

PREPARATION AND CHARACTERIZATION OF VARIOUS COLUMN-FILLING MATERIALS IN ORDER TO OPTIMIZE ^{68}Ge - ^{68}Ga GENERATOR COLUMN

E Ekebaş Çavdar^{1*}, O Oktar¹, E Çantay¹, E Ergun¹, N B Ertaş¹, B Aydın¹, O Abay¹

¹Turkish Energy, Nuclear and Mineral Research Agency, Nuclear Energy Research Institute, Ankara, Turkey

*elif.ekebascavdar@tenmak.gov.tr, okan.oktar@tenmak.gov.tr

^{68}Ge - ^{68}Ga JENERATÖR KOLONUNUN OPTİMİZE EDİLMESİ İÇİN ÇEŞİTLİ KOLON DOLGU MALZEMELERİNİN HAZIRLANMASI VE KARAKTERİZASYONU

ABSTRACT:

In order to obtain ready-to-use ^{68}Ga in Positron Emission Tomography (PET) applications, the $^{68}\text{Ge}/^{68}\text{Ga}$ generator system is an ideal source and allows PET imaging in centers without cyclotrons. Radiochemical separation of Ge (mother) and Ga (daughter) radionuclide through commercial generators is carried out with columns consisted of inorganic metal oxides. In this study, commercially available tin dioxide (SnO_2), laboratory-synthesized SnO_2 , titanium dioxide (TiO_2) and zeolite as a column filling material in $^{68}\text{Ge}/^{68}\text{Ga}$ generators were used. The sorption behavior of column-filling materials as adsorbent was investigated without the use of radioactive materials. All elements, especially Ge and Ga for representing $^{68}\text{Ge}/^{68}\text{Ga}$ generator system, were performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). In addition, since these column-filling materials used in the thesis will be exposed to radiation during the shelf life of the $^{68}\text{Ge}/^{68}\text{Ga}$ generator, their radiation stability were investigated. Structural characterization studies were performed with, Raman Spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD). In order to calculate surface area and pore sizes, Brunauer-Emmett-Teller (BET) method were used. The promising results obtained in this study, calcined at 900 °C Kw_ SnO_2 would be prepared and evaluated of pilot $^{68}\text{Ge}/^{68}\text{Ga}$ generators.

Keywords: radionuclide, $^{68}\text{Ge}/^{68}\text{Ga}$ Generator, metal oxide, adsorption, Positron Emission Tomography (PET)

OZET:

Pozitron Emisyon Tomografisi (PET) uygulamalarında kullanıma hazır ^{68}Ga elde etmek için, $^{68}\text{Ge}/^{68}\text{Ga}$ jeneratör sistemi, ideal bir kaynaktır ve siklotron bulunmayan merkezlerde PET görüntülemeye olanak tanır. Ticari jeneratörlerde Ge (anne) ve Ga (kız)'nın radyokimyasal olarak ayrılması genellikle, içerisinde inorganik metal oksitlerin bulunduğu kolonlarda yapılır. Bu çalışmada ticari olarak temin edilen kalay dioksit (SnO_2), laboratuvarında sentezlenen SnO_2 , titanyum dioksit (TiO_2) ve zeolit $^{68}\text{Ge}/^{68}\text{Ga}$ jeneratörlerinde kolon dolgu malzemesi olarak kullanılmıştır. Adsorban olarak seçilen kolon dolgu malzemelerinin adsorpsiyon davranışları radyoaktif malzeme kullanılmadan incelenmiştir. $^{68}\text{Ge}/^{68}\text{Ga}$ jeneratör sistemini temsil etmek için Ge ve Ga başta olmak üzere tüm element analizleri ise İndüktif Eşleşmiş Plazma Kütle Spektroskopisi (ICP-MS) kullanılarak yapılmıştır. Kullanılan kolon dolgu malzemesi jeneratörün raf ömrü boyunca radyasyona maruz kalacağından radyasyon kararlılıkları da araştırılmıştır. Yapısal karakterizasyon çalışmaları Raman spektroskopisi, Fourier Dönüşümlü Kızılötesi Spektroskopisi (FTIR) ve X-ışını Kırınımı (XRD) ile yapılmıştır. Yüzey alanı ve gözenek boyutlarını hesaplamak için, Brunauer-Emmett-Teller (BET) metot kullanılmıştır. Bu çalışmada elde

edilen umut verici sonuçlar, 900 °C kalsine edilen Kw_SnO₂'nin pilot ⁶⁸Ge/⁶⁸Ga jeneratörlerinde hazırlanıp değerlendirilmesini sağlayacaktır.

Anahtar Kelimeler: radyonüklid, ⁶⁸Ge/⁶⁸Ga Jeneratör, metal oksit, adsorpsiyon, Pozitron Emisyon Tomografisi (PET)

1. Introduction

The ⁶⁸Ge/⁶⁸Ga generator system has been investigated for almost fifty years and emerged as excellent source to provide ⁶⁸Ga in clinical positron emission tomography (PET) application owing to its simplicity and convenience to use in any center without an on-site cyclotron (Bao & Song, 1996; Romero & Morcillo, 2017; Rösch, 2013).

The parent radionuclide, ⁶⁸Ge, the physical half-life of 270.8 days and an excellent positron emitter, allows one to use the generator for a long period, potentially over one year, while the daughter radionuclide, ⁶⁸Ga, with the physical half-life of 68 min, provides the pharmacokinetics of many peptides and small molecules thanks to rapid diffusion, localization at the target and fast blood clearances. Therefore, patients can receive low radiation dose (Romero, et al., 2020).

The development of the first radionuclide generators and the beginning of clinical applications date back more than 60 years. Among the generators such as ¹⁸⁸W/¹⁸⁸Re, ⁸²Sr/⁸²Rb, ⁹⁹Mo/^{99m}Tc currently in use generators have achieved great commercial success worldwide. The applications of generator based on ⁶⁸Ga is used for not only detection by radiolabeling molecular tumor, especially neuroendocrine tumors, targeting vectors, such as protein or peptides, but also diagnosis of various cancers (Rösch, 2013; Saha, 2010)

The working principle of these generators depends on mainly on a chromatographic column to separate the parent and daughter radionuclides, selectively. The parent radionuclide is adsorbed on column support materials, called as adsorbent, and the daughter radionuclide is subsequently and selectively eluted from the column using an elution agent while the parent radionuclide remains on there. These column-filling materials have been developed over the years as either organic or inorganic, depending on ⁶⁸Ga in acceptable pH, the radioactive concentration, acceptable breakthrough of ⁶⁸Ge, the presence of potential metal ions impurities in the elution. The examples of ⁶⁸Ge/⁶⁸Ga generator systems containing organic column-filling materials are cation and anion exchange materials based on phenolic/N-methylglucamine group, silica derivatives, pyrogallol formaldehyde (Bao & Song, 1996; Romero & Morcillo, 2017; Ondrák Fialová, et al., 2023).

