Cu and ^{65}Cu targets with ~90 MeV carbon ions from the Berkeley 60-in. cyclotron [4]. He assigned a 36-min activity to ^{74}Br based on the relative intensity observed with the two different copper targets. ^{73}Br was ruled out because there was no evidence for the known 7.1-h activity of the ^{73}Se daughter.

Later in 1953, Rossi et al. discovered ^{119}I also at Berkeley by irradiating palladium targets with a ^{14}N beam. They linked the observed 18-min activity to the known 4.5-d ^{119}Te daughter activity [5]. A year later Kalkstein and Hollander used a mass separator to achieve simultaneous chemical mass separation of ^{126}Cs and thus establish the decay sequence ^{126}Ba−^{126}Cs−^{126}Xe in the reaction ^{115}In(^{14}N,3n) [6].

The first isotopes discovered in fusion-evaporation reactions in Europe were ^{79}Rb and ^{71}Se in 1956 and 1957, respectively, at the Centre d'Etudes Nucléaires de Saclay, in Gif-sur-Yvette, France. The paper on ^{79}Rb by Beydon et al. [7] was followed

Table 11.1 Isotopes discovered in fusion-evaporation reactions and identified by chemical separation: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evaporation	Isotope
08/11/1953	Hollander	[4]	^{65,63}Cu	^{12}C	3n, 1n	^{74}Br
11/25/1953	Rossi	[5]	^{110,108}Pd	^{14}N	5n, 3n	^{119}I
07/09/1954	Kalkstein	[6]	^{115}In	^{14}N	3n	^{126}Ba, ^{126}Cs[a]
09/28/1956	Beydon	[7]	^{65}Cu	^{16}O	2n	^{79}Rb
01/21/1957[b]	Beydon	[8]	^{nat}Cu	^{14}N	xn	^{71}Se[a]
11/03/1958	Toth	[9]	^{141}Pr	^{12}C	5n	^{148}Tb
04/15/1959	Faler	[10]	^{165}Ho	^{14}N	6n, 5n, 4n	^{173}Ta, ^{174}Ta, ^{175}Ta
05/28/1959	Chackett	[11]	^{184}W	^{14}N	5n	^{193}Tl
05/16/1960	Hoff	[12]	^{71,69}Ga	^{14}N	5n, 3n	^{80}Sr, ^{80}Rb[a]
05/27/1960	Preiss	[13]	^{nat}Mo	^{16}O	2pxn	^{103}Cd
02/23/1961	Diamond	[14]	^{169}Tm	^{16}O	3n	^{182}Ir
11/20/1961	Sheline	[15]	^{121}Sb	^{12}C	7n, 5n, 3n	^{126}La, ^{128}La, ^{130}La
01/10/1962	Preiss	[16]	^{nat}In	^{16}O	pxn	^{123}Ba, ^{125}Ba
03/05/1962	Maxia	[17]	^{75}As	^{12}C	4n, 3n	^{83}Y, ^{84}Y
08/13/1962	Preiss	[18]	^{nat}In	^{16}O	xn	^{127}La, ^{129}La
12/21/1964	Nurmia	[19]	^{58}Ni	^{6}Li	1n	^{63}Ga
07/09/1965	Belyaev	[20]	^{169}Tu	^{15}N	4n	^{180}Os
03/15/1967	Nadjakov	[21]	^{165}Ho	^{16}O	6n, 5n	^{175}Re, ^{176}Re
03/30/1967	Bakhru	[22]	^{nat}Mo	^{11}B	xn	^{99}Ag
1968[c]	Belyaev	[23]	^{169}Tm	^{14}N	4n	^{179}Os
10/17/1969	Murray	[24]	^{59}Co	^{16}O	2n	^{73}Br
1971[c]	Nadjakov	[25]	^{155}Gd	^{20}Ne	5n	^{170}W
04/18/1973	Schmeing	[26]	^{58}Ni	^{16}O	2n	^{72}Kr
09/25/1974	Kaba	[27]	^{54}Fe	^{32}S	2p1n	^{83}Zr
06/19/1981	Bruchertseifer	[28]	^{147}Sm	^{22}Ne	5n, 4n	^{164}Hf, ^{165}Hf
02/10/1982	Bruchertseifer	[29]	^{151}Eu	^{20}Ne	6n	^{165}Ta
07/19/1982	Eichler	[30]	^{151}Eu	^{20}Ne	7n	^{164}Ta

[a] Populated by β^+-decay
[b] Date of session
[c] No date listed

immediately in the same issue of Nuclear Physics by three additional papers by various coauthors from Saclay and Stockholm reporting on the same set of experiments [31–33]. All four papers were submitted on the same day. It is also interesting to note that all authors on the discovery paper of ^{71}Se were female [8].

The husband and wife team of Ken and Alma Chackett discovered ^{193}Tl with the Nuffield cyclotron at the University of Birmingham in England in 1959 [11]. Preiss and collaborators utilized the Yale University heavy-ion linear accelerator to produce ^{103}Cd [13], ^{123}Ba and ^{125}Ba [16], and ^{127}La and ^{129}La [18] between 1960 and 1962.

The other isotopes discovered during this time period were produced at Berkeley with the HILAC (Heavy-Ion Linear Accelerator) where Hoff, Hollander, and Michel used a mass separator in addition to β- and γ-ray measurements to identify ^{80}Sr and its daughter ^{80}Rb [12].

In the subsequent years until 1982 when the last isotope was discovered utilizing chemical separation, the majority of the new isotopes were produced at the Joint Institute for Nuclear Research at Dubna, Russia. While Belyaev and collaborators still utilized the U150 cyclotron to identify ^{180}Os [20] and ^{179}Os [23], the experiments by Nadjakov and collaborators (^{175}Re and ^{176}Re, [21]) and ^{170}W [25] and later by the group of Bruchertseifer (^{164}Hf and ^{165}Hf [28], ^{165}Ta [29], and ^{164}Ta [30]) were performed with the U300 accelerator.

By 1970 the development of high-resolution Ge-detectors allowed the clear identification of isotopes by their γ-ray spectra eliminating the need for chemical separation. Table 11.2 lists the isotopes identified by β- and γ-decay without chemical separation. By that time many institutes had acquired either cyclotrons or various linear accelerators and since the discovery measurements required only a few small detectors, the 52 isotopes published in the 38 papers listed in the table were discovered at 19 different institutions in 9 different countries.

In the first experiments, the produced activities were measured directly at or near the target position of the beam. For example, in 1970, Droste et al. discovered a long-lived isomeric state of ^{137}Nd by placing a Ge(Li) detector and a toroidal electron spectrometer directly next to the target to measure γ-spectra and conversion electrons, respectively. They measured the activities in between the beam pulses from the Dubna U300 accelerator [34]. Later in the same year ^{72}Br was identified by Nolte et al. at the Max Planck Institut für Kernphysik in Heidelberg, Germany. They stopped recoils from the fusion-evaporation reactions in a gold catcher foil and measured off-beam γ-spectra with a Ge(Li) detector [35]. Zioni et al. used a mechanical beam chopper at the EN tandem of the Racah Institute of Physics of the Hebrew University in Jerusalem, Israel, to determine the short half-life (260 ± 6 ms) of ^{46}Cr [37]. For isotopes with longer half-lives longer beam-on and beam-off periods were chosen for the irradiations and measurements, respectively.

Measurements at the target position were limited to the strongest decay channels. In order to populate and detect the weaker channels it was necessary to increase the beam intensities which also increased the background activities. In addition, neutrons which were present in the target area during the irradiation damaged the Ge(LI) detectors. Thus it was necessary to move the irradiated targets to a separate, well shielded detection station. For the identification of the relatively long-lived isotopes ^{87}Nb (3.5 ± 0.2 min) and ^{88}Mo (8.2 ± 0.5 min) with ^{32}S beams from the Rochester University MP tandem Van de Graaff accelerator, Doron and Blann moved the irradiated targets manually in front of a Ge(Li) detector [36].

For shorter-lived activities the helium-jet technique developed in the early 1960s by Macfarlane and Griffioen [72] to measure short-lived α-emitters (see Sect. 11.4), was widely used. It was first applied for the discovery of a β-emitting isotope in 1974 by Newman et al. in the identification of ^{146}Tb with the Oak Ridge Isochronous cyclotron (ORIC) [40]. A schematic diagram of the helium-jet transfer system at

