



Atomic Energy of Canada Limited

**NONDESTRUCTIVE NEUTRON ACTIVATION
ANALYSIS OF SILICON CARBIDE**

by

T.T. VANDERGRAAF and A.G. WIKJORD

**Whiteshell Nuclear Research Establishment
Pinawa, Manitoba
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ABSTRACT

Instrumental neutron activation analysis has been used to determine trace constituents in silicon carbide. Four commercial powders of different origin, an NBS reference material, and a single crystal were characterized. A total of 36 activation species were identified nondestructively by high resolution γ -spectrometry; quantitative results are given for 12 of the more predominant elements. The limitations of the method for certain elements are discussed. Consideration is given to the depression of the neutron flux by impurities with large neutron absorption cross sections.

Radiation fields from the various specimens have been estimated assuming all radionuclides have reached their saturation activities.

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Analyse par activation neutronique
non destructive du carbure de silicium

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Résumé

On a eu recours à une analyse instrumentale par activation neutronique pour déterminer les infimes constituants se trouvant dans le carbure de silicium. Quatre poudres commerciales ayant différentes origines, une matière de référence NBS et un cristal unique ont été caractérisés. On a identifié en tout 36 espèces par activation non destructive au moyen d'une spectrométrie gamma à haute résolution; des résultats quantitatifs sont donnés pour 12 des éléments les plus importants. Les limitations de la méthode pour certains éléments font l'objet de commentaires. On signale le fait que le flux neutronique était réduit par des impuretés, dans le cas de grandes sections efficaces d'absorption des neutrons.

On a fait une estimation des champs de radiation des divers spécimens, en assumant que tous les radionuclides atteignent leur activité de saturation.

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1. INTRODUCTION

Silicon carbide has received considerable attention as a potential structural and fuel sheathing material for high temperature reactor use because of advantageous characteristics such as good irradiation stability, favorable thermal properties, low neutron absorption cross section, and high resistance to chemical attack. This interest has emphasized the need for reliable analytical procedures to determine impurities in silicon carbide. Impurities, particularly strong neutron absorbers, would not only adversely affect the reactor neutron economy but could be transformed into undesirable activation products, creating radiation fields which make post-irradiation examination of components more difficult.

The analysis of silicon carbide by wet chemical techniques is very difficult because the material is extremely chemically inert and refractory in nature. The only convenient means to chemically dissolve silicon carbide involves an alkali fusion reaction, but because of the copious amounts of fluxing agent and extreme reaction conditions required, contamination from chemicals and crucibles poses serious limitations for any subsequent trace analysis. For this reason, physical methods of analysis must generally be used. Of the various instrumental techniques, emission spectrography, mass spectrometry, and neutron activation analysis have received the most attention and offer substantial practical benefits for trace analysis.

Direct spectrographic methods ⁽¹⁻⁴⁾ have been developed for determining impurities in silicon carbide with detection limits for many elements in the range 10 to 300 ppb. This sensitivity has generally been achieved for elements which can be selectively volatilized from the silicon carbide matrix under mild excitation conditions so that interference from volatilization of silicon carbide itself is suppressed. A technique involving a lithium fluoride fusion has shown promise for less volatile constituents ⁽⁵⁾.

Spark source mass spectrometry⁽⁶⁾ has been successfully employed to determine trace inorganic constituents in silicon carbide samples. With precautions to prevent contamination from the electrode holders and care to achieve uniform sparking conditions, detection limits in the 3 to 30 ppb range have been attained for certain elements.

Activation analysis also has high sensitivity for selected elements, particularly some of those that pose problems in nuclear applications, and has the advantage of freedom from post-irradiation contamination and the virtual absence of matrix effects. There are several reports of multi-element radioactivation analysis of silicon carbide using destructive techniques^(7,8) as well as analysis of specific elements such as oxygen⁽⁹⁾ by the fast neutron reaction $^{16}\text{O}(n,p)^{16}\text{N}$ and phosphorus⁽¹⁰⁾ by $^{31}\text{P}(n,\gamma)^{32}\text{P}$.

In this study, thermal neutron activation analysis has been used to characterize a number of commercial silicon carbide powders and a single crystal of high purity. The activation products were identified and quantified by high resolution γ -spectrometry with no attempt to undertake chemical separations of interfering nuclides.

In addition, calculations were made of the gamma radiation fields which would result from irradiation to saturation of one-gram samples of carbides of different origin and purity. These can be useful in assessing the relative radiation levels of irradiated components fabricated from the different carbides.

2. EXPERIMENTAL

The samples described in Table 1 were irradiated in the pneumatic transfer irradiation facility of an organically cooled research reactor.*

* Whiteshell Reactor No. 1 (WR-1)

This facility uses high purity iron capsules with an internal volume of 1.3 cm^3 and can accommodate capsule liners with a maximum internal volume of 0.3 cm^3 . At full reactor power level the thermal and fast ($E_n > 1 \text{ Mev}$) neutron fluxes are 8×10^{13} and $8 \times 10^{11} \text{ n cm}^{-2} \text{ s}^{-1}$ respectively. The irradiation facility is described in greater detail elsewhere⁽¹¹⁾.

After thorough mixing to ensure homogeneity, aliquots weighing approximately 100 mg were loaded in small capsule liners of high density polyethylene*, and irradiated for 2 and 60 minutes to produce short- and medium-lived isotopes. Long-lived isotopes were studied using 3-day irradiations. For these, the samples were wrapped in high-purity aluminum foil. Synthetic mixtures of standards were prepared from high-purity chemicals. After irradiation, the samples and standards were transferred into tared polystyrene containers, weighed and counted. Irradiation and decay times were chosen to obtain the maximum information with minimum demand on analyzer time and are listed in Table 2.

The counting equipment consisted of an 80 cm^3 closed end coaxial Ge(Li) detector (Nuclear Diodes) located in a copper - and-cadmium-lined lead shield with internal dimensions of $100 \times 100 \times 100 \text{ cm}$. The signal from the detector was fed into a Nuclear Data 2200 multi-channel analyzer with a 2048 channel memory. The analyzer was calibrated to 1 keV/channel. The spectra were plotted on a high speed XY recorder and the counts/channel typed out separately.

