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Laboratory Experiment

Radiochemical Separation Techniques in Classroom Settings

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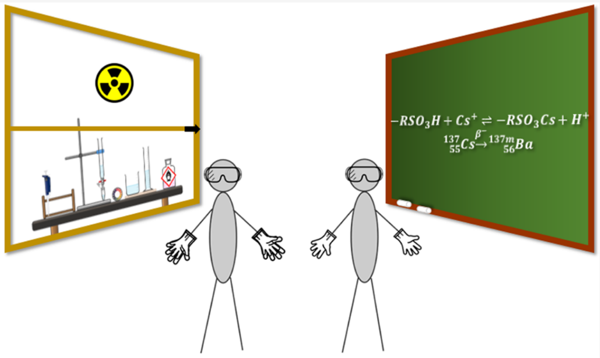
ABSTRACT: In view of the mounting requirements for courses in nuclear chemistry and radiochemistry, hands-on experience in the separations of radioisotopes is imperative. Three separation techniques commonly used were introduced, coprecipitation, liquid−liquid extraction, and ion-exchange chromatography. Their principles and the associated fundamental thermodynamic concepts are detailed. Their respective experimental applications to the separations of radioisotopes of one rare earth element (europium) and two transition metals (cobalt and nickel) are discussed. In-classroom experimental settings are proposed, and experiment outcomes are presented, which can be beneficial for future implementation within nuclear chemistry and radiochemistry programs in higher education.



KEYWORDS: *Upper-Division Undergraduate, Interdisciplinary/Multidisciplinary, Hands-On Learning/Manipulatives, Nuclear Chemistry/Radiochemistry, Separation Science*

1. INTRODUCTION

The past few years have witnessed increased needs for a workforce in nuclear chemistry and radiochemistry (N&RC) expertise due to sustained efforts in radiopharmaceutical development, medical imaging and radiation oncology technology renewal, nuclear power production, waste management operations, and several other industrial sectors. Unfortunately, there is an unequivocal training and recruitment crisis that has led to a widening gap between a retiring workforce and early career radiochemists in many countries including the United States.[1] This is partly attributable to the fact that the United States currently offers only a handful of undergraduate and graduate programs in N&RC. The number of people with N&RC expertise has stagnated at a low level, if not steadily decreased, over the past five decades in the United States,[2] although N&RC-pertaining programs (e.g., chemistry, chemical engineering, and nuclear engineering) are prevalent. In contrast, China is experiencing a renaissance in these fields because of a very large demand for nuclear energy, and many academic programs have been established to meet this demand including both undergraduate and graduate-level degrees in radiochemistry and nuclear chemical engineering.[3] To fill this gap in the United States, degree-granting programs, or courses at the minimum, in N&RC ought to be widely accessible. The utilization of virtual reality technology has enabled an unprecedented education mode and such application has been attempted in teaching introductory N&RC courses, too.[4,5] This is particularly meaningful during the COVID-19 pandemic. However, the N&RC profession requires the mastery of hands-on experience, so the simulated experiments may assist but can never replace hands-on experiments. “Real” N&RC experiments often use either sealed sources to detect radiation[6,7] or surrogates in radiometric analysis[8,9] to avoid direct handling of dispersive radioactive materials. Working with dispersive radioactive materials is a critical component in the N&RC profession, especially in radiochemical separation.

Benefiting from a well-established research ecosystem in nuclear and chemical sciences, the University of California at Berkeley (UC Berkeley) has long sought to familiarize students with N&RC principles and to provide hands-on training for the safe handling of radioactive materials in the laboratory. To that end, the Radiochemical Methods in Nuclear Technology and Forensics course (CHEM/NE C146) is offered to upper-division undergraduate students and cross-listed between the Departments of Chemistry and Nuclear Engineering. The topics covered in this course were organized largely in accordance with the curriculum created over half a century ago,[10,11] starting with radiation detection and progressing to wet chemistry involving the manipulation of radioisotopes. The main distinction is that the CHEM/NE C146 course decreased the introduction of certain types of detectors (e.g., β-ray counters) and increased the number of wet chemistry experiments (e.g., uranium electrodeposition for nuclear forensics application). Among the numerous radiochemical

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procedures investigated to date, including isotope dilution analysis,[12,13] radiochemical assay,[14] and radiochemical separation, the latter stands out due to its diverse applications in many nuclear sectors such as the production and purification of medical isotopes, the fabrication of nuclear fuel components, and the recovery of fission products and actinides for environmental remediation and strategic purposes. For training purposes, it is crucial to design radiochemical separation experiments that are easy and safe to perform, effective in providing experience in handling dispersive radioactive materials, and accessible to most universities and colleges. Here we aim to disseminate the UC Berkeley course's approach and experimental setups that have been refined over the years so that they can be implemented at other institutions. This work therefore starts with enunciating a few fundamental thermodynamic concepts in separation processes before introducing three separation techniques commonly used in N&RC, coprecipitation (Co-ppt), liquid−liquid extraction (LLE, also known as solvent extraction), and ion-exchange chromatography (IEC). The exemplary radioisotopes to be separated are europium-152 ($^{152}Eu^{3+}$), cobalt-60 ($^{60}Co^{2+}$), and nickel-63 ($^{63}Ni^{2+}$) (charges of metal ions will be omitted for simplicity from here on). Herein, experimental designs for each technique are proposed, experiment results presented, and possible adjustments discussed.