Table 11.2 Isotopes discovered in fusion-evaporation reactions and identified by β- and γ-decay without chemical separation: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evaporation	Isotope
04/15/1970	Droste	[34]	^{119}Sn	^{22}Ne	4n	^{137}Nd
09/01/1970	Nolte	[35]	^{58}Ni	^{16}O	pn	^{72}Br
10/23/1970	Doron	[36]	^{58}Ni	^{32}S	3p, 2p	^{87}Nb, ^{88}Mo
03/11/1971	Zioni	[37]	^{32}S	^{16}O	2n	^{46}Cr
1972[a]	Akhmadzhanov	[38]	^{169}Tm	^{16}O	7n, 5n, 4n	^{178}Ir, ^{180}Ir, ^{181}Ir
04/26/1972	Ladenb.-Bellis	[39]	^{69}Ga	^{14}N	4n	^{79}Sr
08/27/1973	Newman	[40]	^{141}Pr	^{12}C	7n	^{146}Tb
01/10/1974	Nolte	[41]	^{40}Ca	^{32}S	2p1n	^{69}Se
07/09/1974	Newton	[42]	^{181}Ta	^{19}F	7n	^{193}Pb
02/27/1975	Toth	[43]	^{141}Pr	^{14}N	8n	^{147}Dy
05/12/1975	Hamilton	[44]	^{181}Ta	^{16}O	9n	^{186}Tl
01/30/1976	Chojnacki	[45]	^{181}Ta	^{20}Ne	5n	^{196}Bi
05/13/1976	Varley	[46]	^{92}Mo	^{16}O	p3n	^{104}In
08/19/1976	Leber	[47]	^{159}Tb	^{16}O	9n	^{166}Ta
10/08/1976	Parks	[48]	^{48}Ca	^{7}Li	pn	^{53}Ti
01/25/1977	Korschinek	[49]	^{58}Ni	^{32}S	α2p, αpn	^{84}Zr, ^{84}Nb
					2p1n	^{87}Mo
03/25/1977	Hunter	[50]	^{155}Gd	^{14}N	5n	^{164}Lu
06/23/1977	Nathan	[51]	^{48}Ca	^{9}Be	pn	^{55}V
08/17/1977	Burman	[52]	^{151}Eu	^{16}O	5n	^{162}Lu
01/03/1978	Davids	[53]	^{48}Ca	^{11}B	pn	^{57}Cr
03/06/1978	Norman	[54]	^{48}Ca	^{18}O	αpn	^{60}Mn
06/19/1978	Toth	[55]	^{144}Sm	^{10}B	6n, 5n	^{148}Ho, ^{149}Ho
07/05/1978	Alburger	[56]	^{58}Ni	^{10}B, ^{14}N	2n	^{66}As, ^{70}Br
02/18/1980	Deprun	[57]	^{54}Fe	^{32}S	3p1n	^{82}Y
03/27/1980	Murphy	[58]	^{58}Ni	^{14}N	αn	^{67}As
01/28/1981	Lister	[59]	^{58}Ni	^{24,25}Mg	pn	^{80}Y, ^{81}Y
09/15/1981	Sousa	[60]	^{144}Sm	^{10}B	α6n	^{144}Tb
01/22/1982	Schrewe	[61]	^{142}Nd	^{24}Mg	4n, 3n	^{162}Hf, ^{163}Hf
01/25/1982	Gui	[62]	^{90}Zr	^{58}Ni	pn	^{146}Ho
02/11/1982	Nolte	[63]	^{90}Zr	^{58}Ni	2p1n	^{145}Dy
			^{94}Mo	^{58}Ni	2p, pn	^{150}Er, ^{150}Tm
			^{92}Mo	^{58}Ni	3p, 2p, pn	^{147}Ho, ^{148}Er, ^{148}Tm
01/03/1985	Ollivier	[64]	^{112}Sn	^{35}Cl	2p2n	^{143}Tb
08/01/1986	Szymanski	[65]	^{165}Ho	^{16}O	8n	^{173}Re

(continued)

Table 11.2 (continued)

Date	First author	Ref.	Target	Beam	Evaporation	Isotope
07/17/1987	Runte	[66]	^{139}La	^{36}Ar	4n	^{171}Re
07/16/1990	Heiguchi	[67]	^{60}Ni	^{32}S	p2n	^{89}Tc
07/31/1991	Bosch-Wicke	[68]	^{148}Nd	^{36}Ar	p4n	^{179}Ir
08/15/1991	Zhou	[69]	^{58}Ni	^{35}Cl	p2n	^{90}Ru
06/02/1999	Xie	[70]	^{106}Cd	^{36}Ar	p2n	^{139}Tb
11/20/2003	Xu	[71]	^{92}Mo	^{40}Ca	p2n	^{129}Pm

[a]No submission date listed

Brookhaven National Laboratory used in the discovery of ^{80}Y and ^{81}Y in 1981 by Lister et al. is shown in Fig. 11.1.

In a different technique designed for short-lived activities, the target was moved from the irradiation position to the detection position by a pneumatic transfer or "rabbit" system. First developed by Goosman and Alburger in 1972 [73] it was used for the first time to identify a new isotope by Varley, Cunnane, and Gelletly in 1976 at the HILAC of the Schuster Laboratory at the University of Manchester, UK. They actually used three different methods, "namely the study of radiation emitted between accelerator pulses, the use of a mechanical rabbit system and the He-jet recoil transport system" [46] to identify ^{104}In. Later in the year, Parks, Davids, and Pardo from Argonne National Laboratory discovered ^{53}Ti with a multiple rabbit system. The advantage of using several targets is that it reduced the build-up of background radiation from longer-lived activities produced in the irradiation [48].

In yet another approach, Heiguchi et al. from the University of Tsukuba, Japan, identified ^{89}Tc by catching the recoils from the target on tantalum foils positioned on a rotating disk. After the irradiation, the disk was rotated by 180° to move the activities in front of two high-purity Ge (HPGe) detectors before another foil was moved behind the target [67].

The first isotope ever discovered in China was measured with a similar technique. Zhou et al. identified ^{90}Ru at the HI-13 tandem accelerator of the China Institute of Atomic Energy in Beijing in 1991. The residual nuclei recoiled on tantalum foils of a wheel system with 60 positions. The wheel rotated by 174° so that irradiation and detection could be done simultaneously [69].

Online isotope separators had been well established for the discovery of new isotopes in neutron fission (Sect. 6.5), spallation (Sect. 10.4), and charged-particle fission (Sect. 10.5) by the mid-sixties. In the 1970s several ISOL facilities dedicated for fusion evaporations were established all over the world. Isotopes discovered in fusion-evaporation reactions using online isotope and mass separation are listed in Table 11.3. The first new β-emitting isotope discovered in fusion-evaporation reactions using an online-mass separation system was ^{116}I. It was first produced by Gowdy et al. in 1975 with the Oak Ridge Isochronous Cyclotron (ORIC) and

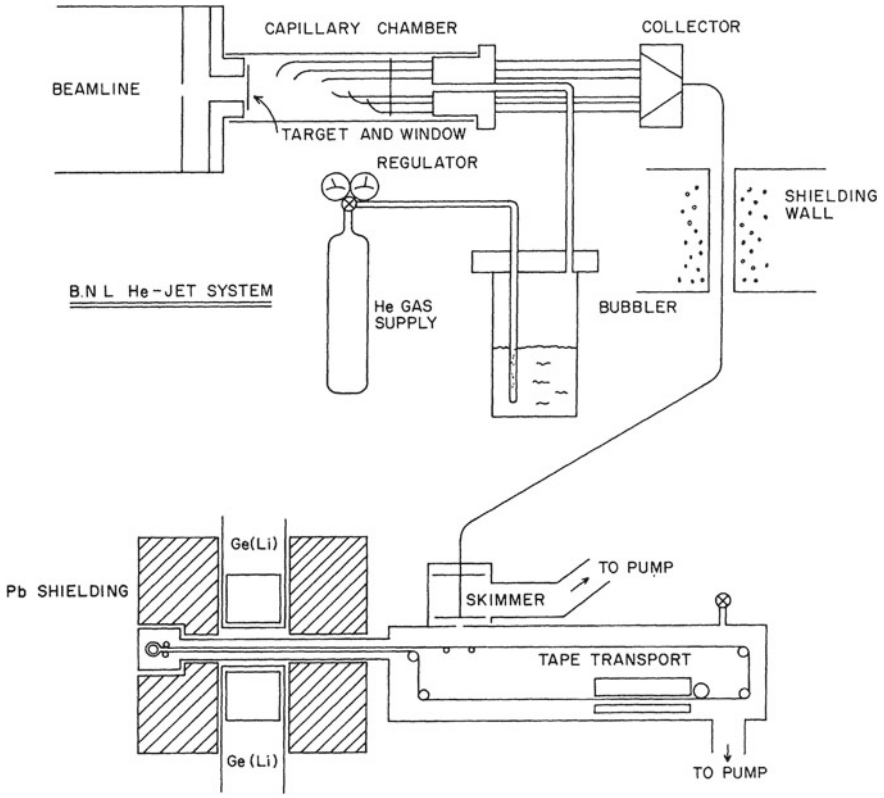

Fig. 11.1 Schematic diagram of the Brookhaven helium-jet transfer system used in the discovery of ^{80}Y and ^{81}Y [59] (Reprinted figure with permission from C.J. Lister et al., *New isotope ^{80}Y, and the decays of ^{79}Sr, ^{81}Y, and ^{82}Y*, Phys. Rev. C 24 (1981) 260. Copyright 1981 by the American Physical Society.)

identified using the UNISOR on-line isotope separator [74]. A total of 23 new isotopes were discovered with the BEMS-2 isotope separator at the Dubna U300 heavy-ion cyclotron in three separate experiments by Bogdanov et al. in 1976 [75] and 1978 [76] and by Nowicki et al. in 1980 [79].

^{103}In [77], ^{97}Ag and ^{98}Ag [78], ^{104}Sn [82], and ^{101}In [90] were discovered by the group of Huyse between 1978 and 1988 with the Louvain isotope separator (LISOL) installed at the CYCLONE cyclotron at Louvain-la-Neuve, Belgium. In 1981 Beraud et al. measured ^{102}In with the Grenoble cyclotron [80] and a year later Hagberg et al. discovered ^{71}Br using the Chalk River online-isotope separator in Canada [81].

After 1984, most isotopes were discovered with the online mass separator at the UNILAC at GSI, Darmstadt, by Kirchner, Klepper, Roeckl, and collaborators [83, 87, 97, 98] and the isotope separator OASIS at the SuperHILAC at Berkeley by Nitschke, Wilmarth, and collaborators [85, 86, 88, 92–95]. In 1986, Redon et al. coupled a helium-jet recoil system with the ion source of the on-line mass separator

