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Abstract

Decays of over forty short-lived ($T_{1/2}$ from $\approx$50ns to 70μs) isomeric states including a new ^{66m}As produced in the quasifragmentation of a ^{112}Sn beam (58 A·MeV,63 A·MeV) in a ^{nat}Ni target were observed at the final focus of the LISE3 spectrometer at Ganil. Their detection, based on the slow ($\approx$10μs) time correlation of the implanted product with the characteristic γ-radiation, represents a novel, unambiguous isotope identification method for projectile fragment separator experiments. Measured intensities of the isomeric beams and the ratio of the isomeric yield to the total production are given.

25.70.-z,25.70.Mn,21.10.Tg,29.30.Kv

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The production of nuclear beams in metastable states is one of the attractive applications of the projectile-fragment separator technique [1–3]. Such projectiles can be used to investigate the properties of a nucleus in an isomeric state like its nuclear radius (see [4,5] for examples of such experiments with radioactive ground-state beams) as well as for the reaction studies. Beams of isomers characterized by a high-spin multiquasiparticle configuration can be used for investigations aimed at the observation and understanding of levels built on exotic band-heads and at the determination of the spin-dependence of selected reaction channels. Systematic data on the isomer-to-total production ratio (F) can contribute to a better understanding of the fragmentation-like reaction mechanism [2]. The feasibility of such studies strongly depends on the projectile intensities achieved. So far the production of only a few beams of isomers with relatively long half-lives, namely ^{26m}Al [2], ^{38m}Cl [6], ^{38m}K [6], ^{42m}Sc [3] and ^{44m}V [7] has been reported. Exceptions are the pioneering work on short-lived ^{18m}F [1,8] and ^{43m}Sc [9]. The total intensities for ^{18m}F (about 2000 pps), ^{42m}Sc (114 pps) and ^{43m}Sc (5 to 60 pps) correspond to the normalized rates R at 10^{10} incident beam particles of 32±6 pps, 38 pps and 100 to 1200 pps, respectively.

Fragmentation-like reactions with heavy projectiles at intermediate energies are characterized by a wide distribution of the products in mass and atomic number (see e.g. [10,11]). The isotope identification in such experiments is based on the known magnetic rigidities ($B\rho$) used to transmit the ions from the target to the final focus together with the measurements of energy-loss (ΔE), total kinetic energy (TKE) and time-of-fligth (TOF). Here, in addition to the data on the production of isomeric beams, we present a novel and global method for the unambiguous identification of nuclei implanted at the final focus of projectile-fragment separators. This method is based on the detection of γ-radiation following the decay of short-lived ($T_{1/2}$ about 0.1 to 100μs) isomeric states in time correlation with the respective heavy-ion implantation signals. For the first time such a sensitive search for isomers has been performed for about 400 nuclei in one single measurement.

Two experiments have been performed with a ^{112}Sn beam at GANIL. During the first one [12], a ^{nat}Ni target (78 mg/cm^2) was placed at the entrance to the LISE3 spectrometer. With a primary beam energy of 58 A·MeV the typical time-of-flight of the fragments through the spectrometer was about 500 ns. The detection set-up at the final focus consisted of a four-fold Si telescope surrounded by a thin plastic β-counter and four large-volume Ge detectors. The summed photopeak efficiency of the γ-detectors reached 11% at 166 keV and was still about 4.5% at 1 MeV.

Among other parameters, the standard TAC signals of the fast coincidence between implanted ion and γ-radiation have been recorded in an event-by-event mode together with corresponding ion- and γ-energies. The TAC range was 500 ns, while the acquisition was kept open by any trigger signal during $\approx 10\mu s$ (ADC's gate). The rate of the heavy-ion triggers was kept well below 10^3Hz. The prompt coincidence peak in the TAC spectrum (FWHM $\approx$10 ns) was basically due to prompt γ-radiation induced by a nuclear reaction of the implanted ions with the Si detector material. Only about 0.2 % of all recorded ions have produced such prompt signals. However, the time distribution of γ-radiation was much broader than the prompt TAC peak (10 ns) and the TAC (500 ns) range. This is due to the delayed γ-radiation following β- and isomer-decays. The β-decay halflives are of the order of hundreds of milliseconds for exotic, weakly produced nuclei, reaching up to very long decay times for nuclei closer to the β-stability line. These decays produce a certain constant level (about 30 per second) of background γ-events which are not correlated with the implanted quasifragmentation products in the $10\mu s$ time interval. In contrast, the recording of the γ-radiation with characteristic decay times in the $10\mu s$ range can be strongly enhanced. This enhancement is due to the requirement of a presence of the specific ion signal and the γ-radiation within $10\mu s$.