The spectra were interpreted qualitatively by comparing the photopeak energies with published data^(12,13).

Quantitative activity values were obtained by integrating the appropriate photopeaks using Covell's method⁽¹⁴⁾. Where no photopeak could be observed, a limit of detection was found using the method described by Rogers⁽¹⁵⁾. Quantitative determination of trace constituents was made by comparing the induced activities in sample and standard, correcting for irradiation and decay times when applicable.

* Supplied by the Biological Laboratory, Free University, Amsterdam, The Netherlands.

3. RESULTS AND DISCUSSION

Figures 1,2 and 3 show characteristic time-dependent gamma spectra of a particular silicon carbide sample P9, obtained after several irradiation and decay times: At the end of the 2-minute irradiation essentially all activity is due to ^{28}Al and ^{52}V (Figure 1a). After a one-hour decay ^{24}Na and ^{56}Mn activities predominate (Figure 1b) and obscure practically all other isotopes with half-lives in the range of 2-20 hours. Isotopes with half-lives between 20 and 200 hours are best determined by a one-hour irradiation followed by a 2-day decay period. ^{140}La , ^{187}W and ^{122}Sb fall into this category (Figure 2b). Isotopes with half-lives longer than 200 hours are not observed to any appreciable extent until decay times of 7 to 10 days are reached. These include ^{60}Co , ^{59}Fe , ^{51}Cr , ^{46}Sc , ^{181}Hf , ^{134}Cs , ^{95}Zr , ^{65}Zn , and ^{175}Yb (Figure 3).

A few photopeaks above 200 keV could not be identified unequivocally on the basis of peak energy and half-life. No attempt was made to identify peaks below ~ 200 keV because of the many interferences and overlapping that occur in this region^(13,16). The presence of the photopeak of fission product ^{137}Cs (662 keV) in a number of the spectra can be explained by contamination which originates in the hot cells where the samples were removed from the capsule after the 3-day irradiation. The 1462 keV photopeak is due to background radiation of naturally occurring ^{40}K .

A complete tabulation of all the isotopes identified through the photopeak energies of their activation products is given in the Appendix. The results of qualitative analysis of each specimen are shown in Table 3 while quantitative results for 12 selected elements are presented in Table 4. For comparative purposes, the NBS* certified concentrations for Ti, Fe and Zr are given. These are the only elements for which comparison was available. The 10 to 15% discrepancy between our results and the certified values provides an indication of the magnitude of errors in this work.

*National Bureau of Standards

It is noteworthy that the impurity levels in the single crystal were generally 1 to 3 orders of magnitude lower than those found in the other powders. The number of observed impurities was also substantially less. In the short irradiations, for example, the only activation species detected initially were ^{52}V and ^{28}Al . After these short-lived species decayed, the presence of ^{31}Si formed by an (n,γ) reaction on natural ^{30}Si became apparent. This was the only case in which activation of one of the matrix elements was observed; for the other samples, the high background radiation from the other impurities obscured the low yield ^{31}Si photopeak.

Although the ^{28}Al photopeak was observed for all specimens, no quantitative results were obtained for aluminum because of interference of the fast neutron reaction $^{28}\text{Si}(n,p)^{28}\text{Al}$. No correction was made for this because a supply of aluminum-free silicon was not available.

Since the two major constituents of the matrix, silicon and carbon, have low neutron absorption cross sections (0.16 b and 3.4 mb respectively), essentially no neutron flux depression occurs except where impurities with large absorption cross sections are present in large quantities. These include B, Rh, Cd, In, Sm, Gd, Dy, Er, Ir and Hg. To determine the effect of these impurities on the quantitative results, concentration levels were calculated for the elements that would give a 5% flux depression for a sample geometry approximating the internal volume of the capsule liner. The maximum allowable concentrations are listed in Table 5 together with the calculated activities of the major isotope of each flux depressant. It can be seen that, with the exception of boron, any flux depression is readily manifested by a high level of activity in the irradiated sample.

In considering silicon carbide for fuel sheath and pressure tube manufacture, it is important to have an estimate of the residual radioactivity and corresponding γ -radiation fields of these reactor components in view of post-irradiation examination. Radiation fields from actual reactor components are a function of their geometry and are therefore extremely difficult to calculate exactly. However, by considering point sources, an estimate of relative radiation levels as a function of decay time can be

obtained using the neutron activation equation and a knowledge of the impurity concentrations in the silicon carbide samples. The calculation is made on the assumption that all radionuclides have reached their saturation activities. The correlations between activities and γ -fields for the various isotopes were obtained elsewhere⁽¹⁷⁾. The results of these calculations are listed in Table 6 and the radiation fields as a function of time shown in Figure 4. It is evident that the strength of the residual radiation field is strongly dependent upon the origin of the material. Again, the high purity of the single crystal is quite apparent.

4. CONCLUSIONS

Thermal neutron activation analysis offers significant advantages in determining certain trace impurities in a chemically resistant silicon carbide matrix. By a judicious choice of irradiation and decay schedules, it is possible to determine a wide variety of elements qualitatively and quantitatively without resorting to post-irradiation chemical separations.

Although the increased resolution of Ge(Li) solid state detectors has placed the emphasis on non-destructive techniques, more could be gained by post-irradiation separation of trace impurities into groups. Thus, a new dimension would be added to the irradiation and decay time variables considered. Dissolution of the silicon carbide can be obtained by reaction with Cl_2 ⁽⁹⁾ or by fusion^(10,11). Separation can be made by the usual techniques. An interesting approach would be to decompose the sample in Cl_2 and separate the chlorides according to their boiling point in a temperature gradient tube⁽¹²⁾. Finally, the thermal/fast flux ratio could be altered by irradiating samples in thermal neutron absorbing shields^(13,14) to depress the formation of highly active interfering nuclides such as ^{24}Na , ^{56}Mn and ^{28}Al .