2. FUNDAMENTAL THERMODYNAMICS CONCEPTS IN SEPARATION PROCESSES

A separating agent (either mass or energy) is added into a mixture and subsequent dynamic separation of target species usually relies on either mechanical forces (e.g., filtration, centrifugation) or differences in mass transfer. When differences in mass transfer occur in different phases, the separation process relies on different thermodynamic equilibria (e.g., liquid−liquid extraction, chromatography, distillation). In contrast, when differences in mass transfer occur in the same phase, the separation process relies on different mass transfer rates (e.g., gas diffusion, reverse osmosis, electrodialysis). The three radiochemical separation techniques discussed here (Co-ppt, LLE, and IEC) are all based on differences in thermodynamic equilibria of substances and are commonly used in the classroom, research laboratory, and industrial settings. Familiarization with these three separation techniques will benefit education and training in N&RC. Separation processes involve aspects of thermodynamics, kinetics, and transport processes (momentum, energy (heat), and mass), with concepts in thermodynamics being most essential. Kinetics and transport processes are beyond the scope of this work, and a variety of textbooks can be referred to for further interest.

2.1. Partition Constant (*K*°), Partition Ratio (*K*), and Distribution Ratio (*D*)

Table 1. Phases Assigned in Different Radiochemical Separation Techniques

	Co-Precipitation	Liquid−Liquid Extraction	Ion-Exchange Chromatography
Phase 1	Filtrate	Aqueous	Mobile
Phase 2	Precipitate or Filtrant	Organic	Stationary

One common confusion that many students have is among partition constant (K°), partition ratio (K), and distribution ratio (D). Although they are often used interchangeably, the IUPAC Orange Book has made distinguished use of each. Both K° and K refer to the distribution of a particular chemical species with a definite form (e.g., a metal, denoted by M) across two distinct phases (eq 1), where the two phases for each of the three separation techniques are summarized in Table 1. However, these two parameters are inherently different. Considering a simple physical distribution of M across two phases without chemical reactions, K° can be derived from the phase equilibrium criterion and correlated to K via the equilibrium constant of the distribution reaction (eq 2). K° is independent of phase composition and dependent on temperature exclusively. In contrast, K, defined as $K = C_{pha2}/C_{pha1}$ (Nernst's distribution law), depends on both composition and temperature and is measured under specific conditions. Another difference is that K° is unitless, whereas K can be unitless or with unit, depending on whether the concentrations across two phases are expressed in the same unit (e.g., in LLE) or different units (e.g., in IEC where mol of M/g stationary phase and mol of M/mL mobile phase are commonly used). It is necessary to reiterate that even if they are approximately equal, as in many radiochemistry studies where solutions are sufficiently dilute, they are not identical. In the interest of metal separations, M often exists as multiple species in a phase (e.g., different complexed forms, different oxidation states, etc.), rendering K° and K inapplicable and necessitating the use of another thermodynamic variable, D:

$$M_{pha1} \rightleftharpoons M_{pha2} \tag{1}$$

$$\begin{aligned}\underbrace{\mu^\circ_{pha1} + RT\ \ln a_{pha1}}_{\mu_{pha1}} &= \underbrace{\mu^\circ_{pha2} + RT\ \ln a_{pha2}}_{\mu_{pha2}} \Rightarrow K^\circ = \frac{a_{pha2}}{a_{pha1}}\\ &= \exp\left(-\frac{\mu^\circ_{pha2} - \mu^\circ_{pha1}}{RT}\right) = const|_T \overset{a=\gamma C}{\Longrightarrow} K^\circ\\ &= \underbrace{\left(\frac{C_{pha2}}{C_{pha1}}\right)}_{K}\frac{\gamma_{pha2}}{\gamma_{pha1}} \Rightarrow K = const|_{T,\gamma_{pha2}/\gamma_{pha1}}\end{aligned} \tag{2}$$

where μ_{pha}, a_{pha}, C_{pha}, and γ_{pha} are, respectively, the chemical potential, activity, concentration, and activity coefficient in a phase; R, universal gas constant; T, absolute temperature.

In contrast to K° and K, the distribution ratio D refers to the total analytical concentration of a solute in two phases, regardless of the chemical form (whether dissociated, associated, hydrolyzed, or complexed) (eq 3) and is dependent on both temperature and phase composition:

$$D = \frac{C_{tot,pha2}}{C_{tot,pha1}} = \frac{\sum_i [M_i]_{pha2}}{\sum_j [M_j]_{pha1}} \tag{3}$$

D, like K, can also be unitless or with unit, depending on the unit expression of concentration. When the solute only exists in one form, D and K are equal. Otherwise, D and K are correlated by the equilibrium constant of a reaction (dissociation, association, hydrolysis, or complexation) that produces the species. For instance, when a metal ion is complexed by a ligand (L) and forms a complex (ML_n, where $n = 1, 2, 3, \ldots$), D can be expressed as a function of K and $\log \beta$, where β is the stability constant of the complex.

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Table 2. Separation Performance Evaluation Parameters Used in This Work