Thanks to chemical stability and higher capacity, organic column-filling materials are most popular ion exchanger, however some crucial properties, high selectivity and radiation stability on repeated elutions over a prolonged period of time, play important role in these generator systems. Radiation stability reduces the capacity of organic material with high selectivity. In addition, organic materials degraded by radiation reduce the chemical purity, which is especially important in the radiopharmaceuticals industry (Bao & Song, 1996; Neirinckx, et al., 1982; Ondrák Fialová, et al., 2023; Aardaneh & van der Walt, 2006; Rösch, 2012).

Inorganic adsorbents, on the other hand, have been developed to use in different areas of nuclear technology (such as separation of fission products from spent fuel, deionization of reactor cooling water at high temperatures) thanks to their high radiation resistance compared to organic adsorbents (IAEA, 2019). In addition, inorganic ion exchanger can be customizable to separate parent and daughter radionuclides with these properties under thermal and chemical conditions. The examples of ⁶⁸Ge/⁶⁸Ga generator systems containing inorganic column-filling materials are alumina (Al₂O₃), tin oxide (SnO₂),

titanium oxide (TiO₂), cerium oxide (Ce₂O), zirconium oxide (ZrO₂). The commercially generator based on inorganic columns are TiO₂ and SnO₂. These are available by Cyclotron Co. Ltd (Russian Federation), Eckert & Ziegler (Germany), Pars Isotope Company (Iran) and by ithemba LABS (Republic of South Africa), respectively (Romero, et al., 2020). These inorganic adsorbents with a hydrated amorphous structure have some physical and chemical disadvantages. The physical and chemical deformation can cause the structure of the column filling material to crack and block the flow of daughter radionuclide during the elution process. It also leads to the presence of potential metal ions impurities in the elution and the breakthrough of ⁶⁸Ge (Romero, et al., 2020; Chakravarty, 2011; IAEA, 2019).

In this present work, to avoid these disadvantages of amorphous inorganic column-filling materials, the different metal oxides (such as Ti and Sn) and zeolite have been exposed to calcinations process. Their adsorption behaviors were performed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for representing ⁶⁸Ge/⁶⁸Ga generator system without the use of radioactive materials and structural properties have been demonstrated and evaluated.

2. Experimental

Materials

All chemicals were used as received without further purification. The reagents, tin(II) chloride (SnCl₂) and glucose (C₆H₁₂O₆) obtained from Merck, ammonium carbonate ((NH₄)₂CO₃) from Honeywell, analytical grade reagents (Metallic gallium, metallic germanium and yttrium (99.999%)) and nitric acid (HNO₃, 37%), hydrochloric acid (HCl, 65%) - from Merck, were used in this study. Deionized water from a Milli-Q ultrapure water system (Millipore Corp.) was used. The studied zeolite namely ZSM-5 (SiO₂/Al₂O₃) were obtained by Zeolyst (coded as ZSM-5), titanium dioxide, anatase, with particle size around 200 nm, supplied by Sigma Aldrich (coded as TiO₂); and titanium dioxide powder in the mix anatase-rutile form was obtained by oven heating at 600 °C (coded as TiO₂-600) and rutile form at 900 °C (coded as TiO₂-900). The tin oxides were: SnO₂ synthesized with mechanochemical method by Chakravarty (2016) (coded as Gl_SnO₂) and SnO₂ nano-powder obtained by Sigma Aldrich (coded as Al_SnO₂). These tin oxides were calcinated at two different temperature (coded as Gl_SnO₂_600, Gl_SnO₂_900, Al_SnO₂_600 and Al_SnO₂_900). The same procedure was applied to Al_SnO₂. In addition, tin dioxide powder commercially available as high purity metastannic acid by Keeling & Walker (coded as Kw_SnO₂) and Kw_SnO₂ heat-treated at 600 and 900 °C for 3 h in an electric furnace and allowed to cool down without temperature control (coded as Al_SnO₂_600 and Al_SnO₂_900 respectively), were also studied. All column-filling materials were sifted through a 150 μm stainless steel sieve for an efficient column operation (Romero & Morcillo, 2017; Ekebas Cavdar, 2022).

Determination of the distribution ratios (*K_d*) of the Ge and Ga

In order to separate Ga and Ge on the different column-filling materials, distribution ratios (*K_d*) of Ge and Ga were investigated experimentally at different concentrations of hydrochloric acid (0.1M-1,5M HCl) by batch equilibration method under static. 20 mL of different concentration of HCl solution and about 200 mg of each column-filling materials were added to each flasks. 100 ppm stock Ge-Ga solution was prepared and 0,1 mL of this stock solution was added to them (Fig.1). The mixtures were shaken for 3 h at room temperature and filtered through 0.45 μm Teflon filter. Aliquots of 5 mL were measured analyzed by ICP-MS. The *K_d*, expressed as mL/g, were calculated using the following expression (Davies, 2012; Ekebas Cavdar, 2022):

$$K_d = \frac{[C_{solid}]}{[C_{solution}]}$$

[C_{solid}] → concentration in the solid at equilibrium (μg/g)

$[C_{\text{solution}}]$ → concentration in the solution at equilibrium ($\mu\text{g/ml}$)

Fig.1. Experimental setup in order to determine K_d under static test conditions



Determination of the sorption capacity

The sorption capacity of column-filling materials was determined by batch equilibration method under static conditions. 10 mg of each column-filling materials, 20 mL of different concentration of HCl solution, 0,1 mL of 100 ppm stock Ge-Ga stock solution were added to each flasks. The mixtures were shaken for 3 h at room temperature and filtered through 0.45 μm Teflon filter. Aliquots of 5 mL were measured analyzed by ICP-MS (Romero & Morcillo, 2017; Davies, 2012; Ekebas Cavdar, 2022).

Germanium adsorbed in the metal oxide, expressed as mg/g, was calculated using the following expression:

$$q_e = \frac{V [C_0 - C_e]}{m}$$

q_e → the capacity of adsorbent (mg/g)

C_0 → the initial concentration of adsorbent (mg/L)

C_e → the final concentration of adsorbent (mg/L)

V → the volume of solutions (mL)

m → the mass (g) of the oxide

The K_d results from static experiments may change under dynamic experimental conditions, so the same experiments were carried out under dynamic conditions with columns representing the generator column. Therefore, this study aimed to determine the possible breakthrough amount of Ge by loading only Ge from column (Ekebas Cavdar, 2022).

Determination of the breakthrough of Ge^{4+}

Using the experimental parameters (the concentration of HCl and the calcination temperature) determined under static experimental conditions, the possible breakthrough amount of Ge^{4+} from the column by loading only Ge into the under dynamic (column) experimental conditions was examined. The breakthrough of Ge^{4+} was calculated by performing Ge analysis in the elution solution. The experimental setup prepared for the column studies is shown in Fig.2.