With only one setting of the LISE spectrometer, known isomeric decays of forty nuclei have been detected. A comparison of an ungated identification spectrum i.e. atomic number Z versus the ratio of a mass A over a charge state Q of the detected ion given in Fig.1a with a spectrum gated by delayed γ-radiation (Fig.1b) shows the presence of a large number of isomeric states with the half-lives of the order of 100 ns to 100 μs (Table 1). Isomeric decays with half-lives for neutral atoms below 100 ns were also observed for nuclei produced at high rates like ^{94m}Mo ($T^{m}_{1/2}=98\pm2$ ns), ^{72m1,m2}As ($T^{m1}_{1/2}=85\pm5$ ns and $T^{m2}_{1/2}=88\pm2$ ns [13]), ^{66}Ga $T^{m}_{1/2}=57\pm1.4$ ns) ^{91m1,m2}Mo ($T^{m1}_{1/2}=47\pm1$ ns and $T^{m2}_{1/2}=38\pm4$ ns [14]). For the decays of ^{72m1,m2}As and ^{91m1,m2}Mo it was not possible to deduce the γ-intensities precisely enough to allow a separation into two components. Only upper limits for the joint production rates R(^{72m1,m2}As) < 0.12 and R(^{91m1,m2}Mo)< 0.03 can be given (in pps per 10^{10} beam particles). The limits for ^{73m}Kr (E*=434 keV) and ^{92m}Ru (E*=2835 keV) are $R < 0.007$ and $R < 0.02$, respectively.

Some examples of the 'heavy-ion correlated' γ-spectra are given in Fig.2. Well-known characteristic lines were clearly observed, confirming unambiguously the ΔE-TKE-TOF isotope identification.

The rates R of the isomeric beams at the final focal point of LISE3 as derived from the measured γ-intensities are listed in Table 1 (column 7). Each rate correspond to a partial production of the isomer in the target and depends on the overall spectrometer transmission efficiency - function of the momentum and charge state distribution of the ions.Even with a spectrometer setting which was presumably not optimized for the detection of one particular isomer, rates at the level of a few pps at 10^{10} primary beam intensity can be reported for several isomers (cf. Table 1).

The isomeric to total ratios F were obtained by dividing the isomeric yield at the target resulting from γ-measurements and corrected for in-flight decay losses by means of ionic half-lives (see Table 1) by the total number of the respective ions (Fig. 1a). The results given in Table 1 indicate a substantial (sometimes dominating) production of nuclei in their isomeric states. Such a reaction feature can be used in mass measurements [15] to test the achieved high resolution by separating the nuclear mass of the ground state and of the isomeric state at a few MeV excitation energy.

Several isomers have been found in two or three ionic charge states Q (see Table 1). In most cases, their F^{Q} ratios are (within error-bars) identical. This indicates that a relative change in velocity of up to about 4% (corresponding to the change in ionic charge by two units) does not affect the relative isomer production.