Table 11.3 Isotopes discovered in fusion-evaporation reactions using online isotope and mass separation: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evaporation	Isotope
09/08/1975	Gowdy	[74]	^{103}Rh	^{16}O	3n	^{116}I
07/23/1976	Bogdanov	[75]	^{102}Pd	^{32}S	3p2n	^{129}Pr
			^{106}Cd	^{32}S	5p3n, 5p2n	^{130}Pr, ^{131}Pr
			^{106}Cd	^{32}S	4pxn	^{130}Nd, ^{131}Nd, ^{132}Nd, ^{133}Nd
			^{106}Cd	^{32}S	3pxn	^{132}Pm, ^{133}Pm, ^{134}Pm
			^{106}Cd	^{32}S	2p2n, 2p1n	^{134}Sm, ^{135}Sm
04/28/1978	Bogdanov	[76]	^{96,98}Ru	^{32}S	2pxn	^{123}La, ^{124}La
					3pxn	^{124}Ce, ^{125}Ce, ^{126}Ce, ^{127}Ce
05/30/1978	Lhersonneau	[77]	^{nat}Mo	^{14}N	xn	^{103}In
08/14/1978	Huyse	[78]	^{92}Mo	^{14}N	2p7n, 2p6n	^{97}Ag, ^{98}Ag
10/18/1980	Nowicki	[79]	^{112}Sn	^{32}S	4p4n, 4p2n	^{136}Sm, ^{138}Sm
					3pxn	^{137}Eu, ^{138}Eu, ^{140}Eu
01/26/1981	Beraud	[80]	^{92}Mo	^{14}N	4n	^{102}In
02/02/1982	Hagberg	[81]	^{40}Ca	^{35}Cl	2p2n	^{71}Br
11/29/1984	Deneffe	[82]	^{92}Mo	^{20}Ne	2p6n	^{104}Sn
11/26/1985	Kleinheinz	[83]	^{96}Ru	^{58}Ni	2p1n	^{151}Yb
06/05/1986	Redon	[84]	^{106}Cd	^{35}Cl	3p1n	^{137}Sm
			^{112}Sn	^{32}S, ^{35}Cl	2p1n, p2n	^{141}Gd, ^{144}Dy
08/04/1986	Toth	[85]	^{96}Ru	^{58}Ni	pn	^{152}Lu
09/23/1986	Wilmarth	[86]	^{92}Mo	^{54}Fe	3p2n	^{141}Tb
12/10/1986	Sekine	[87]	^{12}C	^{40}Ca	p3n	^{48}Mn
03/23/1987	Toth	[88]	^{94}Mo	^{58}Ni	p2n	^{149}Tm
05/11/1987	Kern	[89]	^{92}Mo	^{48}Ti	p3n	^{136}Eu
03/14/1988	Huyse	[90]	^{92}Mo	^{20}Ne	3p8n	^{101}In
07/11/1988	Sekine	[91]	^{92}Mo	^{32}S	p2n	^{121}La
01/09/1989	Vierinen	[92]	^{92}Mo	^{58}Ni	2p3n	^{145}Er
06/26/1989	Nitschke	[93]	^{92}Mo	^{64}Zn	p2n	^{153}Lu
08/31/1990	Firestone	[94]	^{92}Mo	^{54}Fe	3p1n	^{142}Tb
02/23/1993	Toth	[95]	^{92}Mo	^{58}Ni	2p2n	^{146}Er
02/07/1995	Gizon	[96]	^{92}Mo	^{40}Ca	αp	^{127}Pr
02/07/1995	Guglielmetti	[97]	^{58}Ni	^{58}Ni	2n	^{114}Ba
04/14/1997	Janas	[98]	^{60}Ni	^{58}Ni	3n, 2n	^{115}Ba, ^{116}Ba
			^{63}Cu	^{58}Ni	1p2n	^{118}Ba

at the SARA accelerator at Grenoble to identify ^{137}Sm, ^{141}Gd, and ^{144}Dy [84] and in 1988 ^{121}La was discovered by Sekine et al. by mass separation at the Japan Atomic Energy Research Institute (JAERI) in Tokai [91].

11.3 In-Beam γ-Ray Spectroscopy

The discoveries described in the previous section were achieved with techniques developed earlier for isotope discoveries using other probes and reaction mechanisms. They involved the measurements of the β-decay half-lives and were identified based on excitation functions and/or characteristic known radiation of the daughter nuclides. In a different approach, Stephens, Lark, and Diamond from Berkeley realized that heavy-ion fusion-evaporation reactions transfer a large amount of angular momentum to the compound nucleus [99]. If the nuclides populated after particle evaporation are prolate deformed they deexcite by γ-rays of rotational bands. Coupled with excitation function measurements the in-beam detection of these γ-ray cascades can be used to uniquely identify an isotope without measuring the β-decay. Stephens, Lark, and Diamond credit Morinaga and Gugelot [100] for the first observation of γ-rays from a rotational band in (α,4n) reactions. Although this technique was not primarily intended to search for new isotopes but to understand the evolution of nuclear structure in neutron-deficient nuclei, over 40 new nuclides were discovered during these investigations. The isotopes discovered in fusion-evaporation reactions using in-beam γ-ray spectroscopy are listed in Table 11.4.

The first isotopes discovered utilizing this method were ^{166}Hf, ^{172}W, and ^{174}W submitted for publication by Stephens, Lark, and Diamond in 1964 [101]. Until 1973, the Berkeley group was the only one identifying new isotopes with γ-ray spectroscopy. As an example, the ^{124}Ba spectrum and the corresponding rotational band is shown in Fig. 11.2 [103]. In the following 13 years the method was then adopted by nine different laboratories. Anholt, Rasmussen, and Rezanka used γ-ray spectroscopy to identify millisecond isomers. They identified ^{161}Lu using the pulsed beam structure of the Yale heavy ion accelerator to begin the recording of γ-spectra at the end of the 2 ms wide beam pulses [107].

In Germany, isotopes were identified at the tandem accelerators in Heidelberg (^{120}Ba and ^{122}Ba [109]), Munich (^{159}Yb [110] and ^{152}Yb [114]) and the VICKSI (Van-de-Graaff Isochron Cyclotron Kombination für Schwere Ionen) facility at the Hahn-Meitner Institut in Berlin (^{169}W [116]). In addition, ^{151}Tm, ^{78}Sr, and ^{171}W were discovered at Argonne [112], Brookhaven [113], and Louvain-la-Neuve [115], respectively.

The first—of only two—isotopes ever discovered in Australia was ^{167}W in 1985. It was produced by Gerl et al. with the 14UD Pelletron accelerator from the Australian National University in Canberra [117].

Table 11.4 Isotopes discovered in fusion-evaporation reactions using in-beam γ-ray spectroscopy: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
08/24/1964	Stephens	[101]	^{159}Tb, ^{165}Ho	^{14}N	7n	^{166}Hf, ^{172}W
			^{169}Tm	^{11}B	6n	^{174}W
09/06/1966	Burde	[102]	^{169}Tm	^{14}N	5n	^{178}Os
09/29/1966	Clarkson	[103]	^{116}Sn, ^{127}I	^{12}C	4n,5n	^{124}Ba, ^{134}Pr
10/09/1967	Ward	[104]	^{120}Sn	^{40}Ar	4n	^{156}Er
			^{122,124}Te	^{40}Ar	4n	^{158}Yb, ^{160}Yb
06/06/1968	Ward	[105]	^{116}Sn	^{16}O	4n	^{128}Ce
01/18/1971	Stephens	[106]	^{144}Sm	^{28}Si	2p2n	^{168}W
04/09/1973	Anholt	[107]	^{148}Sm	^{19}F	6n	^{161}Lu
04/17/1973	Nakai	[108]	^{116}Sn	^{14}N	5n	^{125}La
07/19/1974	Conrad	[109]	^{106,108}Cd	^{16}O	2n	^{120}Ba, ^{122}Ba
09/15/1975	Trautmann	[110]	^{144}Sm	^{18}O	3n	^{159}Yb
05/23/1977	Gizon	[111]	^{116}Sn	^{16}O	3n	^{129}Ce
03/05/1982	Helppi	[112]	^{92}Mo	^{60}Ni	p	^{151}Tm
05/28/1982	Lister	[113]	^{58}Ni	^{24}Mg	2p2n	^{78}Sr
08/04/1982	Nolte	[114]	^{96}Ru	^{58}Ni	2p	^{152}Yb
10/20/1982	Arciszewski	[115]	^{155}Gd	^{20}Ne	4n	^{171}W
12/19/1984	Recht	[116]	^{154}Gd	^{20}Ne	5n	^{169}W
03/23/1985	Gerl	[117]	^{142}Nd	^{28}Si	3n	^{167}W
05/20/1985	Lister	[118]	^{92,92,94}Mo	^{40}Ca, ^{50}Cr	2p2n	^{128}Nd, ^{138}Gd, ^{140}Gd
06/01/1987	Lister	[119]	^{24}Mg	^{58}Ni	2n	^{80}Zr
08/17/1987	Goettig	[120]	^{92}Mo	^{56}Fe	p2n	^{145}Ho
03/19/1988	Kuroyanagi	[121]	^{58,60}Ni	^{28}Si	p2n	^{83}Nb, ^{85}Nb
07/04/1989	Wadsworth	[122]	^{96}Ru	^{40}Ca	2p2n	^{132}Sm
05/17/1990	Lister	[123]	^{12}C, ^{24}Mg	^{58}Ni, ^{54}Fe	2n	^{68}Se, ^{76}Sr
10/22/1990	Gelletly	[124]	^{28}Si	^{58}Ni	2n	^{84}Mo
03/18/1991	Rudolph	[125]	^{58}Ni	^{32}S	p2n, pn	^{87}Tc, ^{88}Tc
07/18/1991	Gross	[126]	^{40}Ca	^{50}Cr	2p2n	^{86}Mo
04/06/1992	de Angelis	[127]	^{92}Mo	^{58}Ni	2pn	^{147}Er
09/14/1993	Seweryniak	[128]	^{54}Fe	^{58}Ni	3p2n	^{107}Sb
12/19/1997	Parry	[129]	^{96}Ru	^{40}Ca	αp	^{131}Pm
02/13/2002	Krolas	[130]	^{92}Mo	^{54}Fe	2p4n	^{140}Dy
03/20/2002	Wilson	[131]	^{64}Zn	^{64}Zn	p2n	^{125}Pr
04/22/2005	Smith	[132]	^{64}Zn	^{64}Zn	α2n	^{122}Ce

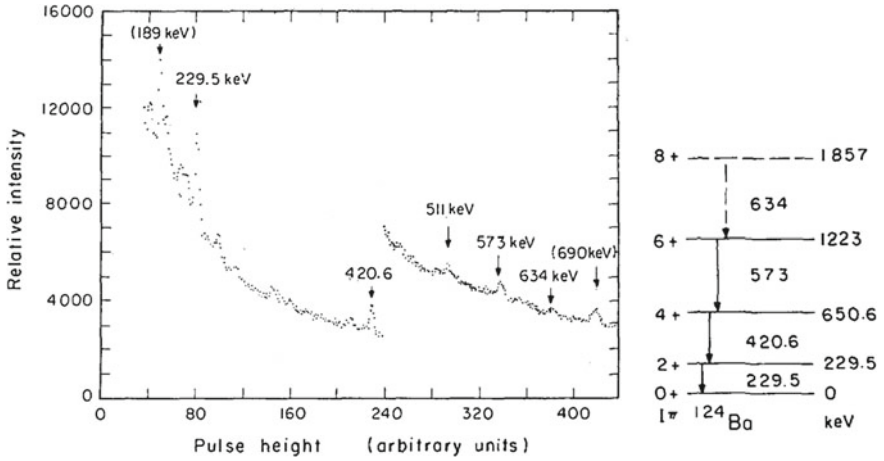

Fig. 11.2 In-beam γ-ray spectrum (*left*) and corresponding level scheme (*right*) of ^{124}Ba [103] (Reprinted from J.E. Clarkson et al., *Collective excitations in neutron-deficient barium, xenon, and cerium isotopes*, Nucl. Phys. A 93 (1967) 272. Copyright 1967, with permission from Elsevier.)

