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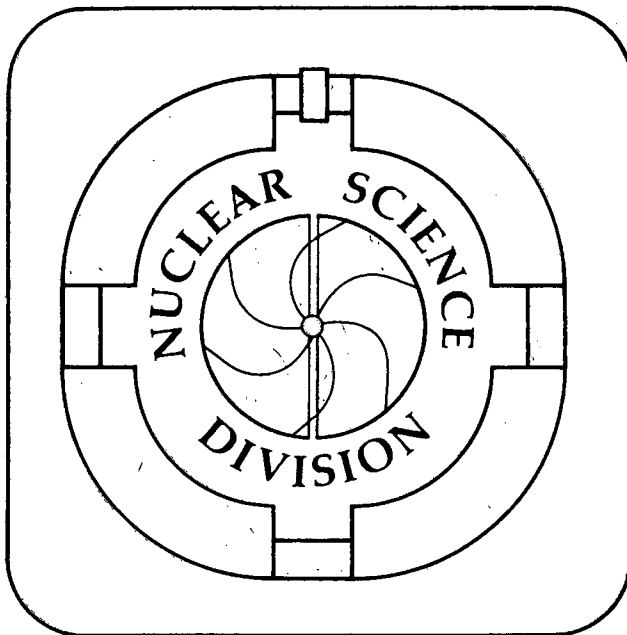
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Instrumentation for Atom-at-a-Time Chemistry of the Heavy Elements

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June 1995



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INSTRUMENTATION FOR ATOM-AT-A-TIME CHEMISTRY OF THE HEAVY ELEMENTS

Birgit Wierczinski and Darleane C. Hoffman

Abstract

Chemical systems that are suitable for the investigation of the chemical behavior of the heavy elements on the basis of one-atom-at-a-time chemistry are reviewed. The special difficulties that arise when working with heavy elements which have half-lives as short as seconds and low production yields are considered. The historical development and the latest results for elements as heavy as hahnium (elements 105) are presented. The possibility for chemical studies of still heavier elements is discussed.

Instrumentation for Atom-at-a-Time Chemistry of the Heavy Elements

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I. Introduction

One hundred years ago, when Henri Becquerel first published his results about uranyl and uranous salts that blackened a photographic plate, few who read the articles realized that this was the beginning of a new era in science [1]. This new phenomenon called radioactivity was not only discovered in minerals containing uranium but also in those containing thorium and the decay products of these natural decay series. Since Becquerel's 1896 discovery of natural radioactivity many more naturally radioactive isotopes have been identified, and more than 2000 artificially radioactive isotopes have now been produced. All of the isotopes of the elements heavier than bismuth ($Z=83$) are radioactive.

Uranium, discovered in 1789, is the heaviest element found in macro amounts in nature, and more than 150 years elapsed before the production of neptunium, the first transuranium element. By 1961, the remainder of the actinide elements had been produced and identified, but it took until 1982 before the elements through 109 could be synthesized and identified. Elements 110 and 111 were not reported until the end of 1994. The periodic table as of mid-1995 is shown in Fig. 1.

Among the difficulties involved in identifying and studying the heaviest elements are the increasingly short half-lives, the very low production rates, and the overwhelming quantities of unwanted nuclides which are produced. This necessitates very special techniques for the analysis and identification of the desired nuclide. Facilities and expertise in preparation and irradiation of radioactive targets and fast radiochemical separations and detection techniques are required.

It is difficult to produce elements heavier than fermium ($Z=100$) in quantities of more than one atom at a time and we will define "heavy elements" as those with $Z>100$. These cannot be produced by neutron irradiation of lighter targets in reactors and must be produced in suitable accelerators by bombarding suitable targets with high-intensity beams of projectiles at least as heavy as helium. Typically, because of their short half-lives, these nuclides are studied near the production site. A chart of the currently known trans-nobelium isotopes is given in Fig. 2. The heaviest element and isotope known today is $^{272}111$ [2] which has a half-life of 1.5 ms and was produced via the $^{209}\text{Bi}(^{64}\text{Ni},n)$ reaction with a cross section of only a picobarn (10^{-36} cm^2).

One of the main decay modes of heavy elements is spontaneous fission (SF) which has been found only in nuclei with $Z>90$. The half-lives for SF generally decrease with increasing Z , but are greatly affected by nuclear shells as shown in Fig. 3 for the isotopes with even numbers of protons and neutrons (e-e nuclei). The SF half-lives of nuclei with odd numbers of protons and/or neutrons are typically longer by 10^3 to 10^5 than their e-e neighbors.. Alpha emission is also a major mode of decay of the heavy elements and has been used to positively identify isotopes of new heavy elements. The alpha decay half-lives of the e-e isotopes of the heavy elements is shown in Fig. 4. Measurement of the α - and SF-decay of the heavy elements forms the basis of most of the physical detection methods. A very important technique for identification of new heavy elements and positively identifying the Z and A of their isotopes involves the measurement of α - α correlations. Measurement of the genetic and time relationships involved in alpha decay of an unknown isotope to known daughter or granddaughter isotopes which can be positively identified from their known α -particle energies and half-lives allows the positive identification of the parent since it is simply related to its α daughter by the Z and A of the ^4He nucleus.

For studies of chemical properties it is necessary that the methods used give the same results for one-atom-at-a-time as would be obtained in a macroscopic experiment

[3]. Suitable methods are ion exchange chromatography, solvent extraction, or gas chromatography. Here one atom takes part in many identical reactions rather than many atoms undergoing one reaction. Guillaumont et al. [4] have shown that in this way it is possible to investigate chemical behavior by cumulating the results from experiments performed with a single atom at a time.

Knowledge about the chemical behavior of the heaviest elements is essential in understanding trends in the periodic table. For example, the chemistry of the transactinides is very different from that of the actinides due to the closure of the 5f electronic shell at lawrencium (103). Relativistic effects are predicted [5] to become increasingly important in influencing the chemical properties of the heavier elements within a given group in the periodic table. These relativistic effects originate from the increasingly high charges of the nuclei of the heavy actinides and transactinides which causes contraction of the radius and energy stabilization of the s and p electronic shells which could actually change the valence electron structure and the relative stabilities of the oxidation states. In addition, spin orbit splitting of $l > 0$ orbitals, anomalous trends in ionic radii, and energetic destabilization of outer d and all f orbitals may occur which can alter chemical bonding and complexing compared to lighter homologs.