In the second experiment [10,11] performed with a ^{112}Sn beam at 63 MeV/nucleon, a segmented BGO ring detector [16] has been used to detect the γ-radiation. The total photopeak efficiency was increased to 50% at 511 keV, however at the expense of a much lower energy resolution than that of the Ge-detectors. The resulting 'isomer identification' plot i.e. the heavy-ions (HI) correlated with γ-emission occuring after the prompt HI-γ coincidence is given in Fig. 3. In addition to the nine known isomers detected in the first experiment, an evidence for a new isomeric state in ^{66}As can be concluded. Since the typical time-of-flight of the ions in the second experiment icreased from 0.5μ (in the first experiment) to 1.5μs, some of the known short-lived isomers like e.g. ^{67m}Ge and ^{92m}Ru were not detected in spite of an optimzed spectrometer setting for this isotope region. The limit for the production of ^{73m}Kr is $R < 0.0025$. The limited resolution of the BGO did not allow to deduce the R-values for ^{76m}Rb and ^{82m1,m2}Y. As compared to the first experiment, the rates of fully stripped ^{96m}Pd and ^{93m}Ru were about three times lower. This is ascribed to the combined effects of the spectrometer transmission efficiency and the different charge state distribution in the two measurements. Due to the use of a charge-changing thin mylar foil in the second experiment, the production rates of ligther nuclei like ^{43m}Sc and ^{54m}Fe were reduced [10,11].

A list of the derived F ratios of isomeric to ground-state production for different charge states Q is given in Table 1. The F-values obtained for fully stripped ions in the two experiments at the two bombarding energies do not differ significantly. This indicates a rather similar production mechanism in both reactions.

The method presented here is well suited for scanning of large parts of the nuclear chart for short-lived isomers in the 0.1μs to 100μs half-life region. Such an experiment can be performed with only one Bρ setting of the projectile-fragment separator equipped with a sensitive γ detection set-up at the final focus. Such a dedicated study can also be performed for isomers whose neutral atoms have even shorter half-lives and decay by highly-converted transitions. Due to the blocking of the main conversion-electron decay channel, fully stripped fragments can be transported over a long path length with small intensity losses (cf. the halflives of ^{80m}Rb, ^{90m}Mo, ^{91m}Zr or ^{93m}Tc in different ionic charge states and as neutral atoms in Table 1).

In conclusion, it has been demonstrated that quasi-fragmentation at intermediate energies provides quite high isomeric yields as compared to the isotope formation in the ground-state (see Table 1). This increases the potential power of such studies, when applied to short-lived isomers in weakly produced proton drip-line nuclei. The search for spin-gap isomers beyond the drip-line is one of the ambitious goals for the follow-up experiment with a ^{112}Sn beam. Fragmentation of neutron-rich projectiles together with the presented isomer detection should allow a search in regions of the nuclear chart which are not populated in fission reactions or in the fusion-evaporation reactions (e.g. very n-rich Sc to Co isotopes). The use of very heavy projectiles like ^{238}U [18] should allow to produce and inspect isomers almost over the complete nuclear chart in one measurement.

In future experiments the yields of high-spin isomers with masses A $\approx$90 can be improved by about an order of magnitude. This can be done by optimizing the spectrometer transmission and by increasing the beam intensity [10,11]. Thus, total reaction cross section measurements with isomeric nuclei used as projectiles and with secondary targets might become feasible.

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FIGURE CAPTIONS

1 Distribution of fully stripped (Q=Z) fragments produced with a ^{112}Sn (58 A·MeV) beam: a)all products registered, b)selected nuclei correlated to γ-radiation within 10μs after the triggering heavy-ion signal ('chart of isomers'). For the groups of nuclei without known isomeric state in the 0.01-100μs half-life range the probability of chance coincidence with γ-radiation was estimated and corresponding (low) background was substracted at part b).

2 Examples of γ-energy spectra obtained in a correlation with fully stripped ions. Known isomeric transitions are marked by their energies in keV. For ^{105m}Cd only the lines used for the estimation of the isomeric rates are indicated. See also [11] for the spectra obtained for other isomers.

3 'Chart of isomers' obtained for fully stripped ions in the experiment with a ^{112}Sn beam at 63 MeV/nucleon, compare to Fig.1. In the inset, a magnified part of the spectrum is shown with an evidence for the new isomer ^{66m}As. Very recently, the presented method has been applied to study the γ-decay properties of this new isomer in experiment with a ^{78}Kr beam (September 1994) at Ganil [17].