The polypropylene (PP) columns (2.5ml) with dimensions of $5 \times 0.8 \times 1.0$ cm (height $\times$ inner diameter $\times$ outer diameter) with $10\mu\text{m}$ filters at the inlets and outlets were used. The column was filled

with 2 g of selected metal oxide and compressed in a vibrator to prevent any space between the particles. In order to remove possible small particles, the column was washed with 30 ml of acid at the working concentration (0.25 ml/min) through the column with a peristaltic pump. The stock Ge solution at different acid concentrations was loaded into the column. To observe possible breakthrough of Ge from the column, it was washed and the eluate with different concentration of HCl is analyzed by ICP-MS (Ekebas Cavdar, 2022).

Fig.2. Experimental setup in order to determine the breakthrough of Ge from column



Characterization of oxides

Structural characterization of metal oxides used as column filling material was made by Fourier Transform Infrared Spectrometer (FTIR), Raman spectroscopy, and X-ray Diffraction (XRD). Additionally, the surface area and pore sizes of metal oxides were calculated by Brunauer–Emmett–Teller (BET) analysis.

The column-filling materials were measured in the range of $525\text{--}4000\text{ cm}^{-1}$ with Thermo Nicolet 8700 FT-IR spectrometer, and in the range of $101\text{--}3434\text{ cm}^{-1}$ with Thermo Scientific Nicolet Omega XR Dispersive Raman spectrometer. X-ray diffraction patterns of the samples were analysed in the range of $10^{\circ}\text{--}80^{\circ}$ (2θ) with a Bruker D8 Advance X-ray Diffractometer operating at 40 kV and 30 mA using Cu- $K\alpha$ radiation ($\lambda = 1.5406\text{ \AA}$). The surface area and pore sizes of metal oxides were calculated by the Brunauer, Emmett and Teller (BET) method using nitrogen gas adsorption at liquid nitrogen temperature. BET analysis was carried out with the Quantachrome brand AUTOSORB-1. Prior to analysis, 0.1-0.4 gram samples were degassed at 200°C for 2 hours, and the specific surface area was determined by performing multi-point BET analysis with N_2 gas adsorption at liquid nitrogen temperature (Ekebas Cavdar, 2022).

3. Results and discussion

Determination of the distribution ratios (K_d) of the Ge and Ga

The adsorption behavior of parent (Ga) and daughter (Ge) radionuclides on a particular adsorbent depends on the distribution coefficients of that radionuclide. The greater the difference between the distribution coefficients of two radionuclides leads to the greater the efficiency of radiochemical separation. The amount of daughter radionuclide in the eluate (low k_d) should be high and the breakthrough of parent radionuclide should be low in there. For this purpose, the K_d of Ga and Ge for

each column-filling materials calcined at different temperatures were determined under static experimental conditions at 8 different HCl concentrations.

The distribution coefficients of the the column filling material, 'Gl_SnO₂' synthesized by the mechanochemical method with different calcination temperatures. The adsorption of Ga is higher at low acid concentration (0.01M HCl) at both calcination temperatures. While a decrease in Ga adsorption is observed with increasing acid concentration, the same trend is observed for Ge. Low distribution ratios of Ge indicates that Ge is not adsorbed by the adsorbent (Ekebas Cavdar, 2022).

Table 1. The distribution coefficients of Gl_SnO₂

The concentration of acid (M)	Gl_SnO ₂ _600		Gl_SnO ₂ _900	
	K _d Ga	K _d Ge	K _d Ga	K _d Ge
0,01	996,5	203,4	1261,6	243,2
0,05	35,3	120,0	29,3	173,5
0,1	9,9	90,4	9,1	185,7
0,25	5,4	133,8	1,9	86,0
0,5	3,0	86,1	0,9	57,5
0,75	6,9	84,8	2,2	65,0
1,0	4,5	78,3	2,3	64,9
1,5	5,2	49,3	1,0	60,6

In table 2, K_d of SnO₂ samples obtained from two different company were calculated before calcination (Kw_SnO₂_nc and Al_SnO₂_nc) and after calcination at two different temperatures. In both samples, adsorptions of Ge and Ga are high at low acid concentrations (<0.05M), regardless of the calcination temperature. While there was a dramatic decrease in the K_d of Ga in both samples with increasing acid concentration, there was no significant decrease in the K_d Ge at all temperatures with increasing acid concentration. However, it is clearly seen from the difference in K_d that the calcination process increased Ge adsorption in the 'Kw_SnO₂' sample. It is seen in the results that the highest K_d(Ge)/K_d(Ga) ratio for 'Kw_SnO₂' and 'Al_SnO₂' is at 0.5 M and 0.25 M HCl concentration.

Table 2. K_d of Kw_SnO₂ and Al_SnO₂ before calcination and after calcination at two different temperatures.

The concentration of acid (M)	Kw_SnO ₂ _nc		Kw_SnO ₂ _600		Kw_SnO ₂ _900	
	k _d Ga	k _d Ge	k _d Ga	k _d Ge	k _d Ga	k _d Ge
0,01	631,7	22525,0	84722,9	62921,0	45637,6	39846,4
0,05	555,5	20869,0	420,0	54610,8	241,0	40575,2
0,1	50,8	15470,9	68,1	39444,3	54,6	30131,6
0,25	13,7	2463,5	18,2	44121,7	8,0	23164,6
0,5	2,9	1552,6	1,2	38409,4	3,2	26658,4
0,75	0,3	1608,4	1,2	39290,1	3,5	22500,3
1,0	3,1	3130,0	4,9	43245,4	6,9	29368,6
1,5	17,7	2008,5	2,7	17813,7	8,8	12903,7
The concentration of acid (M)	Al_SnO ₂ _nc		Al_SnO ₂ _600		Al_SnO ₂ _900	
	K _d Ga	K _d Ge	K _d Ga	K _d Ge	K _d Ga	K _d Ge
0,01	20939,9	71502,3	31248,9	70133,5	26406,9	66926,9
0,05	260,0	67479,4	302,0	54723,8	326,7	60277,0

0,1	43,7	65510,2	47,1	63595,6	60,1	57218,3
0,25	7,4	61530,0	9,1	61397,4	10,9	50332,3
0,5	3,4	40812,9	3,7	59709,3	2,6	49159,3
0,75	3,4	68250,1	3,8	39579,9	10,2	47106,3
1,0	3,3	71421,5	6,6	75971,2	4,8	36435,7
1,5	4,5	33543,0	11,1	33797,9	9,1	30166,9

The distribution ratios of Ge and Ga for the 'ZSM-5' sample, as commercially available, at different acid concentrations are given in table 3. The K_d (Ge)/ K_d (Ga) ratio for 'ZSM-5' was not as high as the ratios found in the other two commercial SnO_2 samples at low acid concentrations.