II. Production of the Heaviest Elements

Neptunium was initially produced by irradiation of ^{238}U with neutrons to make ^{239}U which quickly β -decayed to 2.3-d ^{239}Np . Neutron irradiation is a relatively simple way to produce transuranium elements and irradiation of uranium or heavier actinide targets with neutrons, protons, deuterons, or alpha particles allowed the production of elements through fermium ($Z=100$). To obtain heavier elements, it is necessary to use heavy ion projectiles. So-called "hot" heavy ion fusion reactions in which complete fusion of a deformed actinide target nucleus and heavy-ion projectile takes place were used to produce the elements through seaborgium (element 106). A relatively high projectile

energy must be used to overcome the Coulomb barrier between the two nuclei and after formation of the compound nucleus the remaining excitation energy of many tens of MeV is much higher than the binding energy of the least tightly bound neutron, resulting in multiple neutron emission. It is also above the fission barrier of 5 to 6 MeV with a resulting high probability for prompt fission which competes with neutron emission and decreases the production cross section for the desired product. Although the hot fusion reaction was successfully used in the production of the elements through 106, the cross sections became increasingly smaller and the cross section for the production of ^{263}Sg $^{249}\text{Cf}(^{18}\text{O},4n)$ is only 0.3 nb. Consequently, the elements from 107 through 111 have been produced by the "cold fusion" reaction. In these reactions, targets near the doubly magic configuration of $Z=82$, $N=126$ such as ^{208}Pb or ^{209}Bi are bombarded with very heavy-ion projectiles like ^{54}Cr and ^{58}Fe , resulting in compound nuclei with minimum excitation energy, thus making single neutron emission more probable and minimizing losses due to prompt fission.

The nuclides discussed in this paper are produced in heavy ion reactions using actinide targets and heavy ion projectiles. Table 1 lists the nuclides used, their production reactions, and the chemical techniques that have been used in their chemical separation. Hahnium (element 105) is the heaviest element on which chemical studies have been performed. The following acronyms are used in the table and throughout the rest of the paper: ACCESS=Automated Chromatographic Chemical Element Separation System. ARCA=Automated Rapid Chemistry Apparatus. OLGA=On-Line Gas chemistry Apparatus. HEVI=Heavy Element Volatility Instrument. SISAK=Short-lived Isotopes Studied by the AKUFVE technique; LISSY=Liquid Scintillation SYstem.

TABLE I.

Production Methods for Heavy Element Isotopes Studied by Automated Chemical Separation Systems.

Isotope	Target	Projectile	Beam Energy	Chemical Method	Year [Ref.]
^{253}Md	^{243}Am	^{13}C	69 MeV	ACCESS	1991 [6]
^{254}Md , ^{255}Md	^{249}Bk	^{18}O	100 MeV	ARCA	1987 [7,8]]
^{262}Ha	^{249}Bk	^{18}O	99 MeV	ARCA II	1989 [9,10]
^{262}Ha , ^{263}Ha	^{249}Bk	^{18}O	99 MeV	ARCA II	1992[11.12]
^{260}Lr	^{249}Bk	^{18}O	101 MeV	On-line gas chrom.	1988[13]
^{261}Rf	^{248}Cm	^{18}O	94 MeV	OLGA II	1991 [14]
^{262}Ha , ^{263}Ha	^{249}Bk	^{18}O	99 MeV	OLGA II	1992[15]
^{261}Rf	^{248}Cm	^{18}O	99 MeV	HEVI	1991 [15]
^{262}Ha	^{249}Bk	^{18}O	99 MeV	HEVI	1992 [16]
^{262}Rf , ^{259}Fm	^{248}Cm	^{18}O	114 MeV	SISAK 3	1995[18]
^{261}Ha	^{243}Am	^{22}Ne	139 MeV	SISAK 3	1995[18]

III. Development of Instrumentation for Chemical Studies

Much effort has been put into the development of instrumentation for fast and efficient separation and identification of the short-lived heavy elements. As mentioned earlier, methods like ion exchange and gas chromatography, and liquid-liquid extraction are capable of giving reliable chemical results on the basis of one atom at a time. In this section the historical development of the most commonly used systems is described briefly.

A. Ion Exchange Chromatography

High performance liquid chromatography (HPLC) has been proven to be one possibility for performing fast separations of actinides [18]. Since the first experiments using HPLC, the Automated Rapid Chemistry Apparatus (ARCA) has been developed to perform these experiments automatically, under computer control. ARCA consists of a section for collecting the activity transported via a gas jet, an HPLC portion, an electropneumatic valve system, and a control unit. The reaction products are produced in a target chamber where they are attached to aerosols in a gas jet system. The activity laden aerosols are transported to ARCA and collected on a frit. Here the reaction products are dissolved in a solvent that is pumped through the frit into the tubing which is connected to the valves and separation columns in the HPLC section. All components of the chromatographic system are made of glass, Teflon or Kel-F to allow the use of mineral acids. In the first version of ARCA the columns were typically 500- to 40-mm long with an i.d. of 5 to 1.7 mm [19]. After elution of the desired nuclide from the column, the solvent was collected in small test tubes. A burner was used to heat the test tubes in such way that the solvent evaporated at the same rate as it was delivered from the separation column. At the end of the evaporation, a small volume of about 0.1 ml was manually transferred to a metal or carbon foil for final sample preparation. Alpha and SF counting of the samples was typically performed using silicon surface-barrier detectors. The time that elapsed from producing the nuclides in the target chamber to counting the sample was in the order of several minutes, depending on the chemical procedure that was used. To use ARCA for shorter lived isotopes, shorter separation times were needed which led to the development of ARCA II [20]. For this improved version, the length of the columns was reduced to 8 mm with an i.d. of 1.6 mm. Furthermore, the sample preparation was improved by collecting the solvent directly on tantalum discs which were positioned on a heated metallic turntable. Evaporation of the sample on the metal disc is accelerated by using a lamp with maximum emission in the near infrared. With the improved ARCA II,

typical times from the end of irradiation to the start of measurement are 55 ± 10 s. Fig. 5 shows a schematic drawing of ARCA II.

Another system based on ion exchange chromatography is the Automated Chromatographic Chemical Element Separation System (ACCESS) [21]. Radioactivity is introduced into the system either by an off-line injection loop, or by an automated injection system. The size of a typical column is 20 mm in length with an i.d. of 2 mm. After elution from the column, the eluant is either collected with a fraction collector and samples are prepared by manually transferring the eluant onto a foil, or the eluant is collected directly on metal foils that are positioned on a heated turntable. Typically, it takes a few minutes from production of the nuclides in the target chamber to counting of the sample.

B. Gas-Phase Systems

Since Zvara et al. [22-26] performed the first gas phase thermochromatography experiments with transactinides and their lighter homologs in 1966, gas chromatography has been proven to be a very powerful tool for determining adsorption enthalpies and entropies. The On-Line Gas chemistry Apparatus (OLGA) [27] was developed in 1985 to search for volatile superheavy elements [28]. OLGA was used in 1986 at the 88-Inch Cyclotron at LBL to study the volatility of elemental lawrencium which had been predicted to have p electrons in its valence shell due to relativistic effects. Experiments were conducted using 3-m ^{260}Lr to investigate whether it might be highly volatile like thallium which has a single p electron., but no evidence for Lr volatility under reducing conditions at $1000\text{ }^{\circ}\text{C}$ was found. Soon after, OLGA II, an isothermal gas chromatography system, was developed [29] which was designed for the separation of volatile halide species of short-lived nuclides.