TABLE I. Rates R (pps at 10^{10} incident projectiles) of the isomeric beams measured at the final focus of LISE3 spectrometer and ratios F (in %) of the isomeric to total production for isomers detected among the quasifragmentation products of a ^{112}Sn beam. They are given according to the mass A and to the charge state Q of the ion after the target. In addition to the source data on the isomers corresponding to the neutral atom state (columns 1-4) the half-life of the isomer in the ionic state is also listed in column 6. The latter has been obtained taking only the gamma decay probability for the fully stripped ions, and a respective part of the K-conversion deexcitation probability for hydrogen-like and helium-like ions. Most of the listed results were obtained with 0.5×10^{10}/s ^{112}Sn projectiles at 58 MeV/nucleon and $B\rho$ value of 1.98833 Tm, except those marked with index 'α' measured with 1.5×10^{10}/s ^{112}Sn at 63 MeV/nucleon and $B\rho$=1.876 Tm. The given accuracies of R and F values were calculated taking into account the statistical errors of the observed γ-lines intensities and of the estimated accuracies of the used γ-efficiences as well as of the number of detected ions. The upper limits for summing corrections to the observed photopeak intensities of the cascading gamma-rays were estimated to be about 3% and about 10% for the Ge- and the BGO-setups, respectively, and they are not included in the R values. The data on the isomeric states were taken from: [a]NP A475(87)1, [b]NP A521(90)1, [c]ADNDT 49(1989)189, [d]NDS 68(1993)887, [e]NDS 64(1991)830, [f]NDS 61(1990)461, [g]NDS 64(1991)875, [h]NDS 58(1989)1, [i]NDS 68(1993)579, [j]NDS 69(1993)857, [k]ZP A325(1986)37, [l]NDS 66(1992)623, [m]NDS 69(1993)359, [n]NP A568(1994)202, [o]PR C47(1993)2546, [p]NDS 62(1991)271, [q]NDS 54(1988)527, [r]NDS 54(1988)1, [s]NDS 67(1992)579, [t]NDS 60(1990)835, [u]NDS 66(1992)347, [v]NDS 54(1993)1, [w]NDS 66(1992)1, [x]NDS 68(1993)165, [y]NDS 60(1990)1, [z]NDS 68(1993)935.