5 ACKNOWLEDGEMENTS

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*These are unpublished internal reports of the Whiteshell Nuclear Research Establishment and the Chalk River Nuclear Laboratories of Atomic Energy of Canada Limited.

TABLE 1

DESCRIPTION OF SILICON CARBIDE SAMPLES

| Sample Identification | Supplier | Suppliers Designation | Average Particle Size* (μ) | % Free Silicon* | % Free Carbon* |
|-----------------------|------------------------------|-----------------------|----------------------------|-----------------|----------------|
| NBS | National Bureau of Standards | Standard Sample 112 | - | - | 0.09 |
| P5 | Carborundum Company | 1200 RA | 2 - 4 | 0.2 | 0.21 |
| P9 | Fisher Scientific | C-191 | 41 | - | - |
| P18 | Carborundum Company | 1000 RA | 5 | <0.1 | 0.13 |
| P38 | Carborundum Company U.K. | F-4F | 1 - 2 | 1.0 | 2.6 |
| Single Crystal | Norton Company | - | Large fragments | - | - |

* Analysis performed at WNRE

TABLE 2

IRRADIATION AND DECAY SCHEDULES

| Irradiation Time (t_i) | Decay Times (t_d) | | |
|----------------------------|-----------------------|----------|----------|
| | t_{d1} | t_{d2} | t_{d3} |
| 2 minutes | 10 minutes | 1 hour | 1 day |
| 1 hour | 1 day | 2 days | 7 days |
| 3 days | 10 days | 20 days | 30 days |

TABLE 3

IMPURITIES OBSERVED IN SILICON CARBIDE SAMPLES

| Element | NBS | P5 | P9 | P18 | P38 | Single Crystal |
|---------|-----|----|----|-----|-----|-------------------|
| Na | + | + | + | + | + | + |
| Al | + | + | + | + | + | + |
| Si | - | - | - | - | - | + |
| Cl | + | + | + | + | + | + |
| K | - | - | + | - | - | - |
| Sc | + | + | + | + | + | - |
| Ti | + | + | + | + | - | + |
| V | + | + | + | + | + | + |
| Cr | + | + | + | + | + | + |
| Mn | + | + | + | + | + | + |
| Fe | + | + | + | + | + | + |
| Co | + | + | + | + | + | - |
| Cu | + | + | - | - | - | - |
| Zn | + | - | - | - | - | - |
| As | + | + | - | + | + | - |
| Zr | + | + | - | - | - | - |
| Sb | + | + | + | + | + | - |
| Cs | - | - | + | + | - | - |
| La | + | + | + | + | + | + |
| Ce | + | - | + | - | + | - |
| Eu | + | - | + | - | + | - |
| Tb | + | - | - | - | - | - |
| Dy | + | + | + | + | + | - |
| Yb | + | - | - | - | - | - |
| Lu | + | + | + | + | + | - |
| Hf | + | + | + | + | + | + |
| Ta | - | + | - | + | - | - |
| W | + | + | + | + | + | - |
| Hg | + | + | - | - | - | - |

+ = observed
 - = not observed

TABLE 4

RESULTS OF QUANTITATIVE ANALYSIS

| Element | Isotope | Photopeak (MeV) | $\mu\text{g/g}$ | | | | | | |
|---------|-------------------|--------------------|-----------------|---------------------|------|------|------|--------|-------------------|
| | | | NBS | | P5 | P9 | P18 | P38 | Single Crystal |
| | | | This Work | Certified Value* | | | | | |
| Na | ^{24}Na | 1.368 | 8.3 | | 150 | 510 | 35 | 3300 | 1.3 |
| Sc | ^{46}Sc | 0.889 | 0.7 | | 0.2 | 0.4 | 0.2 | 0.8 | 0.001 |
| Ti | ^{51}Ti | 0.320 | 300 | 250 | 700 | 230 | 350 | <700 | <100 |
| V | ^{52}V | 1.434 | 0.08 | | 33 | 77 | 23 | 120 | 23 |
| Cr | ^{51}Cr | 0.320 | 5 | | 17 | 13 | 8 | 90 | 0.4 |
| Mn | ^{56}Mn | 0.846 | 16 | | 0.24 | 3 | 0.18 | 35 | 0.004 |
| Fe | ^{59}Fe | 1.291 | 3900 | 4500 | 260 | 3040 | 180 | 20,000 | 50 |
| Co | ^{60}Co | 1.333 | 2.3 | | 0.3 | 4 | 0.4 | 8 | <0.2 |
| Zr | ^{95}Zr | 0.757 | 300 | 270 | 73 | 80 | 42 | 320 | <40 |
| Sb | ^{122}Sb | 0.564 | 5 | | 0.3 | 2 | 0.2 | 8 | <0.2 |
| La | ^{140}La | 1.595 | 1.7 | | 0.4 | 2.2 | 0.3 | 7.3 | 0.8 |
| Hf | ^{181}Hf | 0.482 | 7 | | 3 | 2 | 2 | 4 | 0.1 |

* National Bureau of Standards, Certificate of Analysis, Silicon Carbide Standard Sample 112

TABLE 5

CONCENTRATION OF ELEMENTS WITH HIGH NEUTRON ABSORPTION
CROSS SECTION NECESSARY TO DEPRESS FLUX BY 5%*

| Element | Atomic Weight | σ_a (barns) | Concentration ($\mu\text{g/g}$) | Activity major isotope produced after one-hour irradiation (dps/100 mg) [†] |
|---------|---------------|--------------------|-----------------------------------|--|
| B | 10.811 | 760 | 1,352 | no γ -activity |
| Rh | 102.905 | 148 | 66,087 | ^{104}Rh 6.2×10^{11} |
| Cd | 112.40 | 2,460 | 4,343 | ^{117}Cd 6.0×10^6 |
| In | 114.82 | 194 | 56,254 | $^{116\text{m}}\text{In}$ 2.4×10^{11} |
| Sm | 150.35 | 5,860 | 2,439 | ^{155}Sm 9.3×10^7 |
| Eu | 151.96 | 4,200 | 3,439 | $^{152\text{m}}\text{Eu}$ 1.3×10^{10} |
| Gd | 157.25 | 48,000 | 311 | ^{161}Gd 2.1×10^6 |
| Dy | 162.50 | 930 | 16,607 | $^{165\text{m}}\text{Dy}$ 3.5×10^{11} |
| Er | 167.26 | 160 | 99,360 | ^{171}Er 4.2×10^8 |
| Ir | 191.2 | 426 | 42,660 | $^{195\text{m}}\text{Ir}$ 1.2×10^{11} |
| Hg | 200.59 | 370 | 51,528 | ^{205}Hg 4.2×10^7 |