The Heavy Element Volatility Instrument (HEVI) [30] is similar to OLGA, but was designed with a longer quartz column to provide a longer region of more nearly isothermal

temperature. HEVI consists of six different components as shown schematically in Fig. 6. The first part contains the split shell furnaces which heat the quartz column (second part). Between the high temperature part of the column and the cooler isothermal section is a heat sink (part three). The end of the column is connected to a recluster chamber (part four) in which the separated products are reattached to KCl aerosols for transport via a gas jet system (part five) to the detection system (part 5). Products attached to aerosols are transported via a helium gas jet system to the high temperature part of the quartz column, where they are stopped in a quartz wool plug. At this point halogenating gases are added to form volatile halide species. These species then enter the isothermal part of the quartz column and the flowing carrier gas carries them down the length of the isothermal column where the volatile species enter the recluster chamber. Here the volatile halide compounds are reattached to aerosols and transported to the detection system. Non-volatile species decay inside the quartz column. The principal differences between OLGA II and HEVI are the longer quartz column and the heat sinks which are used in HEVI. Normally different detection systems are used: OLGA II uses a moving magnetic tape system to transport the collected activity to a total of seven chambers containing large passivated ion implanted planar silicon (PIPS) detectors and X- or γ -ray detectors where α -, X-, and SF-spectra can be recorded by a computer and searched for time correlated events. HEVI usually uses a horizontal rotating wheel system, the Merry-Go-around (MG)[31]. The horizontal wheel of the MG has 80 collection positions around its periphery. A steel washer with a 0.63 cm i. d. hole covered with thin ($\sim 40\text{-}\mu\text{g}/\text{cm}^2$) polypropylene film is placed in each position. The activity laden aerosols are deposited on the polypropylene films which are stepped at preset intervals between six pairs of PIPS detectors placed above and below the wheel. In this way the kinetic energies of coincident fission fragments and α -particles can be measured. If desired, an intrinsic germanium detector can be added to the setup in order to detect coincident characteristic X-rays or γ -rays.

Since OLGA II and HEVI are similar, they can be used with either of the two mentioned detection systems or with a gamma-ray spectrometer which is convenient for detection and measurement of some of the lighter homologs. Fig. 7 shows a schematic drawing of the MG system that has been used with both OLGA II and HEVI.

C. Liquid-Liquid Extractions

Since 1974 the SISAK system (Short-lived Isotopes Studied by the AKUFVE technique[32] has been developed [33]. This system is based on continuous liquid-liquid extraction using very fast rotating centrifuges typically running at 20,000 to 30,000 rpm. Today, the latest version, SISAK 3, is capable of detecting isotopes with half-lives down to ~1s [34]. The basic setup of the system has remained the same during the last 20 years. It consists of four main sections: the gas-jet target system; a degassing unit; one or more centrifuges; and a detection and data analysis system. In the first section, the reaction products that have been produced in a reactor or the target chamber of an accelerator are attached to aerosols which are produced by heating an inorganic salt, e.g., KCl, in a quartz tube to temperatures near its melting point. The aerosols are then transported to the target chamber by a flowing carrier gas such as helium [35]. After the reaction products are attached to the aerosols they are dissolved in the appropriate aqueous solution in the second unit. This solution enters a first centrifuge, called 'degasser', which removes the carrier gas and the gaseous reaction products from the aqueous solution. In the third unit the aqueous solution is mixed intimately with an organic extracting solution in a centrifuge and the heavy and light phases are separated due to their different densities. One to four of these separation centrifuges can be used if several extraction or back extraction steps are required. After the last extraction, one of the phases contains the nuclide of interest which is then measured in the detection system.

Since 1974, the volume of the centrifuges and, thus, the holdup time within the centrifuges has been decreased: The volume of the first centrifuges was 120 ml and the

hold-up time 2.4 s; for the second version, the volume was reduced to 12 ml and the hold-up time to 0.4 s [36, 37]. Currently, the extraction centrifuges have a volume of 0.3 ml and the corresponding holdup time is only 0.05 s. For the SISAK 2 system, the degasser unit was developed [38]. Its volume and holdup time have also been decreased from 1 ml and 0.05 s for SISAK 2 to 0.1 ml and 0.03 s for SISAK 3 (Fig. 8). The centrifuges and all parts of the system that can contact either organic solvents or mineral acids are made of titanium passivated with palladium, or of polyetheretherketone.

During the last 20 years, the SISAK systems have been mainly used to study the nuclear properties of γ - and X-ray emitting isotopes. For this purpose, intrinsic Ge or Ge(Li) detectors have normally been used. During the last few years much effort has been put into the search for chemical extraction systems for the continuous extraction of transactinides [39-41]. Another task has been the development of detection systems for the identification of α -energies in flowing solution using PIPS detectors [39,40] or liquid scintillation counting [42, 43]. The development of a liquid-scintillation system (LISSY) has been successful and it is now possible to measure α -energies and SF-ratios in flowing organic solutions. To perform these measurements, a scintillator and naphthalene is added to the extracting organic extractant used in the SISAK system and this extractive scintillation cocktail containing the nuclide of interest is then pumped through a quartz cell in front of a phototube enclosed in a hemispherical reflector (Fig. 7). Using this technique efficiencies of nearly 100 % can be achieved for α -particles and fission fragments[44].

IV. Results

At this time, the most promising systems for studying heavy elements are ARCA II, HEVI, OLGA, and SISAK 3. In the following section the results of the more recent experiments are discussed.

In 1987 ARCA was used to study the elution behavior of ^{260}Lr , ^{254}Md , and ^{255}Md from HDEHP columns with dilute HCl. It was shown that even in the presence of

V²⁺ and Cr²⁺ there was no evidence for reduction of Lr³⁺, although Md³⁺ was reduced to Md²⁺ [8,9].