	E^* keV	I^π	$T_{1/2}$ μs	Q	$T^Q_{1/2}$ μs	R pps at 10^{10}	F^Q %
$^{18}\mathrm{F}^{a}$	1121	5^+	0.162	9	0.163	9(2)e-3	25(5)
$^{22}\mathrm{Na}^{b}$	583	1^+	0.244	11	0.244	1.9(3)e-2	18(3)
$^{43}\mathrm{Sc}^{b,c}$	3123	$19/2^-$	0.469	21	0.524	0.10(1)	15(14)
						1.9(4)e-2 $^{\alpha}$	27(6) $^{\alpha}$
$^{54}\mathrm{Fe}^{d}$	6527	10^+	0.364	26	0.406	6.8(8)e-2	18(2)
						2.3(4)e-2 $^{\alpha}$	11(2) $^{\alpha}$
$^{63}\mathrm{Ni}^{e}$	87	$5/2^-$	1.67	28	3.34	2.2(8)e-2	22(8)
$^{66}\mathrm{Cu}^{f,c}$	1154	6^-	0.596	29	0.598	8.4(12)e-3	40(6)
$^{66}\mathrm{Ga}^{f,c}$	1464	7^-	0.0574	31	0.073	1.7(5)e-2	74(22)
$^{67}\mathrm{Zn}^{g}$	604	$9/2^+$	0.333	30	0.334	7.3(7)e-2	68(7)
				29	0.333	4.4(20)e-2	63(29)
$^{67}\mathrm{Ge}^{g}$	752	$9/2^+$	0.1109	32	0.1111	4.1(7)e-2	88(15)
$^{69}\mathrm{Ge}^{h}$	398	$9/2^+$	2.81	32	2.84	1.59(5)	52(2)
				31	2.82	0.12(1)	46(4)
$^{69}\mathrm{Se}^{h}$	574	$(9/2^+)$	0.853	34	0.857		
						1.7(3)e-3 $^{\alpha}$	42(11) $^{\alpha}$
$^{71}\mathrm{Se}^{i}$	260	$(9/2^+)$	19	34	20.9	0.11(3)	17(4)
						0.39(3) $^{\alpha}$	
				33	20.1	4(1)e-2	23(6)
$^{73}\mathrm{As}^{j}$	427	$9/2^+$	5.7	33	5.8	0.36(2)	36(2)
				32	5.7	4.2(7)e-2	33(5)
$^{76}\mathrm{Rb}^{k}$	317	(4^+)	3.2	37	4.0	1.1(3)e-2	35(10)
$^{80}\mathrm{Rb}^{l,c}$	561	6^+	1.6	37	9.6	0.89(3)	20(1)
				36	3.3	0.33(2)	24(2)
				35	2.0	2.1(3)e-2	26(4)
$^{81}\mathrm{Sr}^{m}$	79	$(5/2)^-$	0.34	38	1.4	0.10(4)	3.2(11)
$^{82}\mathrm{Y}^{n,o}$	403	(4^-)	0.22	39	0.27	0.10(4)	38(14)
$^{82}\mathrm{Y}^{n,o}$	508	(6^+)	0.137	39	0.25	4.1(15)e-2	16(6)
$^{85}\mathrm{Rb}^{p}$	514	$9/2^+$	1.015	37	1.022	5.4(25)e-3	50(23)
$^{85}\mathrm{Y}^{p}$	266	$5/2^-$	0.178	39	0.184	9.2(9)e-2	9.3(10)
				38	0.181	3.6(5)e-2	8.1(12)
$^{86}\mathrm{Sr}^{q,c}$	2956	8^+	0.457	38	0.946	5.2(7)e-2	49(7)
				37	0.670	5.7(19)e-3	40(13)
$^{88}\mathrm{Zr}^{r}$	2888	(8^+)	1.320	40	5.13	2.9(1)	58(2)
				39	1.84	1.19(8)	60(3)
				38	1.59	6.4(15)e-2	51(12)
$^{90}\mathrm{Zr}^{s}$	3589	8^+	0.131	40	0.172	2.9(5)e-2	54(9)
$^{90}\mathrm{Nb}^{s,c}$	1880	11^-	0.472	41	0.98	0.78(5)	15(1)
				40	0.69	0.41(3)	17(2)
				39	0.54	3.1(6)e-2	22(5)
$^{90}\mathrm{Mo}^{s,c}$	2875	8^+	1.12	42	8.3	3.46(8)	50(3)
				41	2.4	3.15(8)	42(3)
				40	1.40	0.47(3)	54(4)
$^{91}\mathrm{Zr}^{t,c}$	3167	$21/2^+$	4.35	40	105	3.3(7)e-2	62(14)
$^{91}\mathrm{Nb}^{t,c}$	2034	$17/2^-$	3.76	41	57	0.86(7)	32(3)
				40	8.8	0.31(4)	31(4)
$^{92}\mathrm{Nb}^{u,c}$	2203	11^-	0.167	41	0.28	3.7(8)e-2	22(5)
$^{92}\mathrm{Mo}^{u}$	2761	8^+	0.190	42	0.246	0.49(4)	22(2)
				41	0.221	0.27(3)	24(3)
				40	0.201	1.5(4)e-2	22(6)
$^{92}\mathrm{Tc}^{u}$	270	(4^+)	1.03	43	11.3	0.23(2)	3.3(4)
				42	2.33	0.21(2)	2.2(3)
				41	1.30	3.6(6)e-2	2.8(5)
$^{93}\mathrm{Tc}^{v,c}$	2185	$17/2^-$	10.2	43	190	3.7(4)	29(4)
				42	24.4	3.5(3)	27(3)
				41	13.0	0.46(5)	30(4)
$^{93}\mathrm{Ru}^{v}$	2083	$21/2^+$	2.150	44	2.9	0.34(3)	23(2)
						0.11(1) $^{\alpha}$	35(4) $^{\alpha}$
				43	2.54	0.49(4)	
				42	2.28	0.13(2)	17(3)
$^{94}\mathrm{Mo}^{w,c}$	2956	8^+	0.098	42	0.117	2.0(5)e-2	49(12)
$^{94}\mathrm{Ru}^{w,c}$	2645	8^+	71	44	95	1.7(3)	26(5)
				43	84	2.1(3)	18(3)
				42	75	0.75(15)	37(9)
$^{96}\mathrm{Pd}^{x}$	2531	8^+	2.2	46	4.7	3.4(5)e-2	38(6)
						1.0(1)e-2 $^{\alpha}$	39(6) $^{\alpha}$
				45	3.3	9.1(9)e-2	
				44	2.5	4.1(6)e-2	
$^{100}\mathrm{Rh}^{y,c}$	112	7^+	0.130	45	0.25	0.19(4)	35(10)
$^{105}\mathrm{Cd}^{z,c}$	2517	$21/2^+$	4.5	48	7.4	0.44(4)	11(1)
				47	5.9	0.17(3)	11(2)