* capsule liner 0.56 cm right cylinder, sp. gr. SiC 3.22

† $\phi = 10^{14}$ n/cm².s

TABLE 6

SATURATION ACTIVITIES (A_{∞}) AND γ -RADIATION FIELDS (F) FOR 1 GRAM SAMPLES OF SIC*

| Sample+ | NBS | | P5 | | P9 | | P18 | | P38 | | Single Crystal | |
|-------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | A_{∞} (dps) | F (mR/h @ 1 ft) | A_{∞} (dps) | F (mR/h @ 1 ft) | A_{∞} (dps) | F (mR/h @ 1 ft) | A_{∞} (dps) | F (mR/h @ 1 ft) | A_{∞} (dps) | F (mR/h @ 1 ft) | A_{∞} (dps) | F (mR/h @ 1 ft) |
| ²⁴ Na ⁺ | 1.2E7 | 6.5E0 | 2.0E8 | 1.1E2 | 7.1E8 | 4.0E2 | 5.0E7 | 2.7E1 | 4.6E9 | 2.6E3 | 1.8E6 | 1.0E0 |
| ³¹ Si | 5.1E9 | 6.9E1 | 5.1E9 | 6.9E1 | 5.1E9 | 6.9E1 | 5.1E9 | 6.9E1 | 5.1E9 | 6.9E1 | 5.1E9 | 6.9E1 |
| ⁴⁶ Sc | 2.1E7 | 6.5E0 | 6.0E6 | 1.9E0 | 1.2E7 | 3.7E0 | 6.0E6 | 1.9E0 | 2.4E7 | 7.4E0 | 1.8E4 | <1.0E-2 |
| ⁵¹ Ti | 2.8E6 | 1.8E-1 | 6.6E6 | 4.2E-1 | 2.2E6 | 1.4E-1 | 3.3E6 | 2.1E-1 | <6.6E6 | <4.2E-1 | <9.4E5 | <6.0E-2 |
| ⁵² V | 4.6E5 | 1.2E-1 | 1.9E8 | 4.8E1 | 4.5E8 | 1.1E2 | 1.3E8 | 3.3E1 | 6.8E8 | 1.7E2 | 1.3E8 | 3.3E1 |
| ⁵¹ Cr | 4.3E6 | 2.0E-2 | 1.4E7 | 8.0E-2 | 1.1E7 | 6.0E-2 | 6.8E6 | 4.0E-2 | 7.7E7 | 4.5E-1 | 3.4E5 | <1.0E-2 |
| ⁵⁵ Cr | 5.0E4 | <1.0E-2 | 1.7E5 | <1.0E-2 | 1.3E5 | <1.0E-2 | 8.0E4 | <1.0E-2 | 9.1E5 | <1.0E-2 | 4.0E3 | <1.0E-2 |
| ⁵⁶ Mn | 2.4E8 | 5.3E1 | 3.6E6 | 8.0E-1 | 4.5E7 | 1.0E1 | 2.7E6 | 6.0E-1 | 5.2E8 | 1.2E2 | 6.0E4 | <1.0E-2 |
| ⁵⁵ Fe | 7.0E8 | - | 4.9E7 | - | 5.5E8 | - | 3.3E7 | - | 3.6E9 | - | 9.0E6 | - |
| ⁵⁹ Fe | 1.7E7 | 4.6E2 | 1.1E6 | 3.1E1 | 1.3E7 | 3.5E2 | 8.0E5 | 2.2E1 | 8.0E7 | 2.2E3 | 2.1E5 | 5.8E0 |
| ^{60m} Co | 4.1E7 | 3.6E-2 | 5.4E6 | <1.0E-2 | 7.2E6 | <1.0E-2 | 7.2E6 | <1.0E-2 | 1.4E8 | 1.3E-1 | 3.7E6 | <1.0E-2 |
| ⁶⁰ Co | 8.5E7 | 5.8E1 | 1.1E7 | 7.5E0 | 1.5E7 | 1.0E1 | 1.5E7 | 1.0E1 | 3.0E8 | 2.0E2 | 7.4E6 | 5.0E0 |
| ⁹⁵ Zr | 2.8E6 | 7.5E-1 | 6.7E5 | 1.8E-1 | 7.4E5 | 2.0E-1 | 3.9E5 | 1.0E-1 | 2.9E6 | 7.9E-1 | 3.7E5 | 1.0E-1 |
| ⁹⁷ Zr | 2.8E5 | 7.0E-2 | 6.7E4 | 2.0E-2 | 7.4E4 | 2.0E-2 | 3.9E4 | <1.0E-2 | 2.9E5 | 7.0E-2 | 3.7E4 | <1.0E-2 |
| ¹²² Sb | 8.5E6 | 5.5E-1 | 5.1E5 | 3.0E-2 | 3.4E6 | 2.2E-1 | 3.4E5 | 2.0E-2 | 1.4E7 | 8.7E-1 | 3.4E5 | 2.0E-2 |
| ¹²⁴ Sb | 3.5E6 | 9.5E-1 | 2.1E5 | 6.0E-2 | 1.4E6 | 3.8E-1 | 1.4E5 | 4.0E-2 | 5.6E6 | 1.5E0 | 1.4E5 | 4.0E-2 |
| ¹⁴⁰ La | 6.6E6 | 2.1E0 | 1.6E6 | 4.9E-1 | 8.6E6 | 2.7E0 | 1.2E6 | 3.7E-1 | 2.8E7 | 8.9E0 | 3.1E6 | 9.5E-1 |
| ¹⁷⁵ Hf | 1.7E6 | 7.0E-2 | 7.2E5 | 2.9E0 | 4.8E5 | 2.0E-2 | 4.8E5 | 2.0E-2 | 9.6E5 | 4.0E-2 | 2.4E4 | <1.0E-2 |
| ^{180m} Hf | 6.5E4 | 1.0E-2 | 2.8E4 | <1.0E-2 | 1.9E4 | <1.0E-2 | 1.9E4 | <1.0E-2 | 3.7E4 | <1.0E-2 | 9.3E2 | <1.0E-2 |
| ¹⁸¹ Hf | 8.4E6 | 9.1E-1 | 3.6E6 | 3.9E-1 | 2.4E6 | 2.6E-1 | 2.4E6 | 2.6E-1 | 4.8E6 | 5.2E-1 | 1.2E5 | <1.0E-2 |