Between 1985 and 1991 the field was again dominated by a single laboratory. With the exception of ^{83}Nb and ^{85}Nb which were discovered by Kuroyanagi et al. [121] at the tandem accelerator of Kyushu University in Fukuoka, Japan, all isotopes during this period were produced with the Daresbury Laboratory Van de Graaff accelerator in the UK. For the identification of ^{128}Nd,^{138}Gd, and ^{140}Gd [118] and ^{145}Ho [120] these weaker residue channels were enhanced by measuring the γ-ray spectra in coincidence with evaporated neutrons and light-charged-particles. In subsequent experiments an increasing number of bismuth germanate (BGO) suppressed germanium detectors were placed at the target position of the Daresbury recoil separator. In the discovery of ^{87}Tc and ^{88}Tc by Rudolph et al. the 20 element array had been named POLYTESSA (TESSA—The Energy Suppression Shield Array) [125].

The combination of high-resolution suppressed γ-ray arrays and light-charged-particle arrays and recoil separators was a sensitive tool to measure γ-ray spectra of residues populated with small cross-sections. In 1992, ^{147}Er was discovered with four Compton suppressed germanium detectors and the Recoil Mass Spectrometer (RMS) of the Laboratori Nazionali di Legnaro (LNL) in Italy by de Angelis et al. [127]. Seweryniak et al. identified ^{107}Sb in 1993 using the NORDBALL array consisting of 15 detectors and a 21 element ΔE silicon detector array at the Tandem Accelerator Laboratory of the Niels Bohr Institute in Roskilde, Denmark [128]. Similarly, ^{131}Pm was identified by Parry et al. at the TASCC (Tandem Accelerator SuperConducting Cyclotron) facility of Chalk River, Canada, in 1997. They used the 8π array, consisting of an outer shell of 20 Compton suppressed HPGe detectors and an inner shell of 71 BGO scintillation detectors. It was used in conjunction with a 4π modular array of cesium iodide detectors for the reaction channel selection [129].

In 2002, Krolas et al. placed the Clover Germanium Detector Array for Recoil Decay Spectroscopy (CARDS) at the focal plane of the Recoil Mass Spectrometer RMS of the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge in order to measure short-lived isomers and discovered a 7 μs isomer in ^{140}Dy [130].

The sensitivity was improved even further for the discovery of the two most recent isotopes by utilizing 78 75 %-efficient high-purity germanium detectors of Gammasphere coupled to the Microball and the Neutron Shell in addition to measuring the recoils in the Fragment Mass Analyser (FMA). The experiment was performed at the Argonne Tandem Linear Accelerator System (ATLAS) by Wilson et al. [131] and Smith [132] discovering the neutron deficient isotopes ^{125}Pr and ^{122}Ce, respectively.

11.4 Alpha Emitters

As mentioned in the introduction fusion-evaporation reactions were originally intended for the discovery of transuranium elements. These nuclides decay predominantly by the emission of α-particles so that techniques to detect these α-particles were developed in order to identify the new isotopes. The realization that the recoils were leaving the targets after the reaction by Ghiorso et al. was then also used to identify α-emitters in lighter mass regions. Table 11.5 lists α-emitting isotopes discovered in fusion-evaporation and identified following chemical separation or by implantation in a solid catcher.

The second facility to accelerate heavy-ions after the initial success at Berkeley was the 60-in. Nuffield cyclotron of the University of Birmingham, UK. In 1954, Burcham used a ^{14}N beam with a continuous energy distribution up to 120 MeV to irradiate gold foils and measured α-spectra following chemical separation of radon to identify ^{206}Rn and ^{207}Rn. The α-spectrum is shown in Fig. 11.3 [133]. The discovery of ^{149}Dy, and ^{150}Dy, ^{151}Dy by Toth and Rasmussen at the Berkeley 60-in. cyclotron was achieved without chemical separation by measuring the α activities of the irradiated gold foil directly. ^{149}Dy is a β^+-emitter which was identified by the subsequent α-decay of the ^{149}Tb daughter nucleus [134]. Five neutron-deficient astatine isotopes were measured after chemical separation for the first time by Latimer et al. [135] and Hoff et al. [136] using the HILAC at Berkeley. For the discovery of ^{200}At and ^{201}At Hoff, Asaro, and Perlman employed a magnetic spectrograph to measure the energy of the α-particles.

Rotter et al. collected the recoils from "complete amalgamation reactions" of 80 MeV carbon ions irradiating lead and bismuth targets from the Dubna 150 cm cyclotron on an aluminum foil. The collecting foil was tilted by 45° so that it also faced a Au-Si semiconductor detector measuring the α energies from the decays of ^{213}Rn, ^{214}Ra, ^{215}Ra, ^{216}Ac, ^{214}Fr [137]. Also at Dubna—using the U300 cyclotron (U stands for Uskoritel, russian for accelerator)—Sung-Ching-Yang et al. identified ^{216}Pa by slowing the recoils in a gas to collect them on filters which were then pneumatically transported in front of two Si(Au) detectors [138].

Table 11.5 Isotopes discovered in fusion-evaporation and identified by their α-decay following chemical separation or by implantation in a solid catcher: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
03/09/1954	Burcham	[133]	^{197}Au	^{14}N	5n, 4n	^{206}Rn, ^{207}Rn
09/13/1957	Toth	[134]	^{141}Pr	^{14}N	6n, 5n, 4n	^{149}Dy[a], ^{150}Dy, ^{151}Dy
07/12/1960	Latimer	[135]	^{197}Au	^{12}C	7n, 5n, 3n	^{202}At, ^{204}At, ^{206}At
04/03/1963	Hoff	[136]	^{197}Au	^{12}C	9n, 8n	^{200}At, ^{201}At
12/13/1965	Rotter	[137]	^{208}Pb	^{12}C	6n, 5n, 3n	^{214}Ra, ^{215}Ra, ^{213}Rn[b]
			^{209}Bi	^{12}C	5n, 3n	^{216}Ac, ^{214}Fr[b]
07/12/1971	Sung-Ching-Yang	[138]	^{190}Os	^{31}P	5n	^{216}Pa
10/13/1971	Cerny	[139]	^{40}Ca	^{6}Li	2n	^{44}V
06/14/1972	Nomura	[140]	^{208}Pb	^{14}N, ^{12}C	5n, 4n	^{217}Ac, ^{216}Ra
05/22/1973	Hiruta	[141]	^{209}Bi	^{14}N	5n	^{218}Th
06/05/1973	Häusser	[142]	^{207}Pb	^{16}O	4n, 3n	^{219}Th, ^{220}Th
12/22/1995	Batchelder	[143]	^{144}Sm	^{48}Ti	2n	^{190}Po
04/30/1996	Toth	[144]	^{144}Sm	^{40}Ca	4n	^{180}Pb

[a] β^+-emitter, identified by subsequent α-decay of ^{149}Tb
[b] Populated by α-decay

In 1971, ^{44}V was discovered by Cerny et al. at the Brookhaven three-stage MP tandem Van de Graaff facility by its β-delayed α-decay [139]. The short-lived ($\sim$100 ns) α-emitters ^{216}Ra, ^{217}Ac [140] and ^{218}Th [141] were identified by Nomura et al. and Hiruta et al. respectively, using the pulsed-beam of the IPCR cyclotron at RIKEN in 1972 and 1973. The activities were measured at the target position with a silicon surface barrier detector and the identification was achieved from excitation function measurements and the observation of α-energies of known daughter nuclides. Essen-

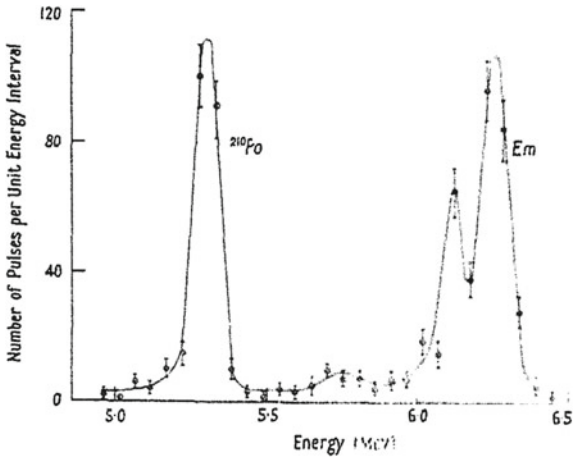

Fig. 11.3 Alpha-spectrum following the 5n, and 4n fusion-evaporation reaction of ^{14}N on ^{197}Au to produce the radon (emanation) isotopes ^{206}Rn and ^{207}Rn, respectively [133] (W.E. Burcham, *The α activity induced in gold by irradiation with nitrogen ions*, Proc. Phys. Soc. A 67 (1954) 555. Copyright IOP Publishing, reproduced with permission, all rights reserved.)

tially at the same time Häusser et al. reported the discovery of ^{219}Th and ^{220}Th using a similar technique at the Chalk River MP tandem by catching the recoils in carbon foil placed behind the target [142].

More than twenty years later, Batchelder et al. and Toth et al. used a rapidly rotating recoil catcher wheel system at the 88-in. Berkeley cyclotron to discover ^{190}Po [143] and ^{180}Pb [144], respectively.

While only about ten isotopes were discovered with solid catchers, well over a hundred isotopes were first identified with helium gas techniques originally developed by Ghiorso et al. for transuranium elements and they are listed in Tables 11.6 and 11.7.