Table 3. Distribution ratios of Ge and Ga for ZSM-5

The concentration of acid (M)	ZSM-5	
	K_d Ga	K_d Ge
0,01	1442,0	5071,0
0,05	41,3	10965,8
0,1	26,6	11554,2
0,25	30,8	12478,4
0,5	36,4	14390,6
0,75	32,9	14603,4
1,0	40,5	16622,7
1,5	34,5	11949,9

TiO_2 has three types of crystallographic structures: anatase, rutile and mix anatase-rutile (Table 4). The most stable phase is the rutile phase, while the anatase and mix anatase-rutile phases are metastable and unstable, respectively. Metastable phases of TiO_2 undergo phase transformation at high temperatures. The anatase phase turns into the rutile phase above 700-800°C (Rzaij & Abass, 2020; Yan, et al., 2017). Temperature-dependent phase transitions of TiO_2 changing its crystal structure directly affected distribution ratios of Ge and Ga. At high calcination temperature, the adsorption of Ge is extremely low. Samples in mix form at room temperature and calcined at 600 °C showed more adsorption capacity of Ge.

Table 4. Distribution ratios of TiO_2 before calcination and after calcination at two different temperatures

The concentration of acid (M)	TiO_2_{nc}		TiO_2_{600}		TiO_2_{900}	
	K_d Ga	K_d Ge	K_d Ga	K_d Ge	K_d Ga	K_d Ge
0,01	158,2	8629,6	270,9	20926,9	162,5	359,9
0,05	4,3	3381,2	7,0	10832,0	5,8	246,2
0,1	3,3	2780,2	2,8	5701,4	2,4	146,4
0,25	1,1	1633,9	2,7	3902,5	1,3	108,0
0,5	5,0	845,0	6,0	2080,6	4,4	95,7
0,75	3,5	641,0	4,9	1650,3	4,2	81,5
1,0	4,6	503,8	2,0	1387,6	3,8	70,6
1,5	9,2	415,3	13,1	1107,0	10,6	78,8

The distribution ratios of Ge and Ga calculated for different column-filling materials provides the determination of the acid concentration on the generator column where Ge is adsorbed mostly and Ga

can be eluted highly. According to the results obtained, it is showed that the suitable HCl concentration for the SnO₂ samples studied is 0.25 M and 0.5 M. Similarly, when we look at the K_d calculated at these concentrations, it is seen that the 'KW_Sn' and 'Al_Sn' samples have the highest adsorption capacity of Ge. In ZSM-5 and TiO₂ samples, the maximum adsorption occurred at 0.1 M HCl.

The adsorption mechanism between Ge and Ge on the synthesized and commercially column-filling materials can be explained by the fact that the metal oxides consist of discrete metal oxide clusters coated with surface hydroxyl groups. Between 0.01 M and 1.5 M HCl acid, pH decreases while acidity increases. At dilute acid concentrations (as pH increases) germanium become negative. ([GeO(OH)₃]⁻, [GeO₂(OH)₂]²⁻ and [Ge(OH)₄]₈(OH)₃]³⁻). The fact that metal oxides have a positively charged surface and their affinity for negatively charged Ge ions is due to their electrostatic attraction. In this mechanism, Ga exists as Ga³⁺ and therefore an almost complete elution can be achieved due to the electrostatic repulsion of the positively charged Ga³⁺ ion from the positively charged surface of the metal oxides (Chakravarty, 2011).

Determination of the sorption capacity

Considering the calculated K_d, the adsorption capacities of Ge⁴⁺ on the column-filling materials studied at different calcination temperatures and acid concentrations (HCl). The high adsorption capacities obtained for Kw_SnO₂ and ZSM-5 samples indicate that surface interaction occurs between Ge⁴⁺ and column-filling materials. In line with the K_d and q_e results obtained, it was decided to determine the breakthrough of Ge⁴⁺ under dynamic experimental conditions with Al_SnO₂_900, Kw_SnO₂_600, Kw_SnO₂_900, TiO₂_600 and ZSM-5 materials.

Table 5. The sorption capacity of column-filling materials at different calcination temperatures with acid concentration

Column-filling materials	Calcination Temperatures	Acid Concentrations (M)	Micrograms that 1 g of column-filling materials can adsorb
Keeling & Walker_SnO ₂	600°C	0,05	613
		0,1	640
		0,25	540
		0,5	533
	900°C	0,05	501
		0,1	475
		0,25	426
		0,5	398
Aldrich_SnO ₂	600°C	0,05	477
		0,1	482
		0,25	453
		0,5	445
	900°C	0,05	470
		0,1	443
		0,25	423
		0,5	418
TiO ₂	600°C	0,05	350
		0,1	280
		0,25	212
		0,5	179
ZSM-5	nc	0,05	680
		0,1	839
		0,25	784

Determination of the breakthrough of Ge^{+4}

Using the experimental parameters (acid concentration and calcination temperature) determined under static experimental conditions, the breakthrough of Ge^{+4} capacity of metal oxide samples under dynamic (column) experimental conditions was examined. The breakthrough of Ge^{+4} was calculated by Ge analysis in the eluate solution. The test results performed under dynamic conditions are given in Table 6. The amount (nanogram) of Ge in the eluate from 'ZSM-5', 'Al₂SnO₂_900' and 'TiO₂' samples is higher than other column-filling materials. Among other samples, the lowest breakthrough of Ge^{+4} in the was observed in 'Kw_SnO₂' samples.

Table 6. The breakthrough of Ge^{+4} in the eluate solutions

Column-filling materials	The amount of column-filling materials (gram)	The amount of spiked Ge (ppm)	The amount of Ge (ng) In eluate
Al ₂ SnO ₂ _900	2,0	10,159	44,522
Kw_SnO ₂ _600	2,0	10,367	4,117
Kw_SnO ₂ _900	2,0	11,140	4,035
TiO ₂ _600	1,3	9,962	57,760
ZSM-5	1,5	9,968	43,617

Characterization of oxides

Determination of radiation stabilities of column-filling materials and column

Since the column filling material prepared for use in the $^{68}\text{Ge}/^{68}\text{Ga}$ generator will be exposed to radiation throughout the shelf life of the generator, their radiation stability must be investigated. The estimated amount of activity and its spatial distribution were obtained from calculations based on FLUKA MonteCarlo code. Polypropylene (PP) columns with dimensions of 5 x 0.8 x 1.0 cm were taken as basis in the calculations. It was calculated that the absorbed dose resulting from 1.85 GBq (50 mCi) ^{68}Ge loading corresponded to approximately 2 MGy. For this purpose, all metal oxides and column-filling materials used in the study were irradiated in the NÜKEN Gamma Irradiation Facility. Due to the low dose rate in the gamma irradiation facility and time constraints, these studies were limited to a total dose of 1000 kGy (2 kGy/hour). The crystal structures of all irradiated metal oxides compared to their unirradiated states in respect to XRD, FTIR and Raman.