	Co-ppt	LLE	IEC
Reaction Equation	$M_{(liq)} + c_{(p)} \rightleftharpoons M_{(p)} + c_{(liq)}$ where c represents carrier.	$M_{(aq)} \rightleftharpoons M_{(org)}$	CEC: $n\overline{RH} + M^{n+} \rightleftharpoons \overline{R_nM} + nH^+$ AEC: $m\overline{ROH} + ML_x^{m-} \rightleftharpoons \overline{R_mML_x} + mOH^-$ where $^{-}$ represents resin.
Selectivity coefficient, $K_{A/B}$	$K_{M/c} = \frac{K_M}{K_c} = \frac{n_{M,p}/n_{M,ml}}{n_{c,p}/n_{c,ml}}$ [a]	Often misused for SF, not recommended by IUPAC	$K_{M/(nH)} = \frac{K_M}{K_H^n}$
SF, $SF_{M_1/M_2} = \frac{K_{M_1}}{K_{M_2}}$ [b]	$SF_{M_1/M_2} = \frac{K_{M_1/c}}{K_{M_2/c}} = \frac{n_{M_1,p}/n_{M_1,ml}}{n_{M_2,p}/n_{M_2,ml}}$	$SF_{M_1/M_2} = \frac{C_{M_1,o}/C_{M_1,a}}{C_{M_2,o}/C_{M_2,a}}$	$SF_{M_1/M_2} = \frac{K_{M_1/(n_1H)}}{K_{M_2/(n_2H)}} \frac{K_H^{n_1}}{K_H^{n_2}}$ [c]
Recovery, $R = \frac{Q_{pha2}}{\underbrace{Q_{pha1}+Q_{pha2}}_{Q_0}}$	$R = \frac{n_p}{CV + n_p}$	$R = \frac{C_oV_o}{C_oV_o + C_aV_a} = \frac{D}{D + 1/\alpha}$	$R = \frac{C_eV_e}{C_sV_s + C_eV_e} = \frac{D}{D + 1/\alpha}$
EF, $EF_{M_1/M_2} = \frac{R_{M_1}}{R_{M_2}} = \frac{Q_{M_1}/Q_{M_2}}{Q_{M_1,0}/Q_{M_2,0}}$ [d]	$EF_{M_1/M_2} = \frac{n_{M_1,p}/n_{M_2,p}}{C_{M_1,0}/C_{M_2,0}}$	$EF_{M_1/M_2} = \frac{D_{M_1}}{D_{M_2}} \frac{D_{M_2} + 1/\alpha}{D_{M_1} + 1/\alpha}$	$EF_{M_1/M_2} = \frac{D_{M_1}}{D_{M_2}} \frac{D_{M_2} + 1/\alpha}{D_{M_1} + 1/\alpha}$

[a] For linear/homogeneous distribution, the Berthelot-Nernst distribution law applies. [b] Assume single species of M_1 and M_2. Replace K with D if M_1 and M_2 have multiple chemical forms. [c] SF in IEC can also be calculated by relative retention. $RR_{i,ref} = \frac{k_i}{k_{ref}} = \frac{K_i}{K_{ref}} = \frac{(x_r' / x_m)_i}{(x_r' / x_m)_{ref}}$, where x is t or $V \Rightarrow SF_{M_1/M_2} = \frac{RR_{1,ref}}{RR_{2,ref}}$. [d] $EF_{M_1/M_2} = \frac{1}{DF_{M_1/M_2}}$.

In radiochemistry, the radioisotope concentration is often too low for chemical analysis to accurately quantify, and radiation detectors are most often resorted to. Detection of radiations usually gives total counts or count rates in counts per unit time that can be converted to radioactivity, from which the isotope concentration can be calculated. Since decay properties are not influenced by the phase in which the radionuclide exists and phase volume ratios are specified prior to the experiment, measuring the ratio of radioactivity between two phases is enough to ascertain D (eq 4):

$$D = \frac{\sum_i [M_i]_{pha2}}{\sum_j [M_j]_{pha1}} = \frac{\left(\frac{\sum_i N_i}{V}\right)_{pha2}}{\left(\frac{\sum_j N_j}{V}\right)_{pha1}} = \frac{\left(\frac{A}{\lambda V}\right)_{pha2}}{\left(\frac{A}{\lambda V}\right)_{pha1}} \xRightarrow{\text{same isotope}} D = \left(\frac{A_{pha2}}{A_{pha1}}\right) / \underbrace{\left(\frac{V_{pha2}}{V_{pha1}}\right)}_{\alpha} \quad (4)$$

where A is the radioactivity; V, phase volume; N, number of atoms or molecules; α, phase volume ratio.

Sometimes the distribution ratio is expressed in terms of total quantity in moles (n) or mass (m) and termed mass distribution ratio (also called retention factor in chromatography and extraction factor in LLE), D_m, which is correlated to D by eq 5. Since potential confusion may arise between D and D_m, the latter variable is employed far less frequently than the former:

$$D_m = \frac{X_{tot,pha2}}{X_{tot,pha1}} = \alpha D, \quad X = m \text{ (mass) or } n \text{ (moles)} \quad (5)$$

2.2. Separation Performance Evaluation

In many cases, multiple metal elements or compounds are to be separated, so a few parameters are necessary to determine separation efficiency. These include, but are not limited to, recovery, separation factor (SF), enrichment factor (EF), and decontamination factor (DF). Recovery is defined as the ratio of the total quantity (either moles or mass) in phase 2, where the solute is enriched after separation (Q_{pha2}) over the total quantity (Q_0) in the feed before separation ($Q_0 = Q_{pha1} + Q_{pha2}$, the summed quantity in phase 1 and 2, respectively, provided the separating agent used is initially free of the solute to be separated). SF is used to indicate how efficient the separation is between two metal elements (M_1 and M_2). In Co-ppt and LLE, SF can be directly calculated from K or D. However, in IEC, it can be calculated either directly using K or D or indirectly through a reference species for which relative retention (RR) and selectivity over H^+ or OH^- come into play. RR is the ratio of some quantity (adjusted retention time or volume, D_m, or K) of a species to that of a standard, obtained under identical conditions. Of note, SF is sometimes called selectivity, which is a misnomer. According to IUPAC, selectivity, more precisely selectivity coefficient ($K_{A/B}$), describes the distribution tendency of a target element (M) relative to a reference species (e.g., carrier in Co-ppt ($K_{M/C}$), H^+ in cation exchange chromatography - CEC ($K_{M/(nH)}$), and OH^- in anion exchange chromatography - AEC ($K_{M/(nOH)}$)), while SF is the separation between two target elements. EF describes the change in the quantity ratio of two elements from pre- to postseparation and is numerically equal to the reciprocal of DF. A comparison of calculations of these parameters is listed in Table 2.