Essentially all isotopes discovered until 1970 listed in Table 11.6 were first identified at Berkeley. Macfarlane and Griffioen first adopted the helium gas technique for α-emitters in the lighter mass region [72, 164] (see Fig. 11.4) and discovered 24 new neutron-deficient nuclides with the HILAC in several papers between 1962 and 1964 [145–149]. Subsequently several other researchers used similar experimental set-ups at the HILAC to identify an additional 65 isotopes until 1970. As a sole author Siivola discovered nine platinum [150], seven iridium [151], four polonium [155], and five gold [159] isotopes. Valli and collaborators added four astatine [152], five radon [153], one francium [154], seven radium [156], seven actinium [158], and five thorium and one protactinium [160] isotopes during this time.

In addition, in 1971, Borggreen, Valli, and Hyde measured the three protactinium isotopes ^{222}Pa, ^{223}Pa, and ^{224}Pa as well as their α-decaying daughters and two of their granddaughters [162]. Borggreen and Hyde then also observed three osmium isotopes (^{172}Os, ^{173}Os, and ^{174}Os) in the same year [163].

The only isotopes not discovered at Berkeley during this period with this method were ^{182}Hg identified by Demin et al. at the U300 Dubna cyclotron [157] and ^{221}Th and ^{222}Th as well as their daughter nuclides ^{217}Ra and ^{218}Ra, and the grand-daughter

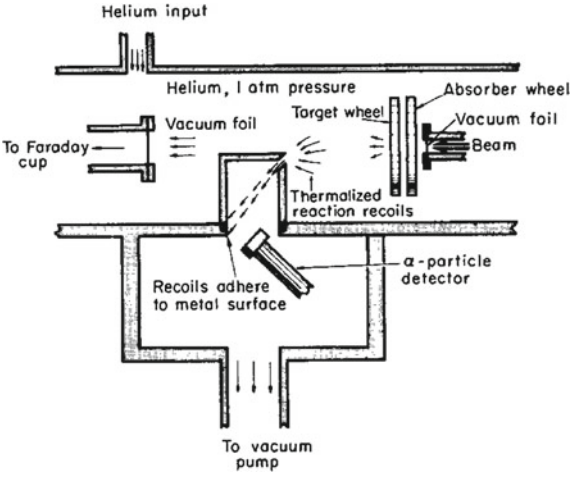

Fig. 11.4 Schematic of the set-up to collect recoils in helium gas by Macfarlane and Griffioen [72] (Reprinted from R.D. Macfarlane and R.D. Griffioen, *System for studying accelerator-produced short-lived alpha emitters*, Nucl. Instrum. Meth. 24 (1963) 461. Copyright 1963, with permission from Elsevier.)

Table 11.6 Isotopes discovered in fusion-evaporation and identified by their α-decay using helium-gas transfer techniques until 1970: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
12/10/1962	Macfarlane	[145]	^{141}Pr	^{16}O	7-4n	^{150}Ho, ^{151}Ho, ^{152}Ho, ^{153}Ho
04/22/1963	Macfarlane	[146]	^{142}Nd	^{16}O	6-4n	^{152}Er, ^{153}Er, ^{154}Er
09/20/1963	Griffioen	[147]	^{197}Au	^{16}O	9-6n	^{204}Fr, ^{205}Fr, ^{206}Fr, ^{207}Fr
			^{205}Tl	^{12}C	9-6, 4n	^{208}Fr, ^{209}Fr, ^{210}Fr, ^{211}Fr, ^{213}Fr
11/02/1963	Macfarlane	[148]	^{144}Sm	^{19}F, ^{20}Ne	7n, 6n	^{155}Lu, ^{156}Lu, ^{157}Hf, ^{158}Hf
07/15/1964	Macfarlane	[149]	^{141}Pr	^{20}Ne	8n, 7n	^{153}Tm, ^{154}Tm
			^{144}Sm	^{16}O	6n, 5n	^{154}Yb, ^{155}Yb
01/28/1966	Siivola	[150]	^{nat}Er	^{20}Ne	xn	^{173}Pt, ^{174}Pt, ^{175}Pt, ^{176}Pt, ^{177}Pt
			^{nat}Yb	^{16}O	xn	^{178}Pt, ^{179}Pt, ^{180}Pt, ^{181}Pt
09/09/1966	Siivola	[151]	^{162,164}Er	^{19}F	10n, 9n	^{171}Ir, ^{172}Ir, ^{173}Ir, ^{174}Ir
			^{166}Er	^{19}F	10-8n	^{175}Ir, ^{176}Ir, ^{177}Ir
01/18/1967	Treytl	[152]	^{185}Re	^{20}Ne	9-6n	^{196}At, ^{197}At, ^{198}At, ^{199}At
01/19/1967	Valli	[153]	^{197}Au	^{14}N	10-6n	^{201}Rn, ^{202}Rn, ^{203}Rn, ^{204}Rn, ^{205}Rn
03/19/1967	Valli	[154]	^{197}Au	^{16}O	10n	^{203}Fr
04/17/1967	Siivola	[155]	^{185}Re	^{19}F	11-8n	^{193}Po, ^{194}Po, ^{195}Po, ^{196}Po
04/28/1967	Valli	[156]	^{197}Au	^{19}F	10-7n	^{206}Ra, ^{207}Ra, ^{208}Ra, ^{209}Ra
					6-4n	^{210}Ra, ^{211}Ra, ^{212}Ra
06/20/1967	Demin	[157]	^{170}Yb	^{20}Ne	8n	^{182}Hg
10/06/1967	Valli	[158]	^{197}Au	^{20}Ne	8-5n	^{209}Ac, ^{210}Ac, ^{211}Ac, ^{212}Ac
			^{205}Tl	^{16}O	8-6n	^{213}Ac, ^{214}Ac, ^{215}Ac
10/24/1967	Siivola	[159]	^{168}Yb	^{19}F	10-8n	^{177}Au, ^{178}Au, ^{179}Au
					6n, 4n	^{181}Au, ^{183}Au
06/14/1968	Valli	[160]	^{206}Pb	^{16}O	9-5n	^{213}Th, ^{214}Th, ^{215}Th, ^{216}Th, ^{217}Th
			^{203}Tl	^{20}Ne	6n	^{217}Pa
01/23/1970	Torgerson	[161]	^{208}Pb	^{16}O	3n	^{221}Th, ^{217}Ra[a]
					2n	^{222}Th, ^{218}Ra[a], ^{214}Rn[a]
05/11/1970	Borggreen	[162]	^{208}Pb	^{19}F	5n	^{222}Pa, ^{218}Ac[a]
					4n	^{223}Pa, ^{219}Ac[a], ^{215}Fr[a]
					3n	^{224}Pa, ^{220}Ac[a], ^{216}Fr[a]
09/23/1970	Borggreen	[163]	^{164}Er	^{16}O	8-6n	^{172}Os, ^{173}Os, ^{174}Os

[a]Populated by α-decay

Table 11.7 Isotopes discovered in fusion-evaporation reactions and identified by their α-decay using helium-gas transfer techniques after 1970: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
08/19/1971	Toth	[165]	^{144,147}Sm	^{14}N	3n, 5n	^{155}Tm, ^{156}Tm
01/02/1972	Toth	[166]	^{144}Sm	^{20}Ne	5-3n	^{159}Hf, ^{160}Hf, ^{161}Hf
03/13/1972	Toth	[167]	^{156}Dy	^{20}Ne	6n, 5n	^{170}Os, ^{171}Os
06/19/1972	Toth	[168]	^{156}Dy	^{20}Ne	7n	^{169}Os
07/10/1972	Gauvin	[171]	^{155}Gd	^{40}Ar	9-5n	^{186}Pb, ^{187}Pb, ^{188}Pb, ^{189}Pb, ^{190}Pb
			^{159}Tb	^{40}Ar	9n, 8n	^{190}Bi, ^{191}Bi
01/09/1973	Bogdanov	[181]	^{96}Ru	^{16}O	4n	^{108}Te
02/08/1973	Eastham	[182]	^{144}Sm	^{24}Mg	7-4n	^{161}W, ^{162}W, ^{163}W, ^{164}W
03/29/1973	Gauvin	[172]	^{159}Tb	^{40}Ar	10n	^{189}Bi
07/09/1973	Le Beyec	[179]	^{181}Ta	^{19}F	9n, 8n	^{191}Pb, ^{192}Pb
12/16/1974	Cabot	[173]	^{141}Pr	^{40}Ca	6n, 5n	^{175}Au, ^{176}Au
			^{150}Sm	^{40}Ca	5n	^{185}Pb
04/28/1975	Toth	[169]	^{156}Dy	^{16}O	7n, 6n	^{165}W, ^{166}W
10/06/1975[a]	Cabot	[174]	^{142}Nd	^{40}Ca	5n	^{177}Hg
06/01/1977	Cabot	[175]	^{106}Cd, ^{110}Cd	^{63}Cu	p2n, 3n	^{166}Os, ^{170}Ir
			^{109}Ag	^{63}Cu	5n, 4n	^{167}Os, ^{168}Os
07/11/1977	Della Negra	[176]	^{182}W	^{20}Ne	10n	^{192}Po
03/21/1978	Cabot	[177]	^{nat}Cd	^{63}Cu	xpxn	^{169}Re, ^{168}Ir, ^{169}Ir, ^{165}Os
05/02/1978	Schrewe	[183]	^{89}Y	^{84}Kr	7n	^{166}Re
12/17/1979	Dufour	[180]	^{148}Sm	^{40}Ca	4n	^{184}Pb
03/26/1981	Della Negra	[178]	^{112}Sn	^{63}Cu	p2n	^{172}Pt
10/24/1988	Toth	[170]	^{94}Mo	^{90}Zr	3n	^{181}Pb
03/16/1992	Meissner	[184]	^{141}Pr	^{32}S	6n, 5n	^{167}Re, ^{168}Re

[a]Populated by α-decay
[b]Date of presentation

^{214}Rn discovered at the Yale University Heavy Ion Accelerator by Torgerson et al. [161].