BET analysis was performed to investigate the surface area, pore size, and pore size distribution (nano, meso, and macro) of the synthesized and commercially available column-filling materials. According to the BET results by physical adsorption of a nitrogen gas on the surface of the solids, all of them have a mesopore structure. The particle size and surface area decreased at high calcination temperatures. Since the space between the particles decreased with the high temperature, uniform stacking occurred between the particles. This uniform stacking in the crystal structure explains the decrease in volume and BET area. It shows that it plays an important role in the radiochemical separation. The holes in the crystal structure reduce the interaction of Ge^{4+} and Ga^{3+} ions so that it brings about low adsorption behavior.

BET surface areas of all SnO₂ and TiO₂ decrease as the calcination temperature increases. Due to the cage structure of ZSM-5, it has a high surface area of 341.95 m²/g (Table 7).

Table 7. The results of BET analysis

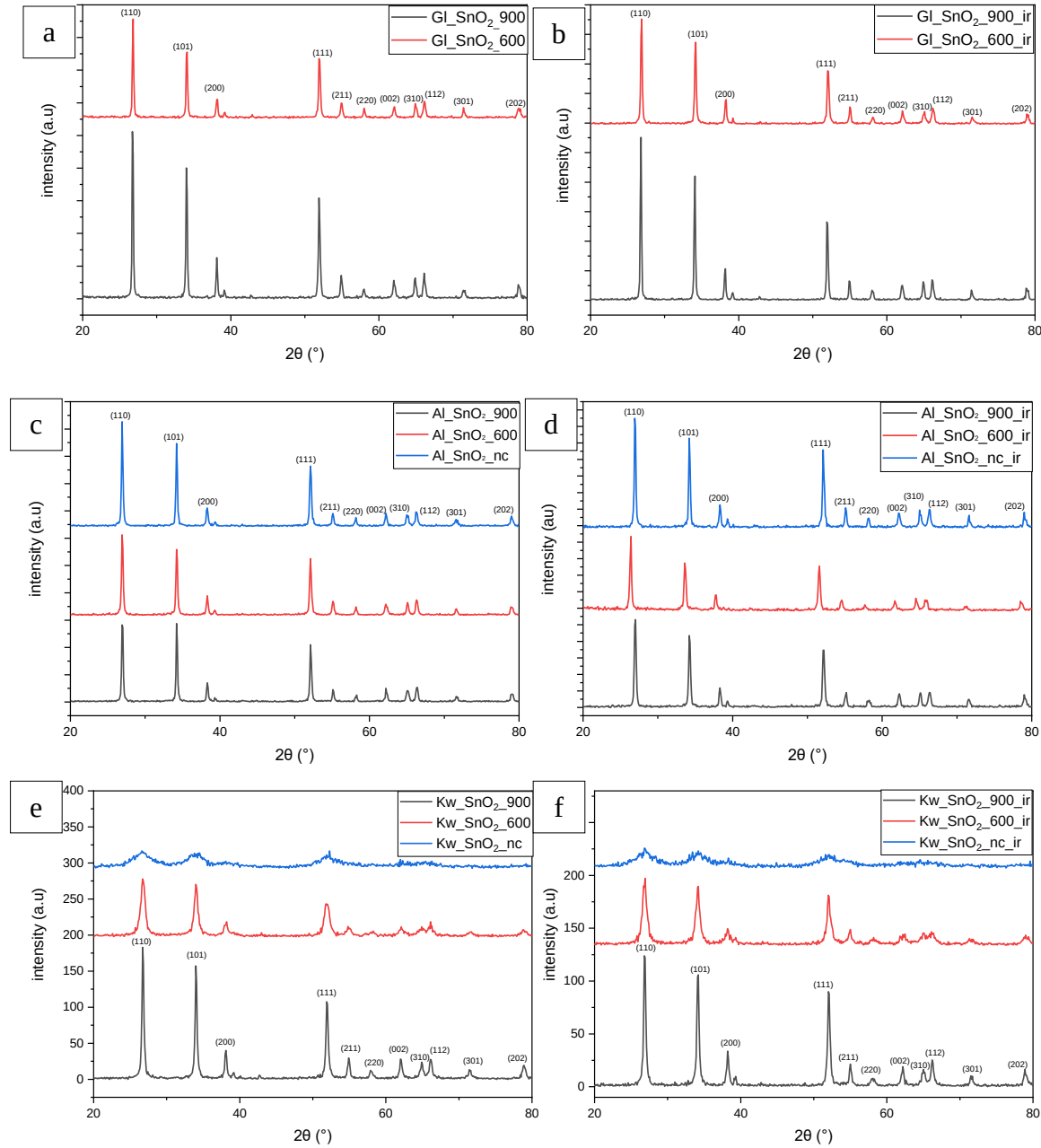
Sample	BET Area m ² /g	Average Pore Size Å	Total Volume cc/g
Glikoz_SnO ₂ _600	5,61	19,84	2,78E-03
Glikoz_SnO ₂ _900	2,77	19,49	1,35E-03
Kw_SnO ₂ _nc	144,90	20,47	6,38E-02
Kw_SnO ₂ _600	21,39	19,97	1,07E-02
Kw_SnO ₂ _900	8,37	19,45	4,07E-03
Al_SnO ₂ _nc	8,91	20,22	4,51E-03
Al_SnO ₂ _600	8,77	20,10	4,41E-03
Al_SnO ₂ _900	8,29	20,17	4,18E-03
TiO ₂ _nc	59,18	19,85	2,94E-02
TiO ₂ _600	44,30	19,94	2,21E-02
TiO ₂ _900	3,93	19,23	1,89E-03
ZSM-5	341,95	20,77	1,41E-01

By comparing the diffraction patterns of each material at two different calcination temperatures, information about the crystal structures of the materials was carried out by XRD. The XRD pattern obtained for ZSM-5 zeolite shows that the peaks are not narrow and sharp which indicated holes in their structure and their large surface areas. Characteristic bands of zeolites at between 1215 cm⁻¹ and 540 cm⁻¹ were exhibited by the Fourier transform infrared (FTIR) spectrum. The most prominent band detected in the Raman spectrum of the ZSM-5 crystal is the O atom vibration in the T-O-T (T: Si, Al) bond plane at 385cm⁻¹. Other observed bands are in the band range of 450-480 cm⁻¹ and belong to Si-O-Si stretching, O-Si-O (Al) bending and Si-O bending modes.

The diffraction patterns of 'Gl_SnO₂', 'Al_SnO₂' and 'Kw_SnO₂' samples were compared with the JCPDS-01-0657 card, respectively. The effects of different calcination temperatures on the crystal structure of the sample were investigated (Chakravarty, et al., 2016) (Karthik, et al., 2012). The first visible difference is that sharper peaks were obtained as the calcination temperature increased in the 'Kw_SnO₂' samples. This indicates that the crystallinity of the metal oxide increases with the increase in calcination temperature. This increase also explains the decrease in the BET area (Table 7).