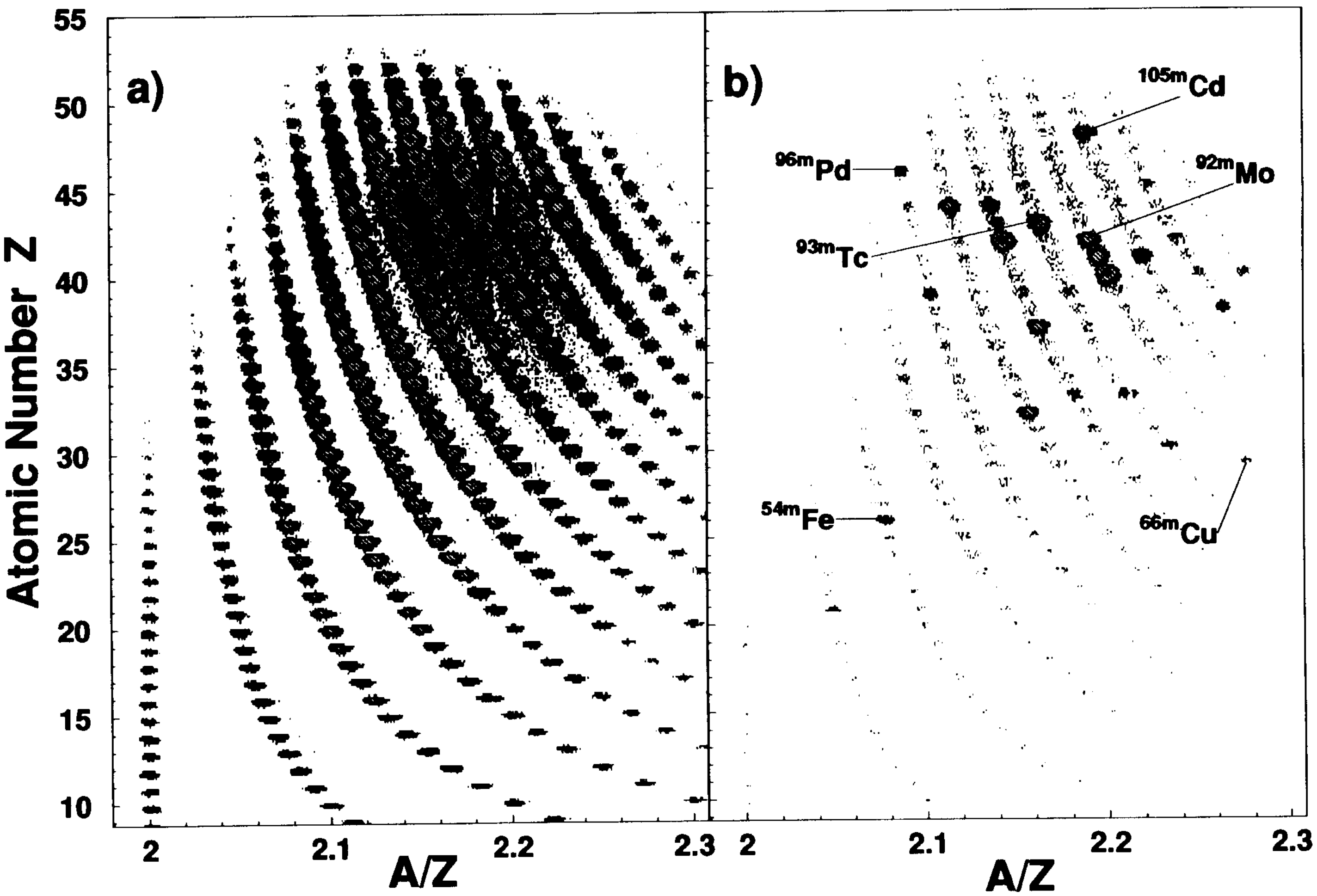
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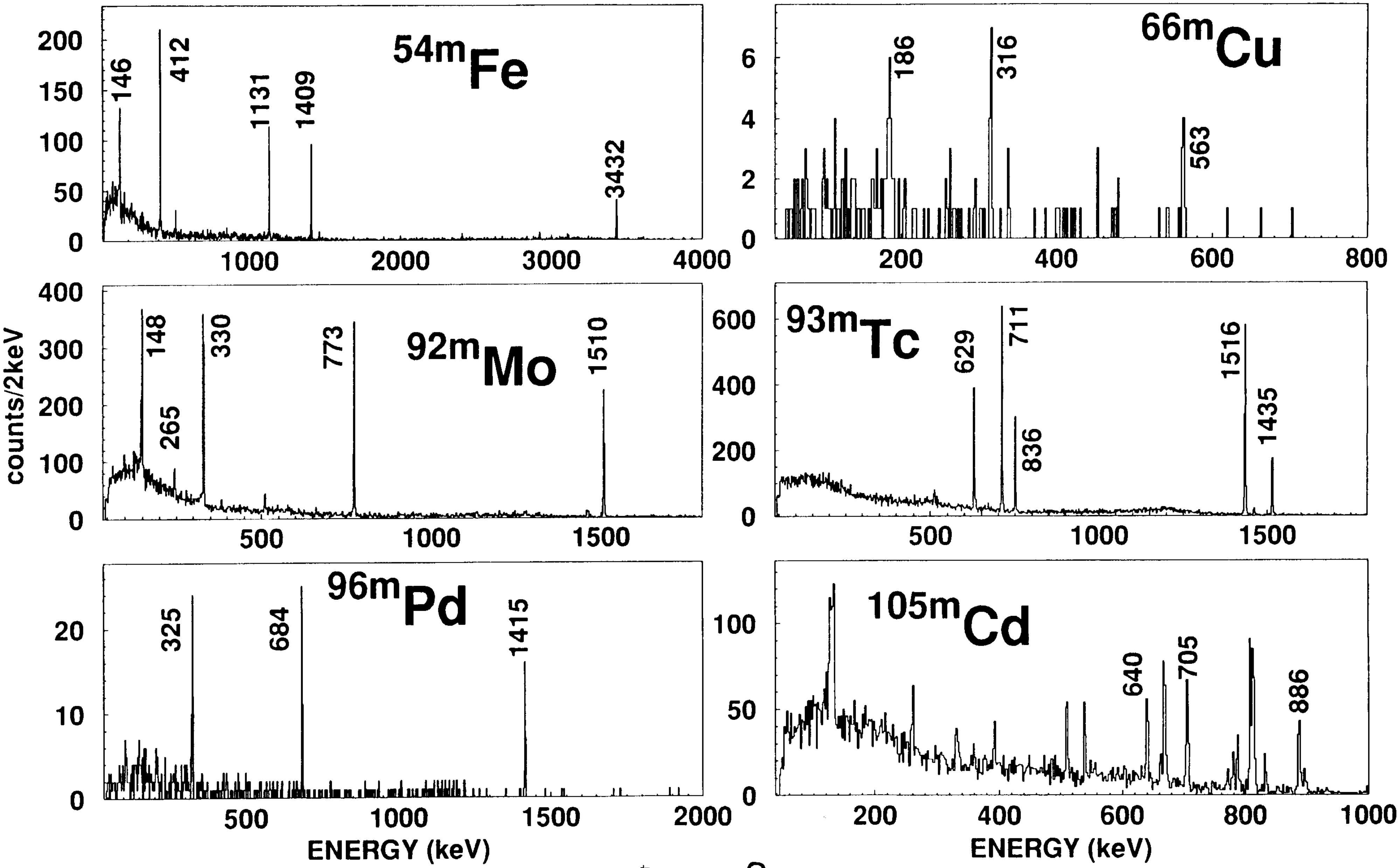
FIG. 1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705
886
counts/2keV
ENERGY (keV)
ENERGY (keV)
0
50
100
150
200
0
2
4
6
0
100
200
300
400
0
200
400
600
0
10
20
0
50
100
1000
2000
3000
4000
200
400
600
800
500
1000
1500
500
1000
1500
500
1000
1500
2000
200
400
600
800
1000