IEC has a unique way to evaluate the separation performance based on the peak resolution that is defined as R in eq 6, where x is the elution time (t) or the elute volume (V); W_{bl}, the peak width at the bottom line (= 4σ = 1.7 FWHM); σ, the peak width at the inflection point; FWHM, the full-width at half-maximum. As a rule of thumb, $R \geq 1.5$ indicates a complete separation and $R \leq 0.8$ denotes no separation. Theoretical plate number and plate height are also parameters that are sometimes useful to evaluate the suitability of the

Table 3. Comparison of Three Isotopes Used in the Experimental Procedures

		Stock solution					
	Half-life (yr)	Specific radioactivity (Ci/L)	Matrix	Volume (μL)	Decay mode	Photopeak energy (keV)	Radiation detector
^{60}Co	5.3	0.2	0.01 M HCl or HNO_3	10	β^-, IT	1173, 1332	Gamma counter[a]
^{63}Ni	100.1				β^-	N/A	LSC[b]
^{152}Eu	13.5				β^-, ε	344	Gamma counter[a]

[a] Either high purity germanium (HPGe) detector (cooled in liquid N_2) or NaI(Tl) detector. [b] Liquid scintillation counter (LSC).

chromatography column; their use is however out of the scope of this paper:

$$R = \frac{x_{r,A} - x_{r,B}}{\frac{W_{bl,A} + W_{bl,B}}{2}} = \frac{\overbrace{x_{B,\max} - x_{A,\max}}^{\Delta x_{\max}}}{2(\sigma_A + \sigma_B)} \tag{6}$$

3. EXPERIMENTAL MATERIALS AND APPARATUS

All reagents and devices used are listed in Tables 3 and 4. All chemicals were used as received without further purification. Although purification of chemicals (such as di(2-ethylhexyl)-phosphoric acid (HDEHP) used in LLE (*vide infra*)) is routinely performed in numerous research endeavors, the educational value in this lab course was not lost without this step, as the primary educational objective is to allow students to focus mainly on the concepts, principles, and hands-on experience of these separation techniques. Quantities indicated therein are based on one workstation (most likely a functional hood) for the three experiments and can be scaled up depending on the number of workstations in the classroom. Detailed experiment procedures, exemplary collected data sets, and guidelines of lab reports in the student's handouts can be referred to in the Supporting Information (SI).

4. COPRECIPITATION

Precipitation was one of the first few methods used in radiochemistry by Marie and Pierre Curie to separate Ra in chloride media.[17] However, it is only applicable when the radionuclide to be separated is present in high enough concentrations that exceed its solubility product. For many radioisotopes, the concentration is too low for direct precipitation to pertain. Coprecipitation has been promoted to enrich the target isotopes. Coprecipitation usually requires extraneous chemicals to serve as carriers for the target isotopes (M_1) that await to be separated from others (M_2) (Figure 1). The mechanisms consist of mixed crystallization, surface adsorption, occlusion, and mechanical entrapment. Mixed crystallization usually exhibits the highest selectivity because the nature of isomorphous substitution rigorously requires the carrier and target atoms to be sufficiently similar in size.

In this experiment, separation of ^{60}Co and ^{63}Ni was performed via coprecipitation by potassium hexanitritocobaltate (also called potassium cobaltinitrite), $K_3Co(NO_2)_6$, with stable Co being the isotopic carrier. A batch of $Co(NO_3)_2$ solutions with different starting concentrations (5, 10, 15, 20, 25, and 30 mM) was prepared and each was spiked with a trace level (~1 μL, ~1−10 nCi) of ^{60}Co and ^{63}Ni. The solution was acidified with acetic acid as the masking agent to hold-back ^{63}Ni[18] and then KNO_2 solution was added to precipitate Co.[19] The yellow precipitate, $K_3Co(NO_2)_6$, forms (eq 7) immediately in concentrated solutions and slowly in diluted solutions. In the classroom demonstration where the concentrations were dilute, precipitation was accelerated by warming and stirring frequently based on Kahn et al.'s procedure.[20] The $K_3Co(NO_2)_6$ precipitate was separated from the mother liquor by a vacuum filtration station. Alternatively, phase separation can be done by centrifuging at 3000 rpm for 5 min[9] in case the precipitate is not well retained on filter paper.[20] The precipitate was washed twice with 5 mL 10 v% acetic acid each time and once with distilled water to remove impurities.[9] Finally, the precipitate was dried using an IR lamp at 110 °C for 5 min, weighed, and counted by the gamma spectrometer for ^{60}Co and by the LSC for ^{63}Ni. The filtrate was counted in the same way. The schematic setup is shown in Figure 2 and SI §1.1 provides more details to guide the students. The count rate of each isotope in the solid and in the mother liquor was used to infer the quantity and, further, the distribution ratio, separation factor, and ^{60}Co recovery based on equations in Table 2. The results (Table S1, Table S2, and Figure S1 in SI §1.2) showed a trend of the separated ^{60}Co as a function of the Co carrier concentration. The method offered the highest recovery of almost 90% with negligible ^{63}Ni in the precipitate. As the starting concentration increased, the recovery decreased because the limiting agent switched from $Co(NO_3)_2$ to KNO_2, which is to say $Co(NO_3)_2$ became excess. This is also the reason for the decrease in the distribution ratio of Co. Of note, the factors value remained high since Ni was effectively retained in the liquid phase. It is also possible to examine if the coprecipitation of ^{60}Co follows a homogeneous distribution based on known added quantities and equilibrium quantities of both ^{60}Co and stable Co. In cases where it is difficult or inconvenient to obtain a quantitative recovery, coprecipitation can be applied in conjunction with isotope dilution analysis to obtain more precise quantification since isotope dilution analysis does not require a quantitative recovery of trace analytes:[21]

$$\begin{aligned} &Co(NO_3)_2 + 7KNO_2 + 2HNO_3 \\ &\quad \rightarrow K_3Co(NO_2)_6 \downarrow + NO \uparrow + H_2O + 4KNO_3 \end{aligned} \tag{7}$$

5. LIQUID−LIQUID EXTRACTION

LLE is one of the most used techniques in separation processes and is preferred in industrial-scale separations, which is ascribed to the ease of changing from batch to multistage operation without significantly increasing the consumption of heat or chemicals. IEC (*vide infra*), another technique that is prevalent in industrial-scale separations, has this advantage too. In contrast, only a few stages are possible without great expenditure of labor for coprecipitation since crystallization procedures may be by nature slow (long wait-time for precipitate formation) and tedious (with several rinse, dry, and reprecipitation steps).[22] Therefore, LLE and IEC outweigh Co-ppt in many applications.