It is also clear from the XRD data that the peaks gradually became sharper and the full width half-maximum (FWHM) decreases with an increasing the calcination temperature of tin oxides. Crystal size and half-height peak width are inversely proportional to each other. Broad peaks have very low crystal size; This corresponds to an undesirable situation. Narrow peaks result in large single crystal regions in a polycrystalline material (Çetin, 2011). No change was observed in the crystal structures of all irradiated metal oxides compared to their unirradiated states. Radiation caused polypropylene which is used in Ge/Ga generator to harden by affecting the cross-links in its structure (Han, et al., 2004).

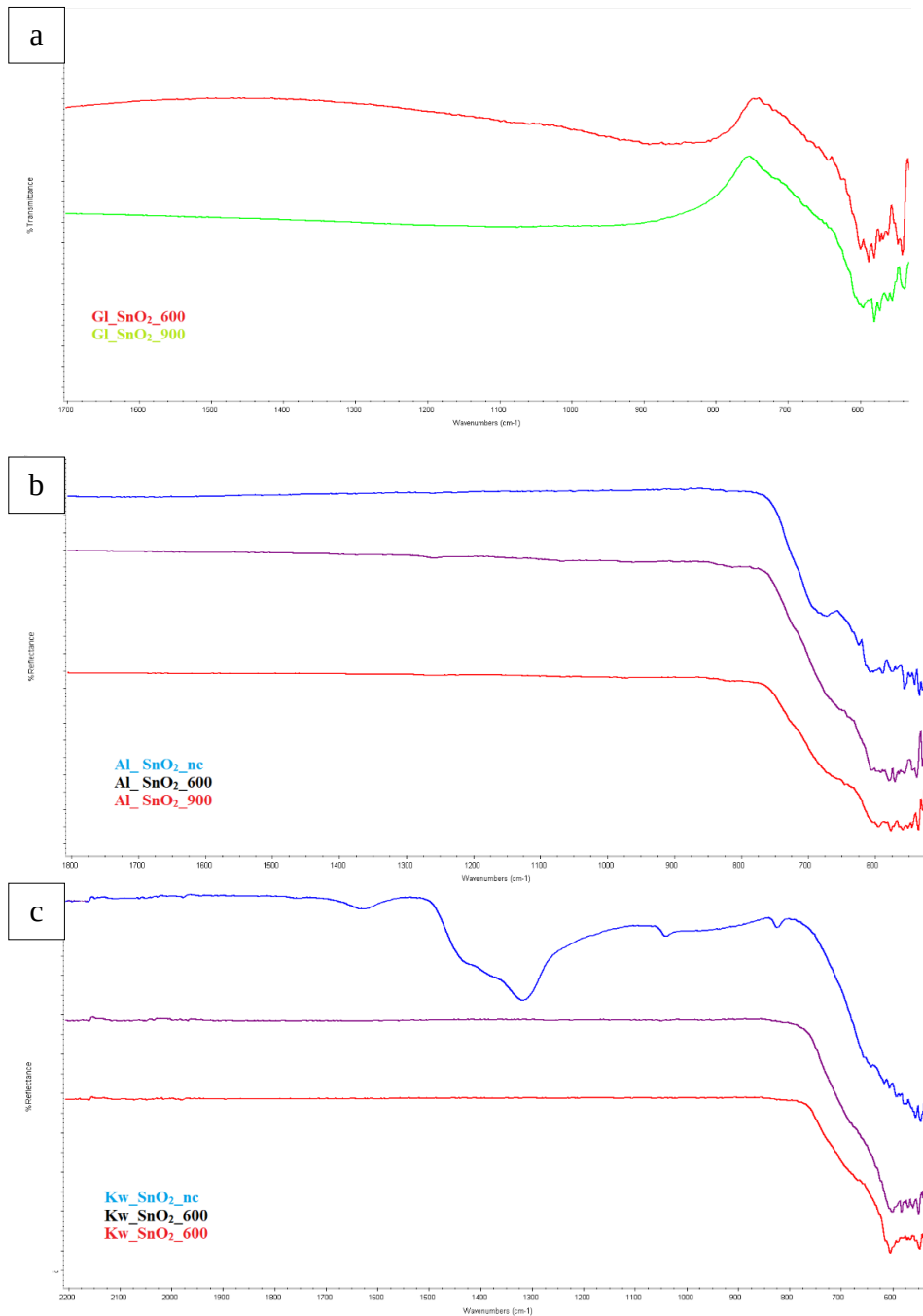
Fig 3. Diffraction patterns of non-irradiated (a,c,e) and irradiated (b,d,f) for “Gl_SnO₂”, “Al_SnO₂” and “Kw_SnO₂” samples



The FT-IR spectra of synthesized SnO_2 at different calcination temperatures (600°C and 900°C) can be explained by the Sn–O–Sn and Sn–OH stretching and Sn–O stretching modes, respectively. As the calcination temperature increases, the peaks at approximately 620 and 540 cm^{-1} become stronger and weaker, respectively. The broad peaks observed around 1630 cm^{-1} in the FTIR spectra of Kw_SnO_2 belongs to the O–H bending vibration. These bands were attributed to hydroxyl group stretching of surface water.

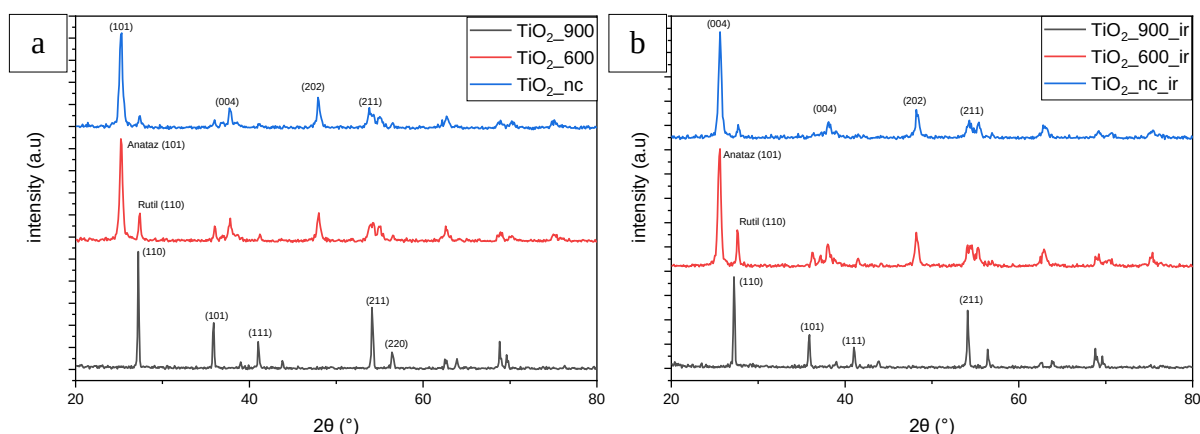
The A2g, A1g, B2g Raman active modes of another SnO_2 , are observed in the ranges of 800–780 cm^{-1} , 650–650 cm^{-1} and 490–470 cm^{-1} , respectively. A1g and B2g modes are related to the stretching and contraction vibration modes of Sn–O bonds. The broad peaks at 1600–1400 cm^{-1} of the GI_SnO_2 600 and GI_SnO_2 900 samples originate from glucose, and the intensity of the peaks decreases with the calcination temperature. The high temperature caused the breakdown of glucose. The peak in the range of 1200–1100 cm^{-1} observed in the Kw_SnO_2 nc sample is due to the hydrate form of SnO_2 (Fig4) (Bhardwaj & Mohapatra, 2015).