FIG. 2

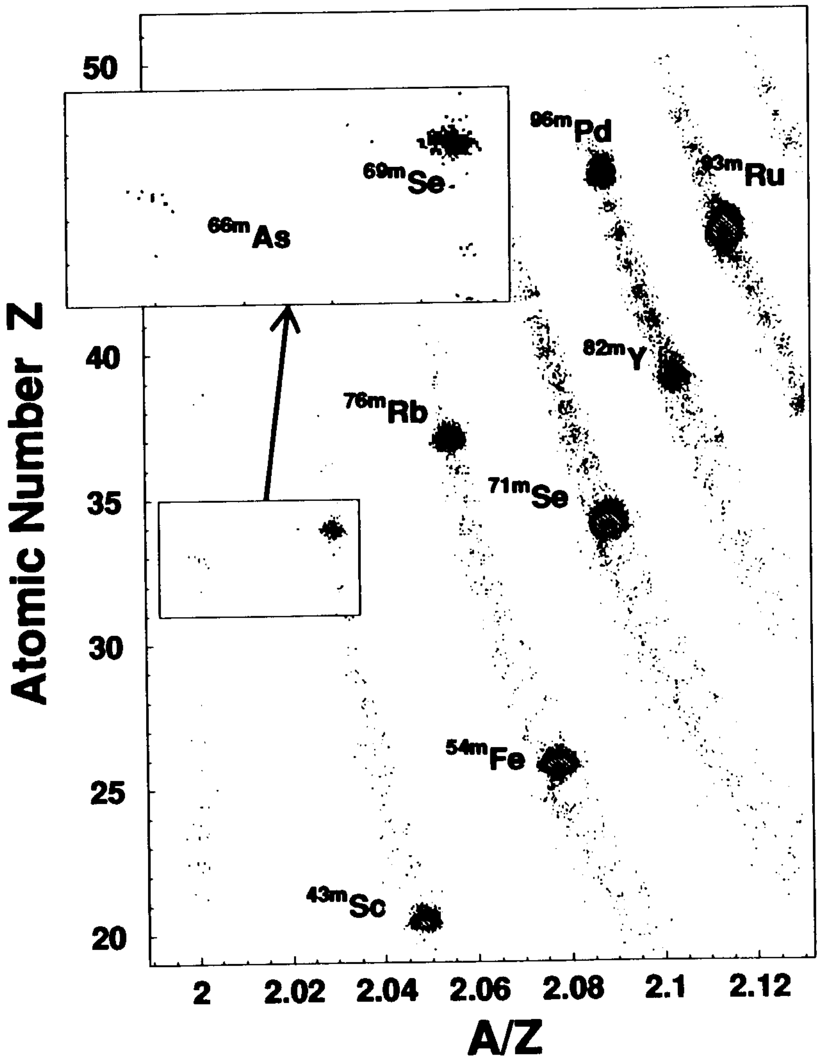
Atomic Number Z
50
40
35
30
25
20
2
2.02
2.04
2.06
2.08
2.1
2.12
A/Z
^{66m}As
^{69m}Se
^{96m}Pd
^{93m}Ru
^{82m}Y
^{76m}Rb
^{71m}Se
^{54m}Fe
^{43m}Sc

FIG. 3