Table 4. Materials and Apparatus Used in the Experimental Procedures

	Reagents	Equipment and wares	Detectors[a]
Co-ppt	15 mL $Co(NO_3)_2$ solutions (5, 10, 15, 20, 25, and 30 mM) (spiked with 1 μL ^{60}Co and ^{63}Ni, both ~1−10 nCi); 5 mL 8 M acetic acid (CH_3COOH) solution; 10 mL 10v% (~1.75 M) CH_3COOH solution; 3 mL 0.3 M KNO_2 solution.	Magnetic stirrer hot plate; filtration station (glass funnel, ball and socket clamp, glass frit with chimney, rubber stopper, filter flask, and vacuum trap);[15] tweezer; infrared (IR) lamp; filter paper.	The ^{152}Eu and ^{60}Co gamma spectroscopy was achieved by the gamma counter. ^{63}Ni is a β^- emitter and does not produce a γ ray, so its radioactivity was counted by the LSC (efficiency ~60−80% for β^- emitters). All three isotopes were supplied by Eckert and Ziegler Isotope Products, Inc. and contained negligible impurities that would have otherwise interfered with the radiation detection.
LLE	50 μL mixture of 0.1 M $Eu(NO_3)_3$, $Co(NO_3)_2$, $Ni(NO_3)_2$ (spiked with 5 μL ^{60}Co, ^{63}Ni, and ^{152}Eu in 0.01 M HNO_3); 450 μL HNO_3 (0.01, 0.05, 0.1, 0.2, 0.3, 0.6, 0.8, and 1 M) in $NaNO_3$ solutions (I = 1 M); 700 μL 0.1 M HDEHP in dodecane.	20 1.5 mL centrifuge microtubes (both screwcap and flip-top); plastic pipettors (100, 200, and 1000 μL); vortexor or shaker; centrifuge; plastic scintillation vials.	
IEC	2 mL loading solution spiked with ^{60}Co, ^{63}Ni, and ^{152}Eu; 10 mL HCl (12 M, 9 M, 4 M); deionized water; 2 mL 0.5 M $AgNO_3$ solution in a dark bottle; 10 mL 3 M NH_4Cl; 10 mL malic acid ($HOOCCH_2CH(OH)COOH$, 0.1 and 0.2 M).	10 1.5 mL centrifuge microtubes (either screwcap or flip-top); plastic scintillation vials; glass column (1 cm × 8 cm) and glass wool; ion-exchange resin (see IEC section for more); pH papers; graduated cylinder; glass beakers.	

[a] HPGe detector used was ORTEC GEM50P4 model equipped with DSPEC-jr 2.0 digital γ-ray spectrometer and MAESTRO software. The LSC used was PerkinElmer Packard Tri-Carb model B4430 LSC equipped with QuantaSmart software and the LSC Cocktail was Ultima Gold. The LSC efficiency may be reduced because of the enhanced physical quenching incurred by the precipitate that forms a heterogeneous solution with the cocktail. This has no significant impact on the quantification since tracking the radioactivities of the mother liquor and the filtrate, both of which form homogeneous solutions with the cocktail, yields the accurate radioactivity of the precipitate. Details of principles of used detectors, necessary electronics, and calibrations can be found in Knoll et al.'s work[16] and are not introduced here.

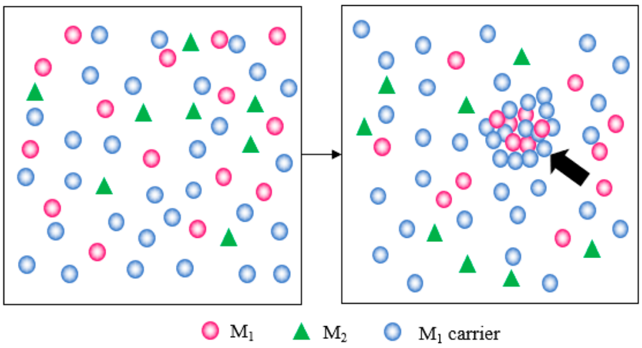

Figure 1. Schematic illustration of the separation of a binary mixture by coprecipitation.

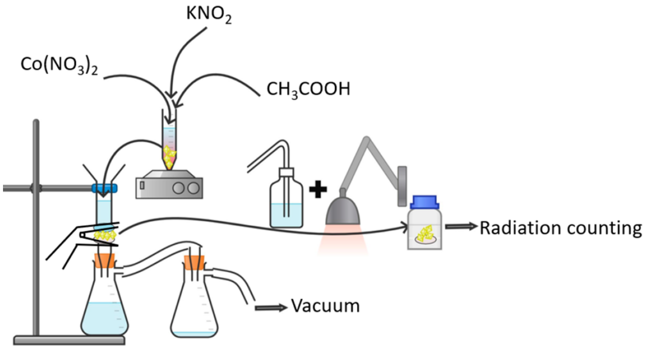

Figure 2. Schematic experimental setup of the separation of ^{60}Co from ^{63}Ni by coprecipitation.