Fig 4. FTIR peaks of the SnO₂ sample a) Gl_SnO₂ b) Al_SnO₂ c) Kw_SnO₂ at different calcination temperature



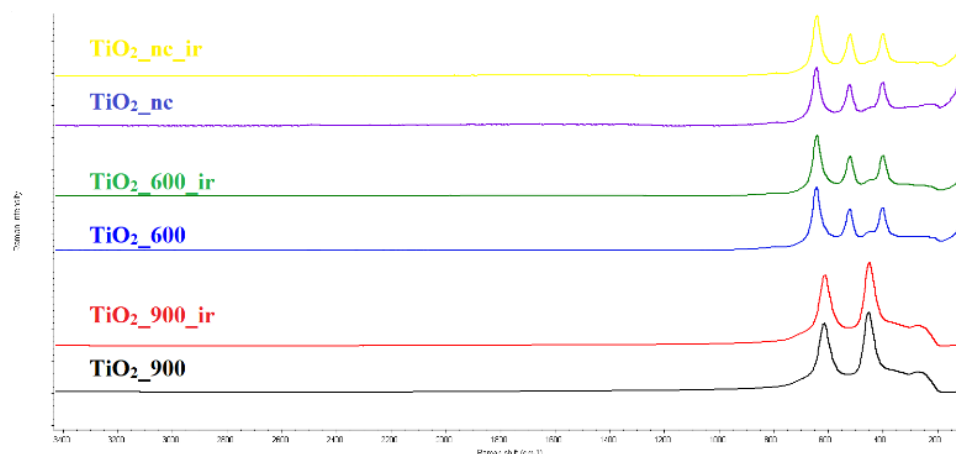
Commercially purchased titanium oxide is in the anatase form (JCPDS 21-1272) and it was observed patterns that it turned into the rutile form (JCPDS 21-1276) when calcined at 900°C. TiO₂ calcined at 600°C is a mixture diffraction pattern and it exists in two different phases because each 'phase' produces a unique diffraction pattern (Buwa, 2014).

Fig 5. Diffraction patterns of non-irradiated (a) and irradiated (b) TiO₂ samples



Phase changes in the TiO_2 with calcination temperatures were investigated using FT-IR spectroscopy. The bands observed in the $800\text{--}400\text{ cm}^{-1}$ region belong to Ti–O and Ti–O–Ti. The bands for TiO_2 in the anatase form are in the range of 540 , 585 , and 610 and for the rutile form in the range of 520 and 580 cm^{-1} (el-sherbiny, et al., 2014). The peaks in Raman spectrum of TiO_2 obtained as a result of different calcination temperatures is obtained at $400\text{--}700\text{ cm}^{-1}$ and they are related to Ti–O stretching and Ti–O–Ti bridge modes. TiO_2 ($\text{TiO}_2\text{_{nc}}$) in anatase form has three characteristic Raman active modes at 400 , 520 and 648 cm^{-1} (B_{1g} , A_{1g} and E_g symmetries), respectively. On the other hand, TiO_2 calcined at 900°C ($\text{TiO}_2\text{_{900}}$), which was in rutile form, exhibited characteristic stress peaks at 450 and 610 cm^{-1} , corresponding to E_g and A_{1g} symmetries, respectively (Challagulla et al., 2017).

Fig 6. Raman spectrum of irradiated and non-irradiated TiO_2 sample at different calcination temperatures



4. Conclusion

In this study, the SnO_2 , prepared by mechanochemical synthesis and commercially available metal oxides (TiO_2 , SnO_2 and zeolite) as a column filling material in the $^{68}\text{Ge}\text{--}^{68}\text{Ga}$ generator was investigated. These column-filling materials was calcinated with two different temperatures, characterized by using different techniques and examined their adsorption behaviors as a means of separating Ga and Ge. It was concluded that the process of calcinations provides their crystalline materials of great purity, distribution of coefficient of Ga and Ge in HNO_3 , sorption capacity of them. Ion exchange studies carried out with them obtained under acidic conditions. The distribution coefficients of Ge and Ga were determined in static experiments using different concentration of HCl ($0.01\text{--}1.5\text{M}$). Metal oxides with the highest ratio of $K_d^{68}\text{Ge}$ to $K_d^{68}\text{Ga}$ are $\text{Kw_SnO}_2\text{_{600}}$, $\text{Kw_SnO}_2\text{_{900}}$, $\text{Al_SnO}_2\text{_{600}}$, $\text{Al_SnO}_2\text{_{900}}$, TiO_2 and ZSM-5. Under static experimental conditions, the adsorption capacities (q_e) of Ge^{4+} of each

of these metal oxides were calculated at different concentrations of HCl (0.05-0.5M). It is observed that the greater the difference between the distribution coefficients and adsorption capacities of ^{68}Ge and ^{68}Ga radionuclides, the greater the efficiency of radiochemical separation. While the maximum adsorption of Ge^{4+} and elution of Ga^{3+} in ZSM-5 and TiO_2 samples occurs at 0.1 M HCl, 0.5 M HCl is required for SnO_2 .

The breakthrough of Ge^{4+} in five different column-filling materials was examined under dynamic experimental conditions by establishing a column setup. According to the data obtained from the experiments, 'Kw_ SnO_2 _900', which has a high Ge^{4+} adsorption capacity, and a low breakthrough of Ge^{4+} with a high K_d Ge and K_d Ga ratio, can be selected as column filling material to produce ^{68}Ga in $^{68}\text{Ge}/^{68}\text{Ga}$ generators. It was observed that 'ZSM-5' had a high affinity for both radionuclides, and it was thought that it could be used as a 'molecular sieve or waste storage' in other studies, although not in generator systems.

Analyzes of characterization for column-filling materials were performed with different characterization techniques (BET, XRD, FTIR and Raman). These characterization studies explained the reasons why the column filling material used in the generator system has high adsorption properties. According to BET results, a decrease in pore size was observed with the calcination process applied to the samples. Since the space between the particles decreased with the high temperature, denser stacking occurred between the particles. This frequent stacking explains the decrease in volume and BET area and is evidence that it plays an important role in the realization of radiochemical separation.