The latest studies that have been performed with ARCA II were investigations of the chemical behavior of hahnium [11-13]. The 34-s ²⁶²Ha produced via the ²⁴⁹Bk(¹⁸O, 5n) reaction was used in these studies. Reversed-phase-extraction chromatography with columns incorporating triisooctyl amine (TIOA) on an inert support was used to study halide complex formation and anion exchange of element 105 and to compare its behavior with its lighter group 5 homologs, Nb and Ta, and the pseudogroup 5 homolog Pa. Elutions with 4 M HCl/0.02 M HF showed that hahnium can be found in the same fraction as niobium and protactinium, but cannot be eluted with 6 M HNO₃/0.015 M HF as is its heaviest homolog, tantalum. In elutions with 10 M HCl/0.025 M HF (Pa fraction) and 6 M HNO₃/0.015 M HF (Nb fraction), hahnium was found to be equally divided between the two fractions. These results indicate that hahnium forms oxyhalide or hydroxyhalide complexes like [NbOCl₄]⁻ and [PaOCl₄]⁻, or [Pa(OH)₂Cl₄]⁻, rather than pure halide complexes as in [TaCl₆]⁻. Subsequent experiments were carried out using the same nuclide to study the elution of Ha from cation exchange resin columns with α-hydroxyisobutyric acid (α-HIB). Hahnium showed the same extraction behavior as niobium, tantalum, and protactinium, providing additional proof that the most stable oxidation state of hahnium in aqueous solutions [45] is +5. Another series of experiments was performed during the same beam time period to investigate the behavior of hahnium during elutions with hydrobromic acid with diisobutylcarbinol (DIBC). Since DIBC is a very selective extracting agent for protactinium, the results of the experiments should show whether hahnium behaves more like niobium or protactinium. Again, hahnium was found in the same fractions as niobium and protactinium which again illustrated the non-tantalum-like chemical behavior of hahnium.

Isothermal gas chromatography has been used to study actinides and transactinides for many years. The most recent research was performed to investigate the volatility of

the halides of rutherfordium and hahnium. Using OLGA II with a KCl gas jet system, it was found that the bromides and chlorides of rutherfordium (element 104) are more volatile than the homologous compounds of element 104 [14]. At about the same time, experiments carried out with hahnium have shown that HaBr_5 is less volatile than the corresponding compounds, NbBr_5 and TaBr_5 [46]. Similar experiments using a MoO_3/He gas jet have been performed with HEVI. Confirmation of the results previously obtained for the Rf chlorides was obtained and the volatility of the chlorides was found to decrease [16] in the series: $\text{Zr} \sim \text{Rf} > \text{Hf}$. Comparison of HaCl_5 with the chlorides of its homologs showed that HaCl_5 and NbCl_5 are more volatile than TaCl_5 [15].

The SISAK 3 system, together with LISSY as the detection system, has been used recently for the investigation of the transactinides for the very first time. At the 88-Inch Cyclotron at Lawrence Berkeley Laboratory, an attempt was made to separate Ha using 1.8-s ^{261}Ha produced in the (^{243}Am , ^{22}Ne , 4n) reaction, expected to have a cross section of about a nanobarn. The aqueous phase was 1 M α -HIB and the organic extractant in the organic scintillator phase was trioctylamine; these extraction conditions are known [43] to extract the lighter group 5 homologs of element 105 (Ha). Unfortunately, no α - α - or α -SF- correlations which could be identified as originating from ^{261}Ha were observed. A possible reason might be a smaller cross-section than expected for this reaction.

Another experiment was carried out to produce the spontaneously fissioning nuclides 2.1-s ^{262}Rf and 1.5-s ^{259}Fm , formed in bombardments of ^{248}Cm with ^{18}O by the compound nucleus, 4n, and ^{11}Be transfer reactions, respectively. The total cross section for producing these nuclides is 10 to 15 nb, and it was hoped that it could be determined whether the short-lived SF activity from this reaction is primarily due to Fm or to Rf. The SISAK extraction system utilized 2 M HCl as the aqueous phase and 0.5 M HDEHP in toluene as the organic extractant in the scintillator phase. The tetravalent Rf will extract into the organic phase while the trivalent Fm remains in the aqueous phase. It was not possible to identify any SF events in the organic extractant although β -pileup due to the

presence of a large amount of β -activity from reactions of the beam with the Be target backing reduced the sensitivity. LISSY was used for the first time for both of these experiments. Although electronic pulse-shape discrimination was used to reduce the expected β -background, β -pile-up events from the very high β -count rates reduced the sensitivity for detection of α and SF events. The development of a β -pile-up rejecter is currently in progress.

V. Future

Until recently the longest-lived known isotope of seaborgium was 0.9-s ^{263}Sg . SISAK 3 was the only system that seemed to be fast enough for performing aqueous chemical separations on seaborgium, but the problem of detecting α -emitting isotopes in the continuously flowing solutions which SISAK produces still had not been solved. This was the situation until two longer-lived isotopes of seaborgium were reported in 1994 by a Dubna-Livermore collaboration [47]. Based on the measured α -decay energies of these isotopes and the decay systematics of Sobiczewski and co-workers [48], the two new isotopes $^{265}106$ and $^{266}106$ were estimated to have half-lives in the range of 2-30 s and 10-30 s, and production cross sections of 260 nb and 80 nb, respectively. These half-lives are long enough to permit studies of their chemical behavior with all the computer-controlled, automated techniques which have been discussed in this paper although the reported cross sections are lower than for the other nuclides so far studied by these techniques. An international collaboration for this purpose has been formed and preliminary investigations are currently in progress.

The reported discoveries of $^{265,266}\text{Sg}$ [47], $^{267}\text{Hs}(108)$ [49], and several isotopes of the new elements 110 and 111[2,50,51] shown in Fig. 2 furnish strong evidence for the enhanced stability predicted [48] in the region of the deformed shells at $N=162$ and $Z=108$. This makes the prospect for making isotopes of elements heavier than 106 with half-lives long enough for chemical studies appear extremely promising although the ever

smaller production cross sections present a major challenge. The use of "cold fusion" reactions does not appear particularly promising because the isotopes produced are usually rather neutron deficient and will probably be too short for chemical studies, but it may be possible to produce isotopes near the region of deformed stability using "hot fusion" or "fusion-evaporation compound nucleus reactions such as the following: $^{249}\text{Bk}(^{20,22}\text{Ne},\text{xn})^{266-268}\text{Ns}(107)$, $^{54}\text{Es}(^{18,16}\text{O},\text{xn})^{264-268}\text{Ns}$, $^{251}\text{Cf}(^{22}\text{Ne},4\text{n})^{269}\text{Hs}(108)$, and $^{254}\text{Es}(^{20,22}\text{Ne},\text{xn})^{270-272}\text{Mt}(109)$; These isotopes are expected to have half-lives in the range of a second or more. For example, ^{266}Ns is expected to have a half-life of about 10 s with a production cross section of the order of 30 pb and might be the best candidate for extending chemical studies to element 107, expected to exhibit properties similar to the Group 6 elements Tc and Re. Use of the rare, neutron-rich target ^{250}Cm with appropriate projectiles might also facilitate access to more neutron-rich isotopes. However, with production cross sections of picobarns or even less, production of a sufficient number of atoms for statistically significant studies of chemical properties remains a real challenge and may require development of new and imaginative experimental techniques such as rotating multiple target systems and ever higher beam intensities.

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Figures

Fig. 1: Current periodic table (1995).

Fig. 2. Chart of transnobelium isotopes.

Fig. 3. Spontaneous fission half-lives of even-even nuclei.