In the 1970s the technique was most productively used to discover new α-emitting nuclides at Oak Ridge and Orsay (see Table 11.7). Toth and collaborators identified ten isotopes of elements between thulium and osmium using the Oak Ridge Isochronous Cyclotron (ORIC) [165–169] and^{181}Pb in 1988 [170]. Between 1972 and 1981, the group of Le Beyec discovered twenty-four isotopes of elements between rhenium and bismuth mostly with the ALICE accelerator at Orsay [171–178]. For the discovery of ^{191}Pb and ^{192}Pb they used the Berkeley HILAC [179]. Also at Orsay, Dufour et al. identified ^{184}Pb in 1979 by using an electrostatic deflector to deposit lead recoils stopped in nitrogen gas onto the surface of a solid state detector [180].

Other than in Oak Ridge and Orsay, Bogdanov, Karnaukhov, and Petrov identified ^{108}Te with the 300 cm Dubna cyclotron [181], Eastham and Grant measured several tungsten isotopes at the University of Manchester HILAC [182], and Schrewe et al. reported the observation of ^{166}Re at the GSI UNILAC [183]. In 1992, measurements by Meissner et al. at the VICKSI accelerator of the Berlin Hahn-Meitner Institut resulted in the revision of previous assignments of neutron-deficient rhenium isotopes and they are credited with the discovery of ^{167}Re and ^{168}Re [184].

Although the helium gas jet technique was used in the discovery of many nuclides it had the disadvantage that the identification relied on excitation function measurements and/or the observation of known daughter α-emitters. With the application of the Isotope Separation On-Line (ISOL) method for the fusion-evaporation recoil products it was possible to identify the mass of the fragments and measure the subsequent α-decay. Table 11.8 lists the α-emitting isotopes discovered with the ISOL technique.

Already in 1969, Tarantin, Kabachenko, and Demyanov discovered five bismuth isotopes with the heavy-ion beam mass separator at the U300 Dubna cyclotron [185]. Several years later, Toth et al. used the UNISOR facility at Oak Ridge to identify ^{184}Tl, ^{185}Tl, and ^{187}Tl [186]. All other ISOL measurements of new α-emitters were performed with the GSI online mass separator by the group of Kirchner, Klepper, Roeckl, and collaborators, who observed sixteen new isotopes between 1977 and 1981 as listed in the table.

An even more efficient method to measure and identify the evaporation residues and correlate the subsequent α-emission was to separate the recoils directly, rather than stopping them in an ion source of a mass separator. One of the first such devices was the velocity filter SHIP (Separator for Heavy Ion reaction Products) developed at GSI shown in Fig. 11.5. It was not only instrumental in the discovery of many transuranium and especially superheavy nuclides, SHIP was also used in the discovery of many lighter-mass α-emitting isotopes as listed in Table 11.9. Almost fifty isotopes of the elements between lutetium and uranium were discovered with SHIP since 1978; the most recent one was ^{197}Fr in 2013 [213].

In addition to SHIP at GSI, recoil separators were installed at several other heavy-ion accelerator facilities around the world. Isotopes discovered at these separators are listed in Table 11.10. In 1979, DiRienzo et al. discovered ^{199}Rn at the three-stage tandem accelerator in Brookhaven using an MIT designed velocity selector [214]. The in-flight kinematic separator VASSILISSA located at the U400 Dubna cyclotron was used by Andreyev et al. to discover ^{225}U [215], ^{223}U, ^{224}U [217], ^{218}U [218], and ^{219}U [219] between 1988 and 1993. Seven year later, Malyshev et al. pushed the knowledge of neutron-deficient uranium isotopes even further to ^{217}U [237]. Page et al. and Sellin et al. measured α-decays in coincidence with fragments identified with the Daresbury recoil separator in the discovery of ^{108}I [216] and ^{172}Au [220], respectively.

One of the most productive devices next to SHIP was the gas-filled recoil separator RITU (Recoil Ion Transport Unit) at the K130 cyclotron of the University of Jyväskylä Accelerator Laboratory (JYFL) in Finland. Between 1994 and 2012, the group of Leino and Uusitalo discovered sixteen α-emitting nuclei with RITU.

Table 11.8 Isotopes discovered in fusion-evaporation and identified by their α-decay using Isotope Separation OnLine (ISOL): The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
10/06/1969	Tarantin	[185]	^{181}Ta	^{20}Ne	9n, 8n, 7n	^{192}Bi, ^{193}Bi, ^{194}Bi
					6n, 4n	^{195}Bi, ^{197}Bi
06/15/1976	Toth	[186]	^{180}W	^{14}N	10n, 9n	^{184}Tl, ^{185}Tl
			^{182}W	^{14}N	9n	^{187}Tl
07/08/1977	Kirchner	[187]	^{63}Cu	^{58}Ni	2p5n	^{114}I
			^{58}Ni	^{58}Ni	4p2n, 2p	^{110}Te, ^{114}Xe
					3p3-0n	^{110}I, ^{111}I, ^{112}I, ^{113}I
07/11/1978	Roeckl	[188]	^{58}Ni	^{58}Ni	2p2n	^{112}Xe
04/17/1979	Schardt	[189]	^{58}Ni	^{58}Ni	2p3n	^{111}Xe, ^{107}T[a]
01/02/1980	Schrewe	[190]	^{142}Nd	^{48}Ti	p6n, 7n	^{183}Tl, ^{183}Pb
			^{107}Ag	^{84}Kr	3n	^{188}Bi
03/30/1981	Schardt	[191]	^{58}Ni	^{58}Ni	2p4n	^{110}Xe, ^{106}Te[a]
08/26/1981	Plochocki	[192]	^{58}Ni	^{58}Ni	pn	^{106}Sb[a]

[a]Populated by α-decay

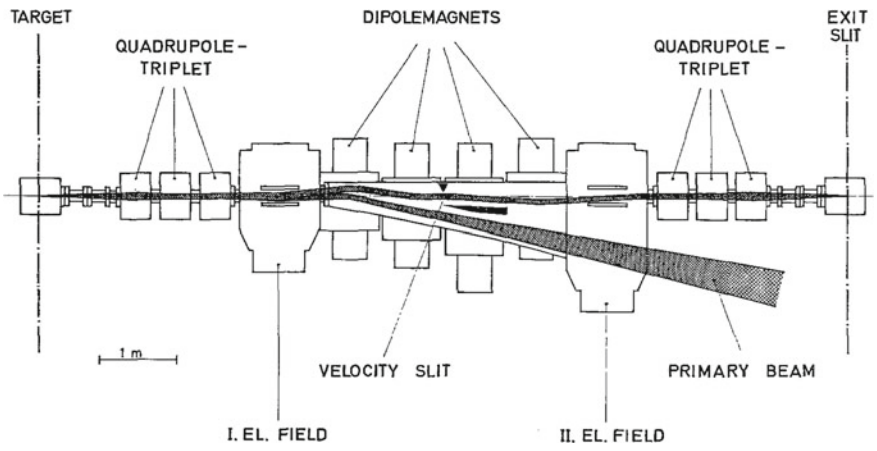

Fig. 11.5 Schematic diagram of the GSI velocity filter [193] (Reprinted from H. Ewald et al., *Report on the heavy ion separator SIS at the GSI*, Nucl. Instrum. Meth. 139 (1976) 223. Copyright 1976, with permission from Elsevier.)

Figure 11.6 shows the measured energies of mother and daughter α-emitters correlated with evaporation residues observed in the discovery of ^{210}Th and ^{211}Th [223]. For the most recent discoveries of ^{161}Os and its α daughter ^{157}W [244] and ^{198}Fr [245] the Gamma Recoil Electron Alpha Tagging (GREAT) Spectrometer [249] was installed at the focal plane of RITU.

Table 11.9 Isotopes discovered in fusion-evaporation reactions and identified by their α-decay using the velocity filter SHIP at GSI: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
08/25/1978	Schmidt	[194]	^{181}Ta	^{40}Ar	6n, 3n	^{215}Pa, ^{218}Pa
11/27/1978	Hofmann	[195]	^{107}Ag, ^{108}Pd	^{58}Ni	p4n	^{160}W, ^{156}Hf[a], ^{161}Ta
			^{109}Ag	^{58}Ni	4n	^{163}Re, ^{159}Ta[a]
			^{109}Ag	^{58}Ni	3n	^{164}Re, ^{160}Ta[a]
			^{107}Ag	^{58}Ni[b]	3n	^{162}Re, ^{158}Ta[a]
09/05/1979	Vermeulen	[196]	^{176}Hf	^{40}Ar	4n	^{212}Th
02/03/1981	Hofmann	[197]	^{110}Cd	^{58}Ni	5n, 4n	^{163}Os, ^{159}W[a], ^{164}Os
			^{nat}Sn	^{58}Ni[c]	xn	^{168}Pt, ^{169}Pt, ^{170}Pt, ^{171}Pt
			^{nat}Cd	^{58}Ni	xpyn	^{155}Hf[a], ^{165}Re
			^{106}Cd	^{58}Ni	2p4n	^{158}W, ^{154}Hf[a], ^{154}Lu[d]
02/24/1983	Schneider	[198]	^{nat}Rb	^{92}Mo	xn	^{173}Au, ^{174}Au
			^{nat}Sr	^{92}Mo	xn	^{175}Hg, ^{176}Hg
			^{89}Y	^{92}Mo	2n	^{179}Tl
05/30/1983	Hingmann	[199]	^{186}W	^{40}Ar	p4n, 4n	^{221}Pa, ^{222}U
09/05/1985	Keller	[200]	^{94}Mo	^{90}Zr	2n	^{182}Pb
11/06/1986	Heßberger	[201]	^{159}Tb	^{51}V	5n	^{205}Ra
02/21/1989	Hofmann	[202]	^{106}Cd	^{58}Ni	2n	^{162}Os
12/22/1992	Quint	[203]	^{100}Mo	^{94}Mo	3n	^{191}Po
12/20/1994	Ninov	[204]	^{170}Er	^{51}V	8n, 7n	^{213}Pa, ^{214}Pa
10/15/1999	Andreyev	[205]	^{142}Nd	^{52}Cr	6n, 5n	^{188}Po, ^{189}Po
03/14/2003	Andreyev	[206]	^{93}Nb	^{94}Mo	3n	^{184}Bi
04/08/2005	Andreyev	[207]	^{144}Sm	^{46}Ti	4n, 3n	^{186}Po, ^{187}Po
10/25/2005	Andreyev	[208]	^{144}Sm	^{51}V	3n	^{192}At
10/02/2006	Andreyev	[209]	^{144}Sm	^{52}Cr	3n, 2n	^{193}Rn, ^{194}Rn
05/04/2009	Andreyev	[210]	^{141}Pr	^{56}Fe	3n	^{194}At
11/13/2009	Andreyev	[211]	^{144}Sm	^{40}Ca	5n	^{179}Pb
07/16/2010	Heredia	[212]	^{147}Sm	^{64}Ni	3n	^{208}Th
01/29/2013	Kalaninova	[213]	^{141}Pr	^{60}Ni	4n	^{197}Fr