* $\phi = 10^{14}$ n/cm²/s

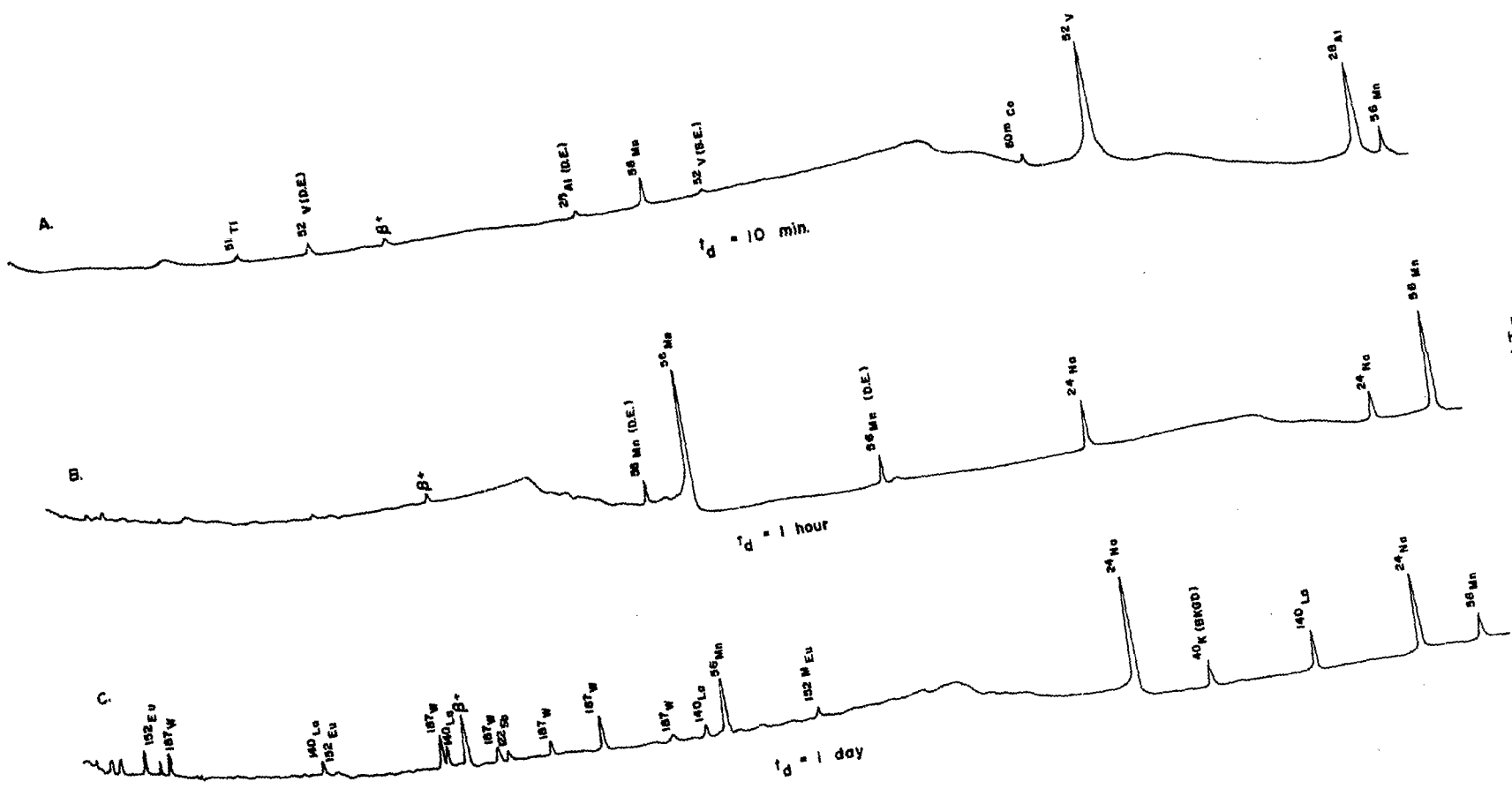


FIGURE 1: γ SPECTRA OF SIC SAMPLE P9 $t_i = 2 \text{ min.}$

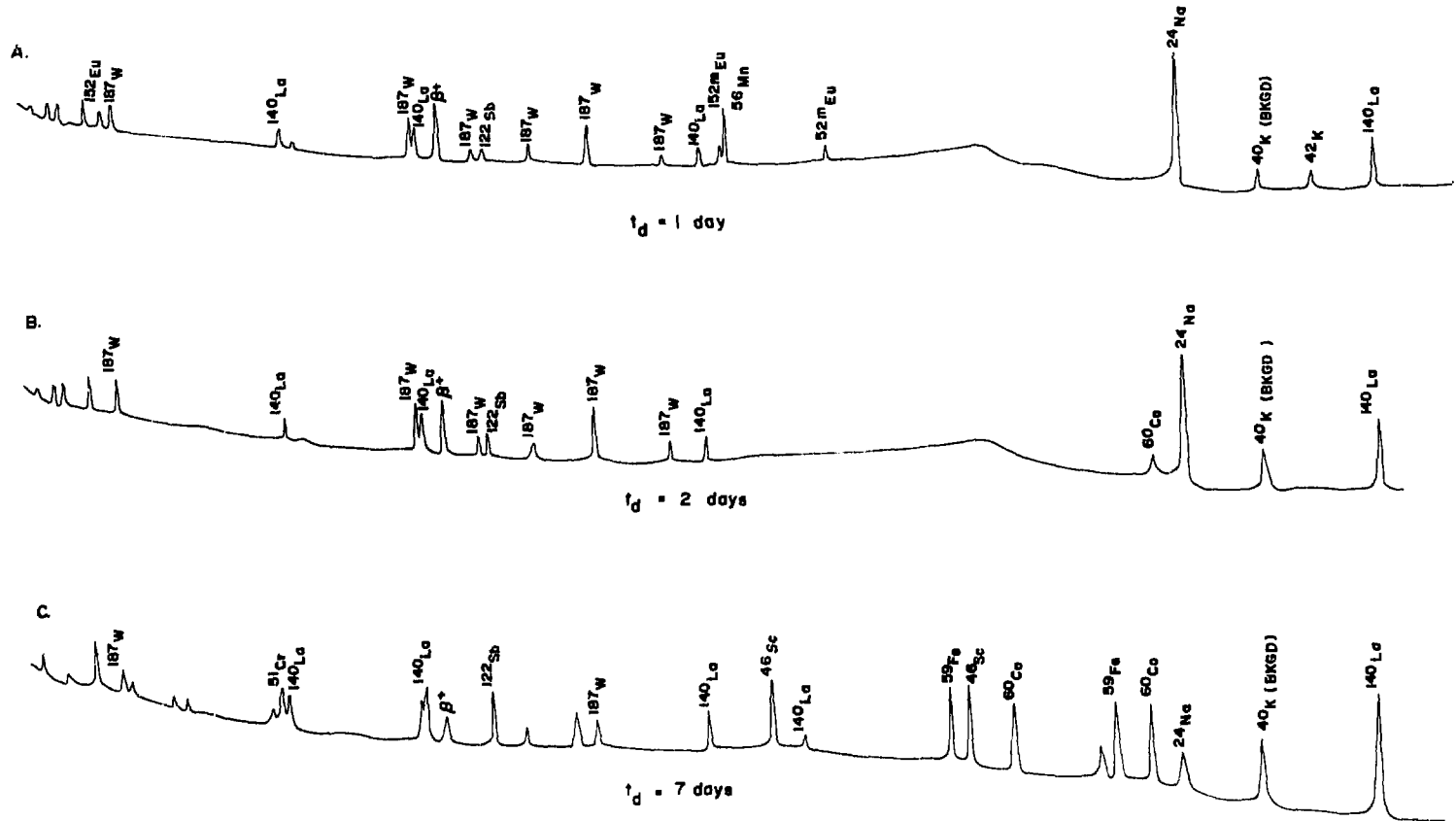


FIGURE 2: γ SPECTRA OF SIC SAMPLE P 9 $t_i = 1 \text{ hr}$

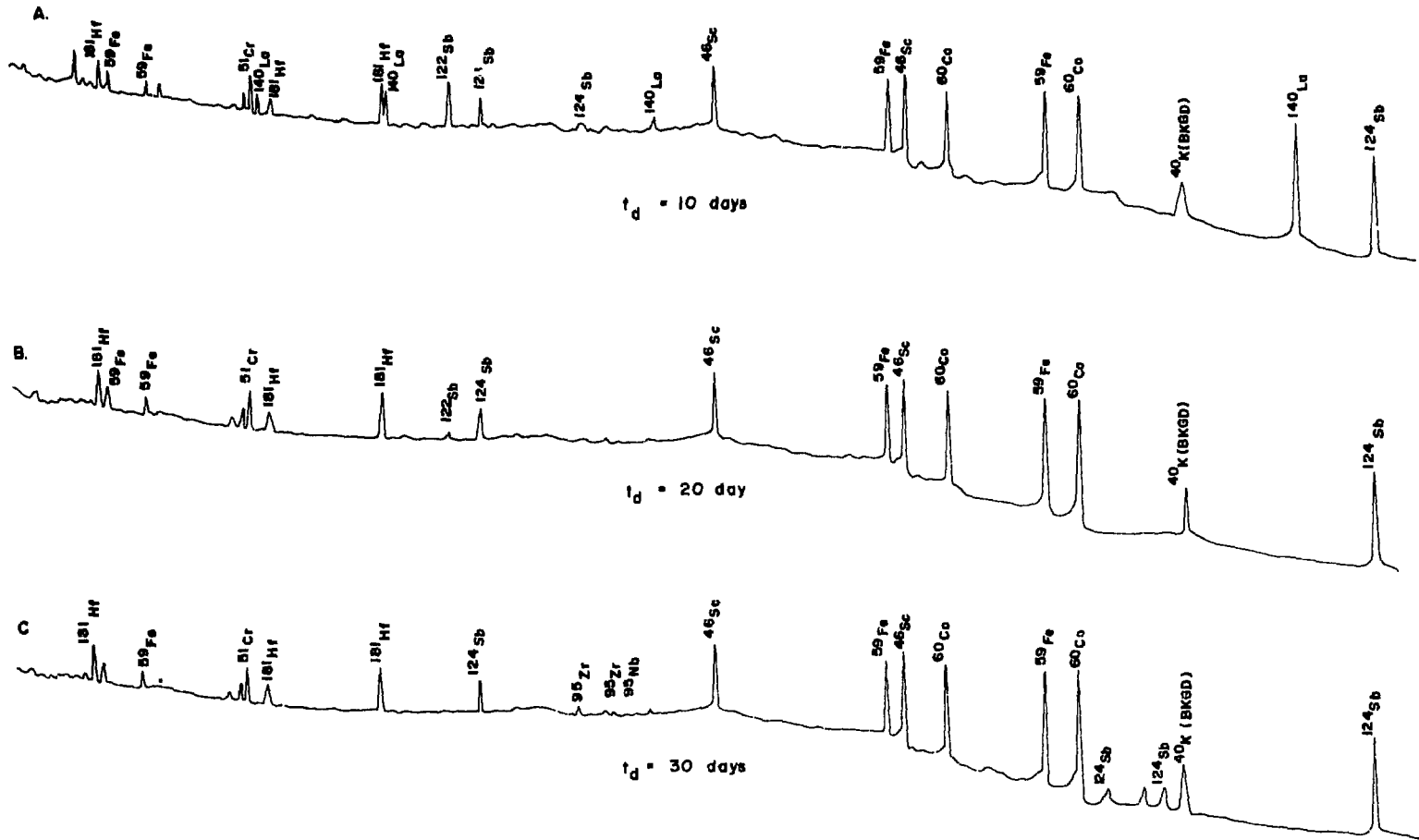


FIGURE 3: γ SPECTRA OF SiC SAMPLE P 9 $t_i = 3$ days

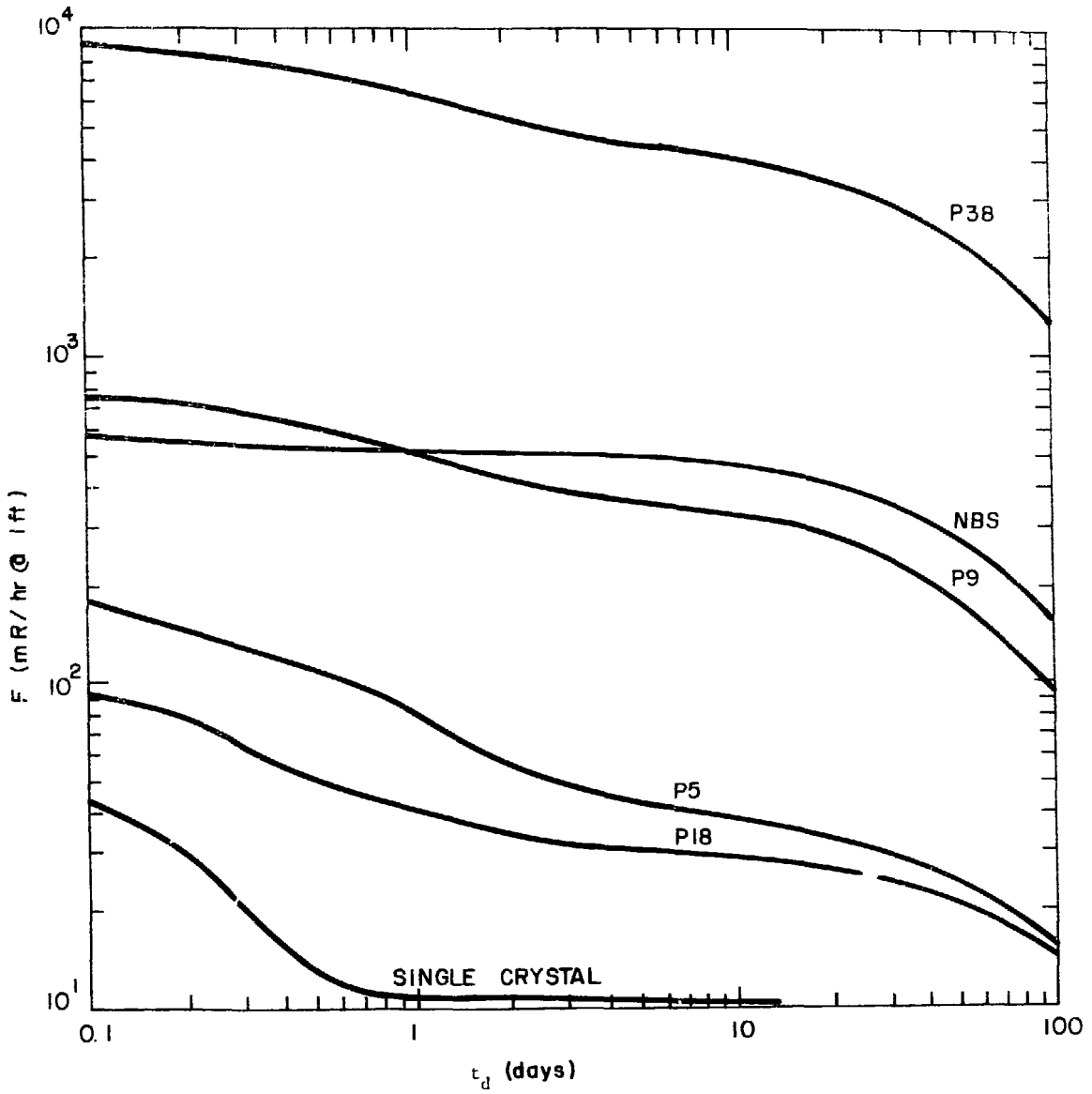


FIGURE 4 GAMMA - RADIATION FIELDS VS DECAY TIME FOR 1 GRAM SiC SAMPLES IRRADIATED TO SATURATION

APPENDIX

NUCLEAR DATA FOR RADIONUCLIDES OBSERVED IN IRRADIATED SiC SAMPLES

| ELEMENT | ISOTOPE | HALF-LIFE | PARENT | CROSS SECTION (b) | % ABUNDANCE | γ-RAY ENERGIES (keV) USED TO IDENTIFY RADIONUCLIDE | PHOTOPEAK INTENSITY NUMBER OF γ's/1000 decays | |
|---------|-----------|-------------------|---------|-------------------|-------------|--|---|-------------------------------------|
| 1 | Sodium | ²⁴ Na | 15.0 h | ²³ Na | 0.53 | 100 | 1368.7 1732.1 | 1000 DE* |
| 2 | Aluminum | ²⁸ Al | 2.3 m | ²⁷ Al | 0.23 | 100 | 1778.9 1267.9 757 | 1000 SE** DE |
| 3 | Silicon | ³¹ Si | 2.60 h | ³⁰ Si | 0.11 | 3.05 | 1266.0 | 0.70 |