Fig. 4: Known partial alpha half-lives for transplutonium isotopes with even neutron number.

Fig. 5. Schematic drawing of ARCA II.

Fig. 6. Schematic drawing of HEVI connected to the MG system.

Fig. 7: Schematic drawing of MG system for measurement of α - and SF activities.

Fig. 8. Schematic of SISAK system.

Fig. 9. Schematic drawing of LISSY, used for detection of α - and SF activities in flowing organic solutions.

Periodic Table of the Elements

GROUP

													VIII				
1A												VIII					
1												2					
H	IIA											He					
3	4											5	6	7	8	9	10
Li	Be											B	C	N	O	F	Ne
11	12											13	14	15	16	17	18
Na	Mg	IIIA	IVA	VA	VIA	VIIA	VIII			IB	IIB	Al	Si	P	S	Cl	Ar
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
87	88	89	104	105	106	107	108	109	110	111	(112)	(113)	(114)	(115)	(116)	(117)	(118)
Fr	Ra	Ac	Rf	Ha	Sg	Ns	Hs	Mt									

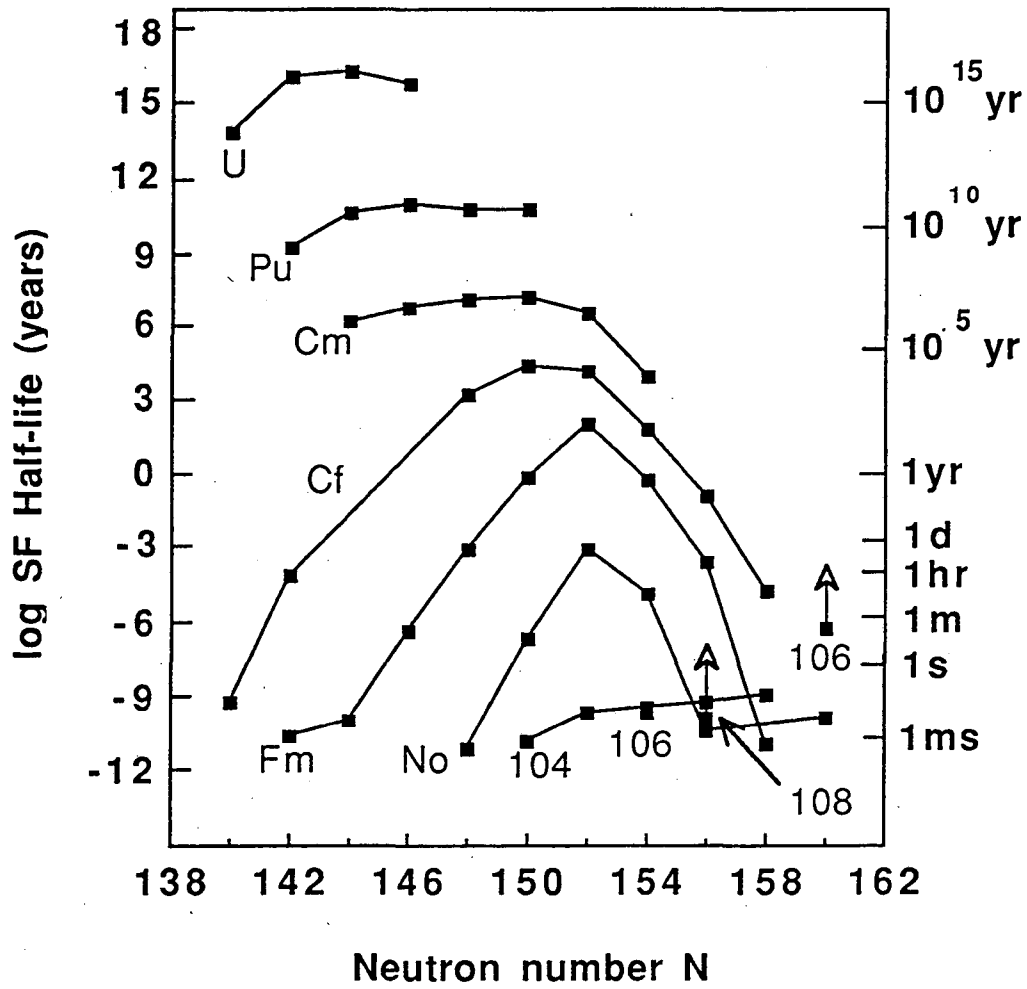
Lanthanides

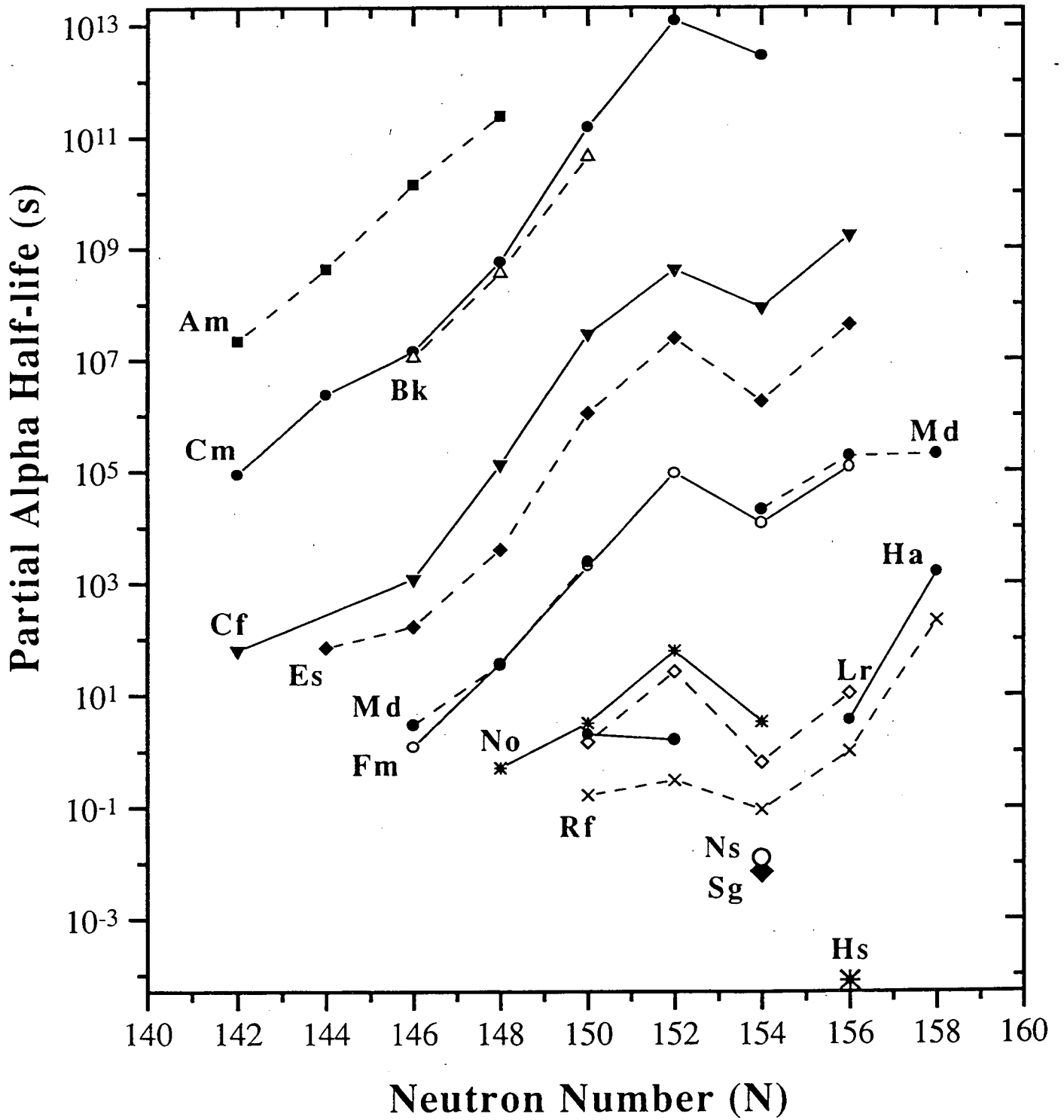
58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