An aqueous phase and an ideally immiscible organic phase are mixed. When the liquids settle and phases are separated, solutes may selectively move to one phase more than to the other as driven by the presence of extractants (Figure 3). If there are more than one type of metal ions, either stable or radioactive, they exhibit different distribution behaviors across two phases and thus separation can be achieved.

Extraction experiments were performed under different acidities at 25 °C and consisted of three steps, as listed below and depicted in Figure 3.

- *Conditioning*. Organic phases (500 μL 0.1 M HDEHP in dodecane) were contacted with fresh 1 M $(H/Na)NO_3$ solution for 10 min prior to extraction.
- *Extraction*. An aqueous mixture of three metal nitrate salts in 1 M $(H/Na)NO_3$ media (each metal has 0.01 M concentration and 1 μCi radioactivity per microtube) was contacted with an equal volume (500 μL) of conditioned organic phase in a 1.5 mL screw-cap centrifuge microtube. All microtubes were vigorously shaken for 1 min to achieve thorough mixing before being centrifuged at 3000 rpm for about 3 min to separate the phases. The extraction reaction proceeded as eq 8:

$$Eu(NO_3)_{3(aq)} + 3HDEHP_{(org)} \rightleftharpoons Eu(DEHP)_{3(org)} + 3HNO_{3(aq)} \quad (8)$$

- *Counting*. A total of 400 μL of the organic phase from the centrifuged microtube was transferred into a labeled flip-top microtube housed in a plastic scintillation vial for radiation counting. The aqueous phase followed the same procedure. A more detailed, step-by-step procedure is provided in SI §2.1 to guide the students. The net counts with error in the characteristic peak for all samples were collected and used to calculate the distribution ratio and the fraction extracted. The counting time can be adjusted based on the radioactivity initially spiked and should be consistent for all samples. The aliquot for radiation detection can also be altered if volume correction is performed afterward.

With this experiment setup, Eu was extracted but Co and Ni were not.[23] *D* and *E* values for Eu in pH 0−2 usually fall into the range of 0.5−8 and 30−90%, respectively, based on Figure S2 in SI §2.2 and Cassidy et al.'s work.[23] Both parameter values decrease as the acidity increases because HDEHP is a cation exchanger and the extraction reaction is pH-dependent.

6. ION-EXCHANGE CHROMATOGRAPHY

Many metal ions may be separated using cation exchangers (CEC) since metal ions are inherently cations. However, the distribution behaviors of certain cations of similar chemical properties do not vary greatly. Fortunately, with judicious choice of complexing agent, it is possible to form anionic complexes of these metal ions (e.g., MCl_x^{y-}, $M(NO_3)_x^{y-}$, etc.) and these complex species can be separated by anion exchangers (AEC) if they exhibit different affinities. For the Dowex strong acid and base resins utilized in the experiment (*vide infra*), the reactions follow eqs 9 and 10 for CEC and AEC, respectively. By varying the concentration of the eluents (usually mineral acids), the fractional ion concentration, existing whether as hydrated cations in CEC or as the complexed anions in AEC, can be varied and large changes in the distribution ratios are thereby produced. Feeds laden with

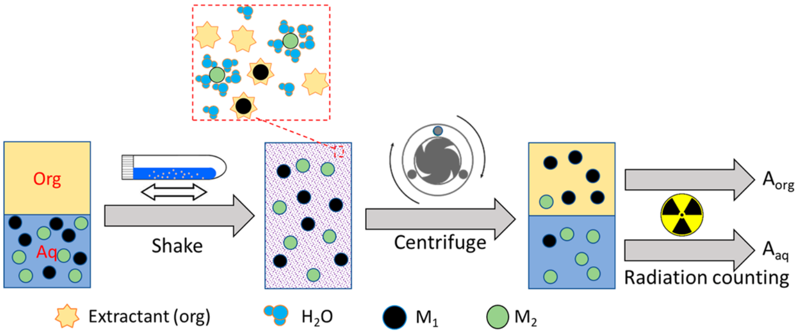

Figure 3. Schematic illustration of the radiochemical separation of a binary mixture by LLE.

a variety of metal ions can thus be eluted at different times or in different volumes and separated (Figure 4). The elution curves of most metallic elements in the periodic table, using hydrochloric acid as the eluent, are shown in the works Modern Nuclear Chemistry[24] and Cation-Exchange Techniques in Radiochemistry,[25] to which one can refer for in-depth introductions of AEC and CEC, respectively:

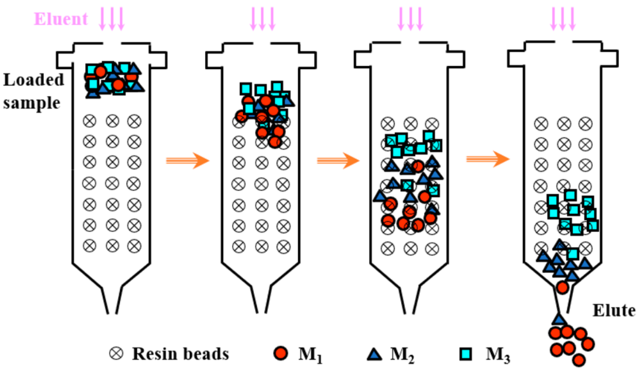

Figure 4. Schematic illustration of the chromatographic separation of a tertiary mixture by IEC with the elution method.

$$\text{CEC: } \overline{nAryl - SO_3^-H^+} + M^{n+} \rightleftharpoons \overline{(Aryl - SO_3^-)_nM^{n+}} + nH^+ \quad (9)$$

$$\text{AEC: } \overline{nAryl - CH_2\overset{+}{N}(CH_3)_3Cl^-} + ML_x^{n-} \rightleftharpoons \overline{[Aryl - CH_2\overset{+}{N}(CH_3)_3]_nML_x^{n-}} + nCl^- \quad (10)$$

Although CEC and AEC differ in used resins, eluents, mechanisms, and so on (Table 5), separations via IEC generally consist of the following four steps, as listed below and displayed in Figure 5.