| 4 | Chlorine | ³⁸ Cl | 37.3 m | ³⁷ Cl | 0.43 | 24.5 | 1642.0 | 380 |
| 5 | Potassium | ⁴² K | 12.50 h | ⁴¹ K | 1.30 | 6.88 | 1524.7 | 180 |
| 6 | Scandium | ⁴⁶ Sc | 84.0 d | ⁴⁵ Sc | 23.0 | 100 | 889.3 1120.5 | 1000 1000 |
| 7 | Titanium | ⁵¹ Ti | 5.8 m | ⁵⁰ Ti | 0.14 | 5.34 | 320.0 928.5 | 955 45 |
| 8 | Vanadium | ⁵² V | 3.8 m | ⁵¹ V | 4.8 | 99.76 | 1434.4 923.4 412.4 | 990 SE DE |
| 9 | Chromium | ⁵¹ Cr | 27.8 d | ⁵⁰ Cr | 16.0 | 4.31 | 320.1 | 90 |
| 10 | Manganese | ⁵⁶ Mn | 2.58 h | ⁵⁵ Mn | 13.3 | 100 | 846.8 1811.0 1090 1601 789 1299 | 990 297 DE SE DE SE |
| 11 | Iron | ⁵⁹ Fe | 45.0 d | ⁵⁸ Fe | 1.23 | 0.33 | 1099.3 1291.6 192.2 | 560 440 25 |
| 12 | Cobalt | ⁶⁰ Co | 5.25 y | ⁵⁹ Co | 37.0 | 100 | 1173.2 1332.5 | 999 1000 |
| | | ^{60m} Co | 10.5 m | ⁵⁹ Co | 19.9 | 100 | 1332.5 | 2.5 |
| 13 | Copper | ⁶⁴ Cu | 12.8 h | ⁶³ Cu | 4.5 | 69.1 | 1345.5 | 5 |
| 14 | Zinc | ⁶⁵ Zn | 243.8 d | ⁶⁴ Zn | 0.82 | 48.9 | 1115.5 | 506 |
| 15 | Arsenic | ⁷⁶ As | 26.5 h | ⁷⁵ As | 4.3 | 100 | 559.1 657.0 1216.3 | 440 66 44 |