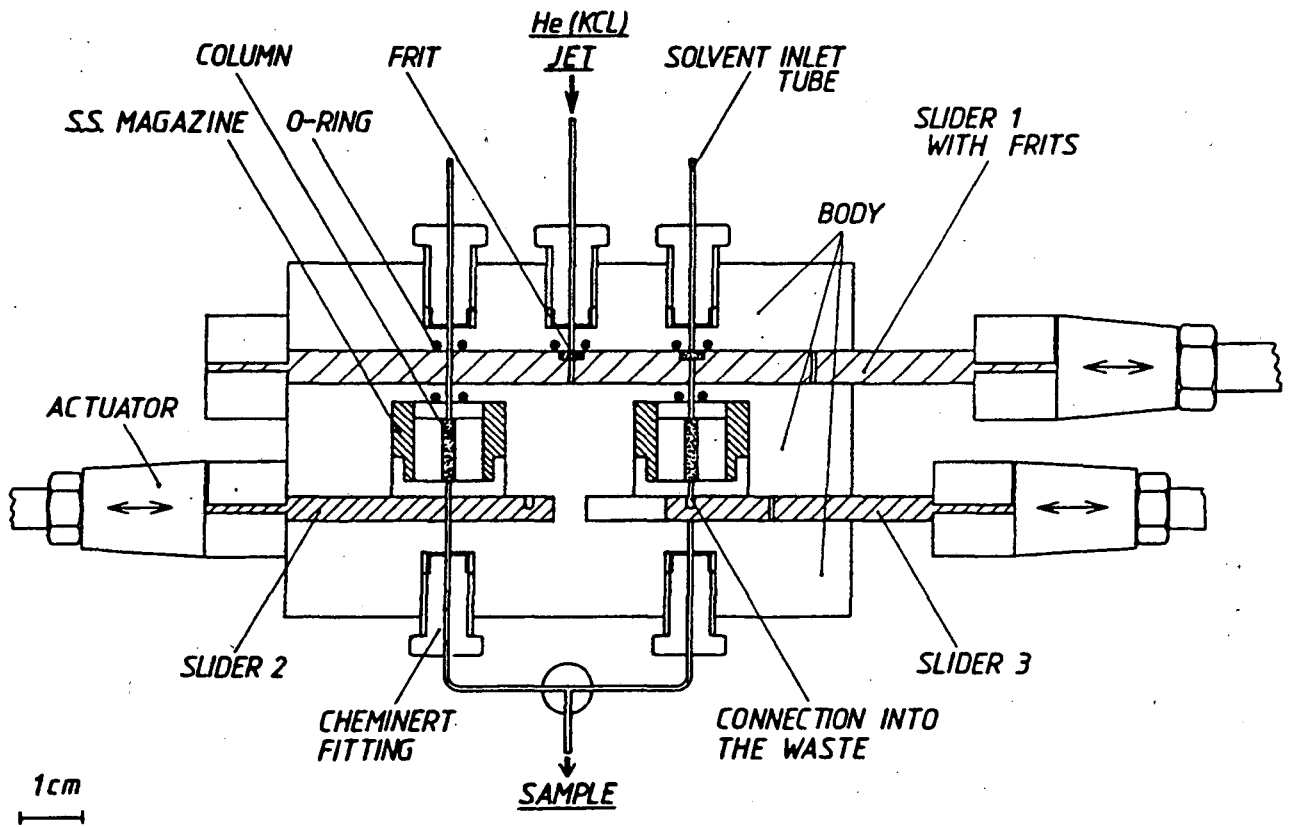
Actinides

90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

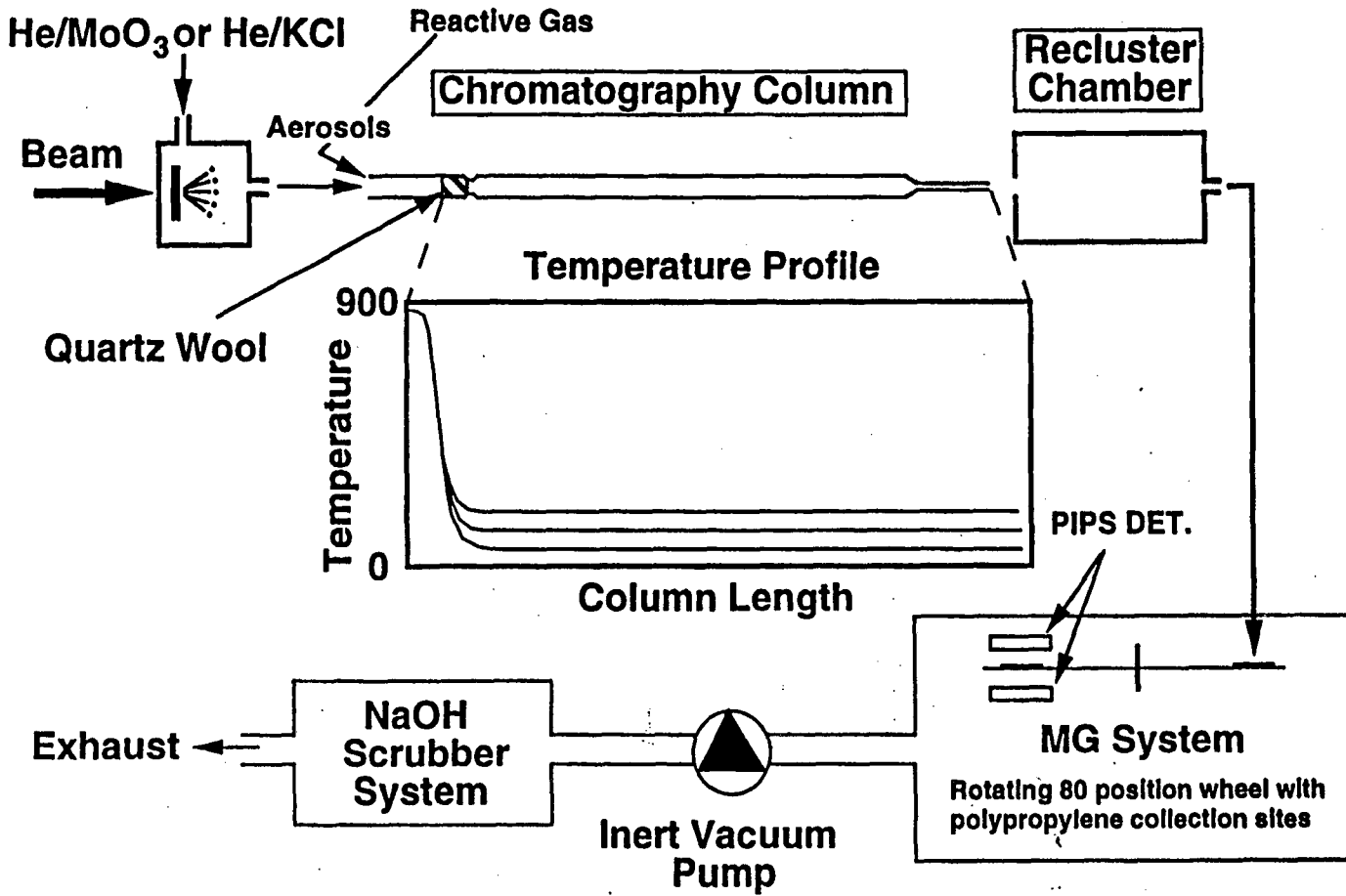
											111	272 1.5ms α												
											110	267? 4 us α		269 0.17ms α		271 1.4ms α		273 ? 0.4ms α						
											109 Mt	266 3.4ms α		268 70ms α										
											108 Hs	263 ? α	264 0.5ms α , SF?	265 2ms α		267 20-70 ms, α								
											107 Ns	261 12ms α , SF?	262 8ms α	0.1s α	264 0.44s α									
											106 Sg	258 2.9ms α	259 0.5s α , SF	260 4ms α , SF	261 0.3s α , SF?		263 0.9s SF, α	265 ? 2-30 s α	266 ? 20-30 s α					
105											105 Ha	255 1.5s SF		257 1.3s α , SF	258 4.4s EC, α		260 1.5s α , SF	261 1.8s α , SF	262 34s EC, α	263 27s SF, α				
104											104 Rf	254 ? 0.5ms SF	255 1.4s SF, α ?	256 7ms α , SF	257 4.8s α , SF	258 13ms SF, α ?	259 3.0s α , SF	260 20ms SF	261 65s α , SF?	262 ms SF	263 ? 2 s SF			
103											103 Lr	253 1.3 s α	254 13 s α	255 22 s α , EC	256 26 s α , EC	257 0.65 s α , EC	258 3.9 s α	259 6.1 s α , SF	260 3 m α , EC	261 39 m SF	262 216 m EC			
												150	152	154	156	158	160	162						
												N												