[a] Populated by α-decay
[b] These reactions also produced the proton-unbound nuclides ^{161}Re and ^{157}Ta (see Sect. 16.4)
[c] These reactions also produced the proton-unbound nuclides ^{166}Ir and ^{167}Ir (see Sect. 16.4)
[d] Populated by β^+-decay

During this time period (1994 through 2006) another ten isotopes were discovered at Argonne National Laboratory with the Fragment Mass Analyzer (FMA) designed and constructed by Davids and Larson [250]. It is interesting to note that out of eight discovery publications only two had first authors from Argonne (^{178}Tl [232] and ^{105}Te [242]). The other discoveries were led by researchers affiliated with six different institutions who collaborated with the group of Davids: ^{204}Ra (University of Manchester) [222], ^{181}Tl (Oak Ridge National Laboratory) [225], ^{166}Pt and ^{167}Pt

Table 11.10 Isotopes discovered in fusion-evaporation reactions and identified by their α-decay using recoil separators: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
12/28/1979	DiRienzo	[214]	^{169}Tm	^{35}Cl	5n	^{199}Rn
12/16/1988	Andreyev	[215]	^{208}Pb	^{22}Ne	5n	^{225}U
05/14/1990	Page	[216]	^{54}Fe	^{58}Ni	p3n	^{108}I
11/01/1990	Andreyev	[217]	^{208}Pb	^{20}Ne	5n, 4n	^{223}U, ^{224}U
02/04/1992	Andreyev	[218]	^{197}Au	^{27}Al	6n	^{218}U
01/18/1993	Andreyev	[219]	^{197}Au	^{27}Al	5n	^{219}U
07/12/1993	Sellin	[220]	^{106}Cd	^{70}Ge	p3n	^{172}Au
03/10/1994	Leino	[221]	^{175}Lu	^{40}Ar	8n, 7n	^{207}Ac, ^{208}Ac
12/28/1994	Leddy	[222]	^{182}W	^{28}Si	6n	^{204}Ra
03/02/1995	Uusitalo	[223]	^{181}Ta	^{35}Cl	6n, 5n	^{210}Th, ^{211}Th
03/21/1995	Morita	[224]	^{166}Er	^{36}Ar	6n, 5n	^{196}Rn, ^{197}Rn
			^{169}Tm	^{36}Ar	5n	^{200}Fr
12/11/1995	Toth	[225]	^{90}Zr	^{92}Mo	p	^{181}Tl
03/06/1996	Leino	[226]	^{175}Lu	^{35}Cl	7n	^{203}Ra
03/11/1996	Bingham	[227]	^{92}Mo	^{78}Kr	4n, 3n	^{166}Pt, ^{167}Pt
06/13/1996	Ikezoe	[228]	^{182}W	^{32}S	5n	^{209}Th
09/03/1996	Batchelder	[229]	^{97}Mo	^{92}Mo	p2n	^{186}Bi
11/13/1996	Mitsuoka	[230]	^{182}W	^{35}Cl	5n	^{212}Pa
02/17/1997	Uusitalo	[231]	^{144}Sm	^{36}Ar	6n	^{174}Hg
02/27/1997	Carpenter	[232]	^{103}Rh	^{78}Kr	3n	^{178}Tl
09/18/1997	Eskola	[233]	^{175}Lu	^{36}Ar	5n	^{206}Ac
09/10/1998	Batchelder	[234]	^{97}Mo	^{92}Mo	pn	^{187}Bi
03/26/1999	Tagaya	[235]	^{169}Tm	^{36}Ar	α6n, 6n	^{195}At, ^{199}Fr
06/02/1999	Seweryniak	[236]	^{78,80}Kr	^{96}Ru	1n, 3n	^{172}Hg, ^{173}Hg
05/18/2000	Malyshev	[237]	^{182}W	^{40}Ar	5n	^{217}U
12/22/2000	Kettunen	[238]	^{142}Nd	^{56}Fe	3n	^{195}Rn
12/16/2002	Kettunen	[239]	^{141}Pr	^{54,56}Fe	4n	^{191}At, ^{193}At
12/09/2003	Kettunen	[240]	^{96}Ru	^{78}Kr	3n	^{171}Hg
10/27/2004	Uusitalo	[241]	^{141}Pr	^{63}Cu	3n, 2n	^{201}Ra, ^{202}Ra
03/09/2006	Seweryniak	[242]	^{50}Cr	^{58}Ni	3n	^{105}Te
05/16/2006	Liddick	[243]	^{54}Fe	^{58}Ni	3n	^{109}Xe
12/20/2009	Bianco	[244]	^{106}Cd	^{58}Ni	3n	^{161}Os, ^{157}W[a]
11/30/2012	Uusitalo	[245]	^{141}Pr	^{60}Ni	3n	^{198}Fr
12/01/2013	Zhang	[246]	^{169}Tm	^{40}Ca	4n	^{205}Ac
04/09/2015	Ma	[247]	^{180}W	^{40}Ar	4n	^{216}U
07/14/2015	Khuyagbaatar	[248]	^{176}Yb	^{50}Ti	5n	^{221}U

[a] Populated by α-decay

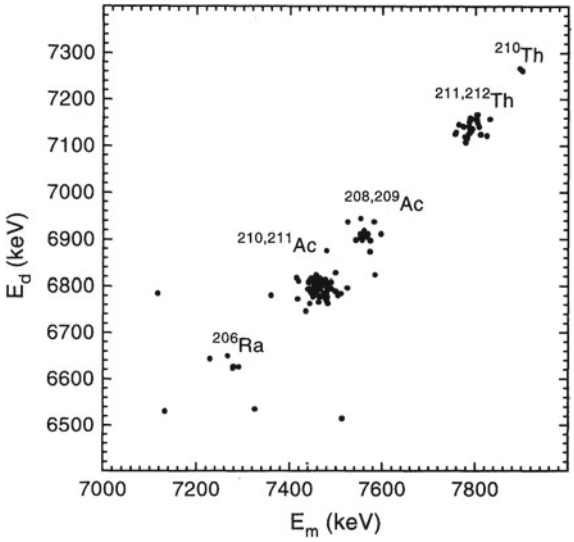

Fig. 11.6 Energies of mother and daughter α-emitters correlated with evaporation residues detected in the gas-filled separator RITU [223] (Reprinted figure with permission from J. Uusitalo et al., *α-decay of the new isotopes ^{210}Th and ^{211}Th*, Phys. Rev. C 52 (1995) 113. Copyright 1995 by the American Physical Society.)

(University of Tennessee) [227], ^{186}Bi (Louisiana State University) [229], ^{187}Bi (Oak Ridge Associated Universities) [234], and ^{172}Hg and ^{173}Hg (University of Maryland) [236].

In Japan, the gas-filled separator GARIS at RIKEN and the recoil mass separator (RMS) at JAERI contributed to the discovery of α-emitting nuclides. At RIKEN, Morita et al. discovered ^{196}Rn, ^{197}Rn, and ^{200}Fr in 1995 [224] and Tagaya et al. identified ^{195}At and ^{199}Fr in 1999 [235]. In 1996, Ikezoe et al. and Mitsuoka et al. discovered ^{209}Th [228] and ^{212}Pa [230], respectively.

In 2006, Liddick et al. employed a digital processing system for the α-particle signals from the decay of ^{109}Xe implanted at the focal plane of the recoil mass separator at Oak Ridge. They were able to separate the first α-decay of ^{109}Xe with a half-life of 13 ± 2 ms from the subsequent α-decay of the daughter nuclide ^{105}Te with a half-life of only 620 ns [243].

Two new α-emitters were discovered at the Heavy Ion Research Facility in Lanzhou (HIRFL), China. Zhang et al. and Ma et al. identified ^{205}Ac in 2013 [246] and ^{216}U in 2015 [247], respectively, with the gas-filled recoil separator SHANS (Spectrometer for Heavy Atoms and Nuclear Structure).

Most recently, Khuyagbaatar et al. used the TransActinide Separator and Chemistry Apparatus (TASCA) at GSI in the discovery of ^{221}U [248].

11.5 Proton Emissions and Delayed Fission

Beta-delayed proton emitters were first observed by Barton et al. in 1963 at McGill University discovering ^{25}Si [251]. Beta-delayed proton emission occurs in neutron-deficient nuclides close to the proton drip-line. In light elements (up to titanium)

they can be populated with light-charged-particle beams, however, in order to reach β-delayed proton emitters in heavier elements fusion-evaporation reactions involving heavy ions are necessary. Isotopes discovered by β-delayed proton emission populated in fusion-evaporation reactions are listed in Table 11.11. The initial nuclide is identified by deducing its β^+ half-life from the decay curve measured by the promptly emitted protons from excited unbound states in the daughter nuclide. In most cases other properties of the daughter nuclides were either already known or no information about them could be extracted from the measured proton spectra.

The first β-delayed proton emitters produced in a fusion-evaporation reaction were ^{109}Te and ^{111}Te, discovered by Karnaukhov et al. in 1966 at the U300 Dubna cyclotron [252]. Subsequently, Bogdanov and collaborators identified the β-delayed proton emitters ^{119}Ba [255], ^{116}Cs, ^{121}Ba [256], ^{117}Ba, ^{129}Nd, and ^{133}Sm [75] at Dubna. For the latter two experiments they used the BEMS-2 mass separator to identify the recoils.

In 1970, Cerny et al. discovered ^{49}Fe at the Harwell variable-energy cyclotron [253]. The energy resolution of the semiconductor telescope used for the proton detection was sufficient to measure a discrete resonance in the daughter nuclide ^{49}Mn which had previously not been observed. The decay scheme is shown in Fig. 11.7.