| 16 | Zirconium | ⁹⁵ Zr | 65.5 d | ⁹⁴ Zr | 0.075 | 17.4 | 756.9 724.3 | 549 431 |
| 17 | Niobium | ⁹⁵ Nb | 35.2 d | ⁹⁵ Zr | 0 | 0 | 765.8 | 1000 |
| 18 | Antimony | ¹²² Sb | 2.8 d | ¹²¹ Sb | 6.2 | 57.3 | 564.0 692.5 602.7 1691.0 722.7 645.8 | 663 33 980 500 98 74 |
| | | ¹²⁴ Sb | 60.3 d | ¹²³ Sb | 3.45 | 42.8 | | |

* DE: Double escape peak ** SE: Single escape peak

Con't.

| | ELEMENT | ISOTOPE | HALF-LIFE | PARENT | CROSS SECTION (b) | % ABUNDANCE | γ-RAY ENERGIES (keV) USED TO IDENTIFY RADIONUCLIDE | PHOTOPEAK INTENSITY NUMBER OF γ's/1000 decays |
|----|-----------------------------|--------------------|-------------------|-------------------|-------------------|---|--|---|
| 19 | Cesium (fission product) | ¹³⁷ Cs | 30.2 y | ²³⁵ U | | 0.72 | 661.6 | 84.8 |
| 20 | Lanthanum | ¹⁴⁰ La | 40.2 h | ¹³⁹ La | 9.55 | 99.9 | 1596.2 487.0 815.8 328.7 925.2 867.9 751.7 432.5 | 970 460 240 210 67 57 45 30 |
| 21 | Cerium | ¹⁴¹ Ce | 53.0d | ¹⁴⁰ Ce | 0.54 | 88.5 | 145.4 | 490 |
| 22 | Europium | ¹⁵² Eu | 12.4 y | ¹⁵¹ Eu | 5700 | 47.8 | 121.8 344.2 1408.1 964.2 1112.2 779.1 1086.0 688.9 244.5 | 294 285 229 162 154 145 118 90 76 |