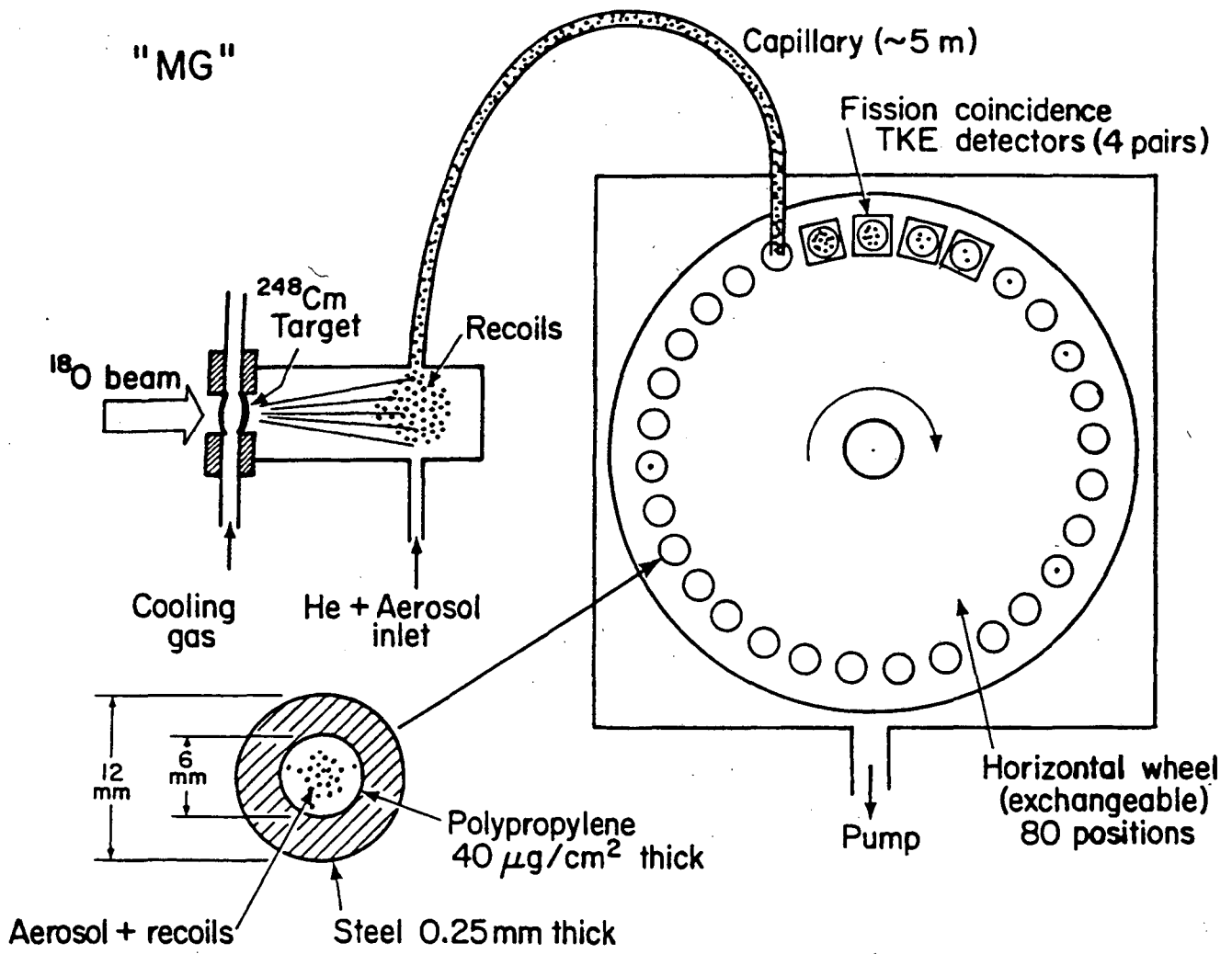


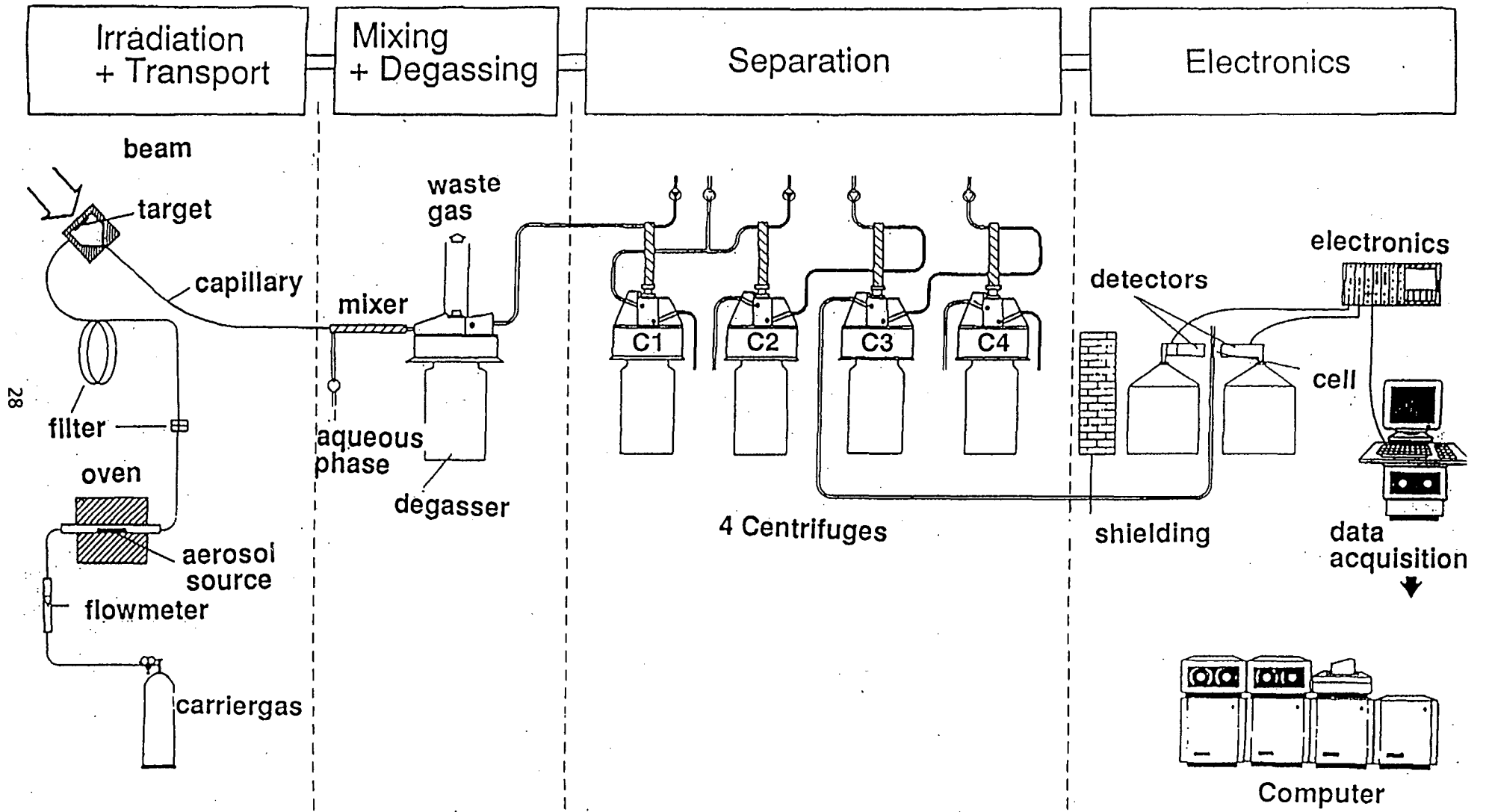