- *Column preparation*. A small wad of glass wool was added to the bottom of a glass column that was then rinsed with appropriate solutions. A slurry of preconditioned ion-exchange resin (strong acid and base used here for CEC and AEC, respectively) was placed in the column until reaching about 70−90% of the column height. Another small wad of glass wool was added to the top of the resin bed. The column was rinsed again to even the resin bed and remove the air bubbles or channels. The air pressure was applied carefully (to avoid the risk of contamination) to speed up the dripping and later eluting processes. The drop size from the column was determined by collecting 20 drops in a graduated cylinder. The free column volume (FCV) was determined by rinsing the column with DI water to expel all Cl^- ions, applying a small quantity of NH_4Cl, and eluting the acid with a $AgNO_3$ solution under the column tip. The number of drops when the white AgCl precipitate just appeared was counted as the FCV.

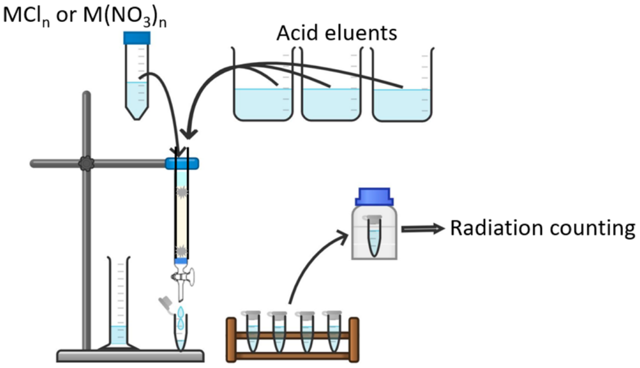

Figure 5. Schematic experimental setup of an anion exchange column used in the chromatographic separation.

- *Loading*. The solution mixture containing ^{63}Ni, ^{60}Co, and ^{152}Eu was loaded onto the resin bed by multiple small additions so as not to put the radioactivity high up on the column reservoir. Fractions of 20 drops were collected in a centrifuge microtube, immediately after loading the feed.
- *Elution*. CEC and AEC varied greatly in this step due to their different separation mechanisms. CEC followed Dadone et al.'s procedure[26] while AEC followed an

Table 5. Comparison of Experimental Conditions for the Separation of ^{59}Ni, ^{60}Co, and ^{152}Eu

Experiment setup		CEC			AEC		
Ion exchange resin type		AG 50W-X4 (1 × 15 cm) or Dowex 50WX8 resin (200−400 mesh) (1.2 × 22 cm)			AG 1-X4 (1 × 15 cm) or Dowex 1X8 resin (100−200 mesh) (0.29 × 26 cm)		
Resin soaked in		3 M NH_4Cl			9 M HCl		
Column rinsing using		3 M NH_4Cl			9 M HCl		
Loading	Solute	MCl_n or $M(NO_3)_n$ (M = Co, Ni, and Eu)					
	Medium	0.1 M malic acid			12 M HCl		
Eluent 1	Acidity	0.2 M malic acid, pH 3.75 for ^{152}Eu			9 M HCl for ^{63}Ni, ^{152}Eu		
	Volume[a]	3−8 FCVs			∼3 FCVs		
Eluent 2	Acidity	0.2 M malic acid, pH 4 for ^{59}Ni			4 M HCl for ^{60}Co		
	Volume[a]	3−8 FCVs			∼6 FCVs		
Eluent 3	Acidity	0.2 M malic acid, pH 4.25 for ^{60}Co			N/A		
	Volume[a]	3−8 FCVs					
Results		^{60}Co	^{63}Ni	^{152}Eu	^{60}Co	^{63}Ni	^{152}Eu
Eluent 1	D (mL/g)[b]	∼32	∼8	unretained	∼40	unretained	
Eluent 2		∼14	unretained		unretained		
Eluent 3		unretained			N/A		

[a] Exact eluting volume is subject to the column size. [b] D values by CEC are from Dadone et al.'s work[26] and those by AEC are from Kraus et al.'s work.[27]

established procedure used in our classroom settings (SI §3.1.1). For both methods, eluents with different acidities (Table 5) were added to elute different isotopes and meanwhile the fraction collection was continued. The air pressure was applied to the column and the volumetric flow rate of the mobile phase was ~3 mL/min.

- *Counting*. The count rates of ^{59}Ni, ^{60}Co, and ^{152}Eu in the collected elute fractions, in the sample solution before and after loading, and in the air-dried column upon the completion of fraction collection, were accomplished in the same way as mentioned above.

The *D* values are summarized in Table 5, from which we can see the separation among the three radioisotopes was effortlessly achieved by CEC. This terrific separation performance was also evidenced by the well-resolved elution bands of the three isotopes with a peak resolution of ~2.3 between ^{60}Co and ^{63}Ni. In contrast, AEC did not differ between ^{63}Ni and ^{152}Eu. Other parameters in assessing separation performance, such as the elution peak resolution, can then be estimated as well.

The actual practice in CHEM/NE C146 used a different isotope trio to teach students about other isotopes. Comprehensive details on each eluted fraction and the elution profile are in Table S4 and Figure S3 in SI §3.1.2, from which the aforementioned thermodynamic parameters can be calculated. The exact procedure and analysis can be made on the proposed ^{59}Ni, ^{60}Co, and ^{152}Eu trio, which is used in the other two proposed separation experiments. Using the same isotopes throughout all experiments offers easier safety control, fewer hazards, and lower cost than introducing new ones, however, at the expense of limited knowledge transfer to students. Educators may tailor to their own needs and make adjustments in selecting appropriate isotopes. For circumstances where experiment time and space layout are constrained, educators may consider using miniaturized isotope generators[28,29] and bypassing the column preparation and metal solution loading steps. A ^{137}Cs/^{137m}Ba isotope generator was used in our practice and elsewhere[30] to demonstrate CEC and radioactive decay (SI §3.2) since the students had already learned about preseparation operations in the previous AEC experiment. This device is typically used to determine the half-life and decay constant, which are beyond the scope of this article. Those who are interested in this subject may consult SI §3.2 and a variety of sources elsewhere.