In the same year, Cerny was also involved in two experiments reporting the discovery of proton radioactivity. He was a collaborator in an experiment by Jackson et al. from Oxford University which discovered the decay of an excited isomeric state in ^{53}Co by proton emission. The experiment was performed with the Harwell variable-energy cyclotron to populate the state and the emitted protons were detected with a semiconductor telescope [254]. In addition to this fusion-evaporation reaction, Cerny essentially immediately confirmed the results with the reaction ^{54}Fe(p,2n) at the 88-in. Berkeley cyclotron. The results were submitted on the same day as the paper by Jackson et al. and published adjacent to each other in the same issue of Physics Letters B [281].

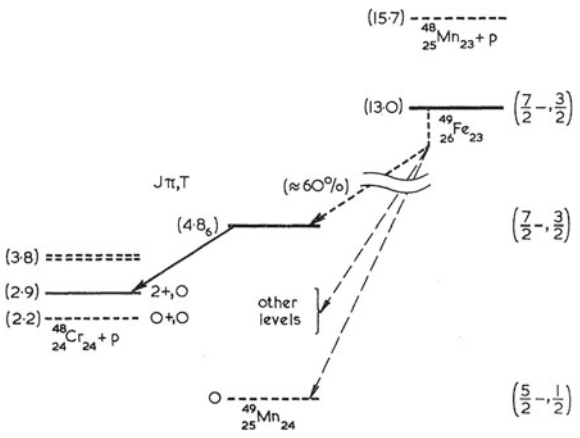

Fig. 11.7 Decay diagram of ^{49}Fe. In addition to the discovery of ^{49}Fe the observation of a discrete level in ^{49}Mn also corresponds to the first observation of this nuclide [253] (Reprinted figure with permission from J. Cerny et al., ^{49}*Fe: A New* $T_Z = 3/2$ *delayed-proton emitter*, Phys. Rev. Lett. 24 (1970) 1128. Copyright 1970 by the American Physical Society.)

Table 11.11 Isotopes discovered in fusion-evaporation reactions and identified by β-delayed proton emission and delayed fission: The submission date, first author and reference of the publication, as well as the target, beam, and the evaporation channel are listed

Date	First author	Ref.	Target	Beam	Evap.	Isotope
01/03/1966	Karnaukhov	[252]	^{92}Mo	^{20}Ne	3n, 1n	^{109}Te, ^{111}Te
04/07/1970	Cerny	[253]	^{40}Ca	^{12}C	3n	^{49}Fe, ^{49}Mn[a]
09/23/1970	Jackson	[254]	^{40}Ca	^{16}O	1p2n	^{53}Co[b]
07/09/1973	Bogdanov	[255]	^{106}Cd	^{16}O	3n	^{119}Ba
02/25/1974	Bogdanov	[256]	^{90}Zr, ^{93}Nb	^{32}S	1p5n, 1p3n	^{116}Cs, ^{121}Ba
03/21/1974	Jackson	[257]	^{32}S	^{16}O	3n	^{45}Cr, ^{45}V[a]
12/02/1975	Vieira	[258]	^{40}Ca	^{16}O, ^{20}Ne	3n	^{53}Ni, ^{57}Zn, ^{57}Cu[a]
05/18/1976	Hardy	[259]	^{40}Ca	^{40}Ca	2p1n	^{77}Sr
07/23/1976	Bogdanov	[75]	^{92}Mo	^{32}S	2p5n	^{117}Ba
			^{102}Pd, ^{106}Cd	^{32}S	2p3n	^{129}Nd, ^{133}Sm
08/11/1980	Nolte	[260]	^{58}Ni	^{40}Ca	2p1n	^{95}Pd
06/25/1981	Tidemand-P.	[261]	^{50}Cr	^{58}Ni	2p3n, 2p1n	^{103}Sn, ^{105}Sn
06/07/1982	Kurcewicz	[262]	^{58,60}Ni, ^{63}Cu	^{40}Ca	2p2n, p3n, 3n	^{94}Pd, ^{96}Ag, ^{100}In
08/23/1982	Hagberg	[263]	^{54}Fe	^{40}Ca	2p1n	^{91}Ru
05/17/1983	Nitschke	[264]	^{90}Zr, ^{92}Mo	^{40}Ca	p3n, αn	^{126}Pr, ^{127}Nd
			^{50}Cr, ^{92}Mo	^{92}Mo, ^{56}Fe	2p1n, αn	^{139}Gd, ^{143}Dy
02/16/1984	Toth	[265]	^{144}Sm	^{12}C	7n	^{149}Er
02/17/1984	Nitschke	[266]	^{58}Ni, ^{92}Mo	^{64}Zn, ^{36}Ar	pn, αpn	^{120}La, ^{122}La
			^{92}Mo	^{36}Ar, ^{54}Fe	αn	^{123}Ce, ^{141}Dy
03/08/1985	Wilmarth	[267]	^{92}Mo	^{40}Ca	3p1n, pn	^{128}Pr, ^{130}Pm
08/25/1986	Hotchkis	[268]	^{40}Ca	^{24}Mg	3n	^{61}Ge, ^{61}Ga[a]
09/23/1986	Wilmarth	[86]	^{92}Mo, ^{96}Ru	^{36}Ar, ^{40}Ca	p3n, 2p3n	^{124}Pr, ^{131}Sm
			^{92}Mo	^{54}Fe	3p3n, 2p2n	^{140}Tb, ^{142}Dy
			^{92}Mo	^{58}Ni	3p2n	^{144}Ho
03/04/1987	Lazarev	[269]	^{144}Sm	^{40}Ca	p3n	^{180}Tl[c]
07/11/1988	Vierinen	[270]	^{92}Mo	^{46}Ti	p3n, p2n	^{134}Eu, ^{135}Eu
01/08/1993	Batchelder	[271]	^{40}Ca	^{28}Si	3n	^{65}Se
07/19/1993	Batchelder	[272]	^{40}Ca	^{36}Ar	3n	^{73}Sr
07/29/1996	Xu	[273]	^{106}Cd	^{32}S	3n	^{135}Gd
02/03/1997	Li	[274]	^{92}Mo	^{32}S	3n	^{121}Ce
09/17/1997	Huang	[275]	^{58}Ni	^{32}S	4p5n	^{81}Zr
04/05/1999	Xu	[276]	^{92}Mo, ^{96}Ru	^{36}Ar	3n	^{125}Nd, ^{129}Sm
			^{96}Ru	^{36}Ar	p3n	^{128}Pm
			^{106}Cd	^{36}Ar	2p3n, 3n	^{137}Gd, ^{139}Dy
05/12/1999	Sonzogni	[277]	^{58}Ni	^{78}Kr	1p4n	^{130}Sm[d]
12/12/2000	Xu	[278]	^{106}Cd	^{40}Ca	p3n	^{142}Ho
03/14/2001	Xu	[279]	^{112}Sn	^{40}Ca	3n	^{149}Yb
07/29/2002	Karny	[280]	^{92}Mo	^{58}Ni	p4n	^{144}Er[d]

[a] β^+-delayed proton emitter
[b] Proton emitter from an isomeric excited state
[c] β^+-delayed fission
[d] Populated by a direct proton emitter

Four years later Jackson et al. observed the next β-delayed proton emitter. In addition to the parent nuclide ^{45}Cr they also identified the proton emitting daughter ^{45}V for the first time with the Chalk River MP tandem accelerator [257]. The intermediate proton-emitting nuclide was also not known in two other cases. At the 88-in. cyclotron at Berkeley, Vieira et al. observed ^{57}Cu in the decay of ^{57}Zn in 1975 [258], and in 1986, Hotchkis et al. discovered ^{61}Ga together with ^{61}Ge [268].

Two more β-delayed proton emitters were discovered with the MP tandem at Chalk River, ^{77}Sr by Hardy et al. in 1976 [259] and ^{91}Ru by Hagberg et al. in 1982 [263]. In the early 1980s six proton emitters were identified in Germany; Nolte and Hick captured the recoils on a rotating wheel behind the target at the Munich MP tandem to discover ^{95}Pd [260] while ^{103}Sn,^{105}Sn [261], ^{94}Pd, ^{96}Ag, and ^{100}In [262] were discovered with the online mass separator at the UNILAC at GSI by Tidemand-Petersson et al. and Kurcewicz et al., respectively.

All identifications of new β-delayed proton emitters in the decade between 1983 and 1993 were achieved at Berkeley. The group of Nitschke and Wilmarth alone discovered fifteen new isotopes using the online isotope separator OASIS at the HILAC [86, 264, 266, 267]. In addition to the discovery of ^{61}Ge mentioned above [268], Toth et al. and Batchelder et al. identified ^{149}Er [265] and ^{65}Se and ^{73}Sr [271, 272], respectively, with the helium-jet technique at the 88-in. cyclotron. ^{73}Sr decayed to an excited state of the proton-unbound nuclide ^{73}Rb which also was identified for the first time in the experiment (see Sect. 16.3) [272].

The helium-jet technique was also employed for the discovery of the ten most recent β-delayed proton emitters, all observed at the sector-focused cyclotron (SFC) of the Institute of Modern Physics in Lanzhou, China [273–276, 278, 279].

Two isotopes were not discovered by subsequent delayed proton emission but by preceding prompt proton emission populating states of the new nuclides. Sonzogni et al. deduced the energy of the first excited 2^+ state in ^{130}Sm from the observation of two peaks in the energy spectrum of the proton emitting parent nuclide ^{131}Eu which was implanted in the focal plane of the FMA at Argonne [277]. Similarly ^{144}Er was identified by observing two proton lines in the decay of ^{145}Tb. Karny et al. used digital data processing to separate the pulses of the short-lived proton emitter ($\sim$3μs) from the implantation signals at the recoil mass separator at Oak Ridge in 2002 [280].

In addition to the isotopes discovered by β-delayed proton emission, one isotope was identified by observing its β-delayed fission decay. Lazarev et al. discovered ^{180}Tl with the U400 Dubna cyclotron in 1987. They irradiated enriched samarium targets deposited on a rotating copper cylinder with ^{40}Ca ions and detected the fission fragments in mica detectors surrounding the cylindrical target. Lazarev et al. argue that the fragments originate from excited states in ^{180}Hg following the β-decay of ^{180}Tl [269].

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