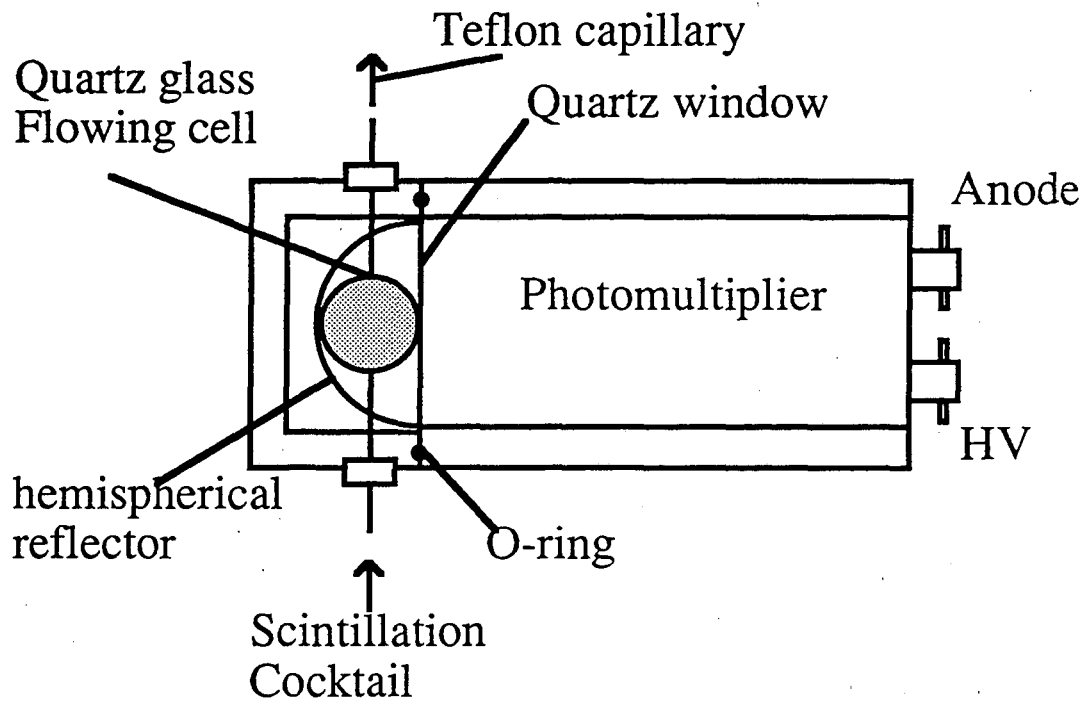


Target System









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