It is proven that the crystallinity increases with the data obtained from the XRD spectra shows that the crystal size of metal oxides increases with temperature. FTIR and Raman spectra provides information about the molecular structure of metal oxides. The calcination process leads to minor differences in all metal oxides except 'Kw_ SnO_2 ' samples. The biggest visible difference is that the O-H band of the water crystal seen in the 'Kw_ SnO_2 ' samples disappears thanks to the calcination process (600°C and 900°C). Column-filling materials used in generator systems are exposed to radiation during the shelf life of the generator and these materials must be resistant to the radioactivity that occurs during repeated elutions. In the characterization tests performed before and after irradiation, it was seen that all metal oxides had the necessary radiation resistance. Only a small amount of hardening of the column was detected due to the effect of radiation. Therefore, if generator filled with tin oxide (Kw_ SnO_2 _900) is produces as a prototype, polyetheretherketone (PEEK) and borosilicate glass column, which is known to have high radiation resistance, can be used instead of polypropylene column.

5. Acknowledgements

The research carried out at the Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Nuclear Energy Research Institute is a part of the studies within the scope of the dissertation and was fully supported by TENMAK.

References

- Aardaneh, K. & van der Walt, T. N., 2006. Ga 2O_3 for target, solvent extraction for radiochemical separation and SnO_2 for the preparation of a $^{68}\text{Ge}/^{68}\text{Ga}$ generator. *Journal of Radioanalytical and Nuclear Chemistry*. 268 (1), pp. 25-32.
- Bao, B. & Song, M., 1996. A new $^{68}\text{Ge}/^{68}\text{Ga}$ generator based on CeO_2 . *Journal of Radioanalytical and Nuclear Chemistry*. 213, p. 233-238.

- Bhardwaj, N. & Mohapatra, S., 2015. Fabrication of SnO₂ three dimensional complex microcrystal chains by carbothermal reduction method. *Advanced Materials Letters*. 6 (2), pp. 148-152.
- Buwa, S., 2014. *Production and Evaluation of a TiO₂ based ⁶⁸Ge/⁶⁸Ga Generator*. s.l., Doctoral Dissertation, University of the Western Cape.
- Çetin, C. E., 2011. *Mikroalga ışınlanması ile çeşitli metal-kükürt yarı iletken nanoparçacıklarının sentezi ve karakterizasyonu*. s.l.:Yüksek Lisans Tezi, Ankara Üniversitesi.
- Chakravarty, R., 2011. s.l.:Doctoral Dissertation, Homi Bhabha National Institute.
- Chakravarty, R. et al., 2016. Mechanochemical Synthesis of Mesoporous Tin Oxide: A New Generation Nanosorbent for ⁶⁸Ge/⁶⁸Ga Generator Technology. *Dalton Transaction*, pp. 45 13361-13372.
- Chakravarty, R. et al., 2011. Development of a nano-zirconia based ⁶⁸Ge/⁶⁸Ga generator for biomedical applications. *Nuclear Medicine and Biology*. 38 (4), pp. 575-583.
- Challagulla, S., Tarafder, K., Ganesan, R. & Roy, S., 2017. Structure sensitive photocatalytic reduction of nitroarenes over TiO₂. *Scientific Reports*. 7 .
- Dash, A. & Chakravarty, R., 2017. Nanomaterial-Based Adsorbent: Promises, Opportunities, and Challenges to Develop Column Chromatography Radionuclide Generators for Nuclear Medicine. *Separation & Purification Reviews*. 46 (2), pp. 91-107.
- Dauids, C. R., 2017. *Monitoring various eluate characteristics of the iThemba LABS*. s.l.:Doctoral Dissertation, Stellenbosch University.
- Davies, C. M., 2012. *Determination Of Distribution Coefficients For Cation Exchange Resin And Optimisation Of Ion Exchange Chromatography For Chromium Separation For Geological Materials*. s.l.:Doctoral Dissertation. The University of Manchester.
- el-sherbiny, S., Morsy, F. A., Samir, M., & Fouad, O. A. (2014). Synthesis, characterization and application of TiO₂ nanopowders as special paper coating pigment. *Applied Nanoscience*, 305-303..
- Ekebas Cavdar, E., 2022. Ge-Ga Jeneratöründe Kullanılacak Olan Çeşitli Kolon Dolgu Malzemelerin Sentezi, Karakterizasyonu Ve Uygulaması. TENMAK
- IAEA, 2019. *Gallium-68 Cyclotron Production*, Vienna: International Atomic Energy Agency.
- Karthik, T. V. K., Maldonado, A. & Olvera, M. d. l. L., 2012. *Synthesis of tin oxide powders by homogeneous precipitation. Structural and morphological characterization*. s.l., s.n.
- Neirinckx, R. D., Layne, W. W., Sawan, S. P. & Davis, M. A., 1982. Development of an ionic germanium ⁶⁸ gallium ⁶⁸ generator III. chelate resins as chromatographic substrates for germanium. *International Journal of Applied Radiation and Isotopes*. 33 (4), pp. 259-266.
- Ocak, M. et al., 2010. Full automation of (⁶⁸)Ga labelling of DOTA-peptides including cation exchange prepurification. *Applied Radiation and Isotopes*. 68, pp. 297-302.
- Ondrák Fialová, K. et al., 2023. Preparation and Surface Characterization of Cerium Dioxide for Separation of ⁶⁸Ge/⁶⁸Ga and Other Medicinal Radionuclides. *Materials*, Volume 16.

- Romero, E. et al., 2020. Development and long-term evaluation of a new $^{68}\text{Ge}/^{68}\text{Ga}$ generator based on nano- SnO_2 for PET imaging. *Scientific Reports*. 10.
- Romero, E. & Morcillo, M. A., 2017. Inorganic oxides with potential application in the preparation of a $^{68}\text{Ge}/^{68}\text{Ga}$ generator system. *Applied Radiation and Isotopes*. 119, pp. 28-35.
- Rösch, F., 2012. Past, present and future of $^{68}\text{Ge}/^{68}\text{Ga}$ generators. *Applied Radiation and Isotopes*. 76, pp. 24-30.
- Rösch, F., 2013. *^{68}Ga radiopharmaceuticals: Current status and future*. s.l.:Johannes Gutenberg University.
- Rösch, F. & Knapp, R. F., 2003. Radionuclide generators. Handbook of Nuclear Chemistry.
- Rzaij, J. M. & Abass, A. M., 2020. Review on: TiO_2 Thin Film as a Metal Oxide Gas Sensor. *Journal of Chemical Reviews*. 2, pp. 114-121.
- Saha, G. B., 2010. *Fundamentals of Nuclear Pharmacy*. New York: Springer.
- Schuhmacher, J. & Maier-Borst, W., 1981. A new $^{68}\text{Ge}/^{68}\text{Ga}$ radioisotope generator system for production of ^{68}Ga in dilute HCl . *The International Journal of Applied Radiation and Isotopes*. 32, pp. 31-36.