7. CONCLUSIONS

The principles of three separation techniques were introduced along with a few fundamental thermodynamic concepts frequently used in the separation process. Applications of these techniques to the separations of a rare earth element (Eu) and two transition metals (Co and Ni) were proposed in a way that is feasible for N&RC-relevant laboratory sessions and/or courses. The introduced techniques are not limited to radionuclide separations. They have a wide range of applications where metal recovery is sought, such as the reprocessing of electronic waste. For institutions that do not easily have access to radioisotopes, these techniques can still be instructed since the quantification by radiation detectors can be substituted by ICP-MS or ICP-AES at the expense of complicated sample dilution and more liquid waste generation. Our teaching experience over the past few years has demonstrated that students with a background in nuclear engineering generally perform radiochemical separation experiments less well than those with a background in chemistry and/or chemical engineering. In contrast, chemistry and/or chemical students typically have more difficulties in radiation detection of radioactive samples than nuclear engineering students (Figure 6). The radiochemical separation experiments discussed here can serve as a bridge between the two domains. Of note, the techniques discussed in this work by no means cover all areas of N&RC but are substantial parts of radiochemical separation. By taking advantage of radiation detection courses, N&RC courses and pertinent programs can advance and meet the deficiencies in both education and industrial settings.

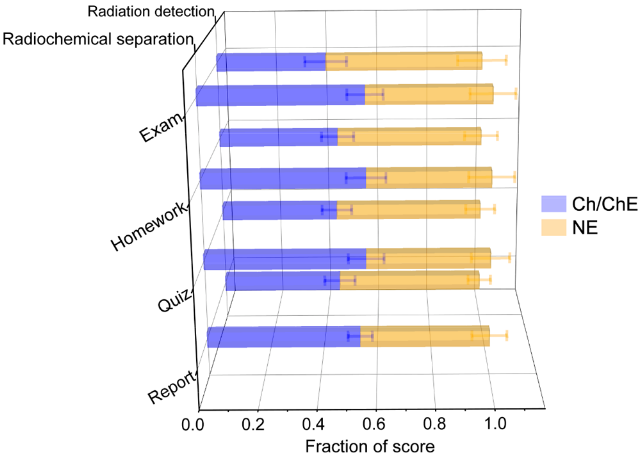

Figure 6. Comparison of the course performance of 20 students majoring in chemistry/chemical engineering (Ch/ChE) or nuclear engineering (NE). The score is normalized to 1, and a value of 0.5 indicates an equal score between Ch/ChE and NE students.

■ HAZARDS

Potential Health Hazards Encountered Are As Follows

Radiological Hazards. All isotopes used in this study, ^{60}Co, ^{63}Ni, and ^{152}Eu, are radioactive materials and should be handled only in specifically designated facilities in accordance with appropriate safety controls. The National Institute for Occupational Safety and Health (NIOSH) Hierarchy of Controls[31] was closely adhered to in order to prevent the spreading of radioactivity throughout the working area, the release of airborne radioactivity outside of the hood, and the potential contamination of the students. For the duration of all experiments, the drains were covered with landscaping fabric or similar materials, and the workbenches were covered with diaper paper. All chemicals and tools were placed in polypropylene trays lined with diaper paper. The quantity handled by the students was restricted to the bare minimum necessary to ensure that the statistical character of radioactive decay had the least possible impact on counting errors. In the LLE experiment, screw-cap vials were used to substitute the conventional large and leak-prone separatory funnels. In the precipitation experiment, a planchet held with forceps was practiced to keep a safe distance between the students and the radioactive substance. We suggest that students work in pairs using a "hot hands/cold hands" approach. One student ("hot hands") works directly with radioactive materials and is double-gloved at all times. The second student ("cold hands") performs nonradioactive work to assist his or her partner, such that no contamination is spread to clean regions. Students and graduate student instructors should conduct full swipes and surveys of the workstations and surrounding floor after each lab experiment to either ensure no contamination or immediately identify contamination.

Chemical Hazards. Mineral acids (HNO_3, HCl), organic acids (acetic acid, malic acid, and HDEHP), and organic solvents (kerosene) must be handled in a properly ventilated hood in accordance with standard operating procedures.

Physical Hazards. Radiation detection equipment poses ergonomic and electrical hazards and should be used by proper guidance.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c01193.

Experimental details, lab handouts, and exemplary gathered data (PDF, DOCX)

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Yufei Wang: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Software, Writing−original draft, review and editing. Rebecca J. Abergel: Supervision, Resources, Writing−review and editing, Funding acquisition.

Notes

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ABBREVIATIONS

Co-ppt coprecipitation.
DF decontamination factor.
EF enrichment factor.
FCV free column volume.
FWHM full width at half-maximum.
HDEHP also called D(2)EHPA,di(2-ethylhexly)phosphoric acid.
HPGe high purity germanium.
I/A/CEC ion/anion/cation exchange chromatography.
ICP-MS/AES inductively coupled plasma mass spectrometry/atomic emission spectroscopy
LLE liquid−liquid extraction.
LSC liquid scintillation counter.
N&RC nuclear chemistry and radiochemistry.
NIOSH National Institute for Occupational Safety and Health.
RR relative retention.
SF separation factor.
UC Berkeley University of California at Berkeley.

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