| | | ^{152m} Eu | 9.3 h | ¹⁵¹ Eu | 3100 | 47.8 | 841.4 963.1 1314.3 | 111 93 8 |
| 23 | Dysprosium | ¹⁵⁹ Dy | 144 d | ¹⁵⁸ Dy | 96 | 0.09 | 58.0 | 40 |
| 24 | Terbium | ¹⁶⁰ Tb | 73 d | ¹⁵⁹ Tb | 27 | 100 | 879 298 966 | 300 271 247 |
| | | ¹⁶⁹ Yb | 32 d | ¹⁶⁸ Yb | 3200 | 0.14 | 63.5 197.8 177.0 | 273 249 202 |
| | ¹⁷⁵ Yb | 4.2 d | ¹⁷⁴ Yb | 65 | 31.8 | 396.1 282.6 113.5 | 60 57 19 | |
| 26 | Lutetium | ¹⁷⁷ Lu | 6.7 d | ¹⁷⁶ Lu | 2100 | 2.6 | 208.4 113.0 | 35 44 |
| 27 | Hafnium | ¹⁸¹ Hf | 42.5 d | ¹⁸⁰ Hf | 12.6 | 35.4 | 483.0 133.0 343.9 136.2 | 119 100 136 60 |
| | | ¹⁸² Ta | 115 d | ¹⁸¹ Ta | 21.0 | 99.98 | 67.8 1121.2 1221.4 1189.0 109.1 1231.0 | 417 350 278 166 142 117 |
| | ¹⁸³ Ta | 5.0 d | ¹⁸² Ta | 8200 | 0 | 246.1 107.9 354.0 161.3 244.3 99.1 | 300 132 129 105 96 81 | |
| 29 | Tungsten | ¹⁸⁷ W | 23.8 h | ¹⁸⁶ W | 38 | 28.4 | 685.7 479.5 72.0 134.2 618.2 551.5 773.9 625.4 864.5 | 330 264 123 97 77 63 49 13 4 |
| | | ²⁰³ Hg | 46.6 d | ²⁰² Hg | 4.9 | 29.8 | 77.6 279.2 | 190 820 |

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