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Neutron Activation Resonance Integral of ^{74}Ge and ^{76}Ge and Evaluation of the ^{74}Ge keV Neutron Radiative Capture Cross Section and Resonance Integral

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Values of the reduced activation resonance integral relative to the thermal cross section I'/σ_0 of ^{74}Ge and ^{76}Ge were determined relative to gold by measuring cadmium ratios in a reactor spectrum.

A lithium-drifted germanium γ-ray spectrometer was used to resolve the activities of the samples.

The results for ^{74}Ge are $I'/\sigma_0 = 1.514 \pm 0.031$ and $I' = 0.681 \pm 0.123$ b with an assumed $\sigma_0 = 0.45 \pm 0.08$ b; for ^{76}Ge $I'/\sigma_0 = 12.00 \pm 0.16$ and $I' = 1.992 \pm 0.359$ with an assumed $\sigma_0 = 0.166 \pm 0.030$ b.

The values obtained for I' are in serious disagreement with the values calculated with neutron resonance parameters and confirm previous results obtained in similar keV average resonance spacing isotopes.

Due to this fact a careful evaluation of the keV neutron radiative capture cross section and resonance integral for ^{74}Ge was undertaken.

The evaluation and comparison with the experimental value of the resonance integral shows first that for nuclides with an average resonance spacing of keV the unresolved resonance integral has been seriously underestimated in many evaluations, and second that between 10 and 100 keV, resonance integrals calculated with smooth low resolution activation cross sections give a better calculation of neutron captures than that obtained with neutron resonance parameters.

Les valeurs de l'intégrale de résonance de l'activation réduite relative à la section efficace thermique I'/σ_0 du ^{74}Ge et du ^{76}Ge ont été déterminées par rapport à l'or, en mesurant les rapports d'abondance du cadmium dans un spectre de réacteur.

Un spectromètre γ germanium–lithium à été utilisé pour déterminer l'activité des échantillons.

Les résultats pour ^{74}Ge sont $I'/\sigma_0 = 1.514 \pm 0.031$ et $I' = 0.681 \pm 0.123$ b avec une valeur supposée de $\sigma_0 = 0.45 \pm 0.08$ b; pour ^{76}Ge, $I'/\sigma_0 = 12.00 \pm 0.16$ et $I' = 1.992 \pm 0.359$ b avec une valeur supposée de $\sigma_0 = 0.166 \pm 0.030$ b.

Les valeurs obtenues pour I' sont en sérieux désaccord avec les valeurs calculées à l'aide des paramètres de résonance des neutrons et confirment des résultats obtenus précédemment pour des isotopes dont les résonances présentent un espacement moyen comparable.

Pour cette raison, une évaluation soigneuse de la section efficace de capture radiative des neutrons dans la région des keV, de même que la détermination de la valeur de l'intégrale de résonance pour ^{74}Ge ont été entreprises.

L'évaluation de l'intégrale de résonance et sa comparaison avec la valeur expérimentale montrent premièrement que pour les noyaux ayant un espacement moyen des résonances de l'ordre des keV, l'intégrale des résonances non résolues a été sérieusement sous-estimée dans plusieurs évaluations, et deuxièmement que dans l'intervalle (10 keV, 100 keV) les intégrales de résonance calculées avec une section efficace d'activation à basse résolution donnent pour les captures de neutrons une meilleur résultat que celui qu'on obtient avec les paramètres de résonance des neutrons. [Traduit par le journal]

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Introduction

Previous results (Ricabarra *et al.* 1968, 1969, 1970) showed that a consistent serious discrepancy existed between calculated and experimental values of the resonance integral for several isotopes in which the predominant resonances were in the keV energy region.

^{74}Ge and ^{76}Ge are elements with these characteristics, and it is interesting to see if these elements confirm our previous results.

Furthermore keV radiative capture cross sections in the Ge isotopes are particularly important for stellar nucleosynthesis (Fowler 1968) and the understanding of keV neutron captures by isotopes with wide average resonance spacing (~keV) is also of interest in fast reactor physics.

In addition one of the outstanding problems of neutron detection has been the detection of keV energy neutrons in the presence of strong gamma radiation and thermal neutron fields.

Recently similar isotopes like ^{80}Se and ^{64}Zn have been proposed (Connolly *et al.* 1968) and used (Müller 1970) to determine neutron flux in the keV energy region of a fast critical

[1]Revision received April 4, 1972.

assembly, but apparently the authors have not checked the radiative capture cross sections and neutron resonances parameters of these elements against experimental values of the resonance integral.

^{74}Ge and ^{76}Ge may be convenient detectors for this energy range but a comparison of the experimental resonance integral with the calculated one has to be made in order to know if resonance parameters may be trusted to calculate keV effective cross sections.

Recently a complete measurement of germanium neutron resonance parameters has been reported (Maletzki *et al.* 1968), and this measurement has been made by a high resolution transmission and radiative capture technique applied to enriched germanium samples. The combination of these techniques is believed to give a reasonable accuracy for radiative width determinations in resonances with large neutron widths, and better information about weaker *p*-wave resonances.

In addition there are, for ^{74}Ge, a good number of differential neutron activation cross section measurements in the keV and MeV energy region and semi-empirical statistical model calculations of the cross section.

Therefore, ^{74}Ge is a suitable element to make critical comparisons of keV neutron captures calculated by different procedures and arrive at a meaningful understanding of the cause of discrepancies in this energy region.

Some provisional data about germanium isotopes together with previously published values were reported in a review of our work in this field in the Helsinki Conference (Ricabarra *et al.* 1970). In this paper we gave a complete description of the technique, evaluation, and results which supersedes previous provisional values.

Method

The cadmium ratio technique was applied to determine the ratio of the reduced resonance integral, I', to the thermal activation cross section, σ_0, as has been discussed in previous work (Ricabarra *et al.* 1968).

The ^{74}Ge cadmium ratio was determined by measuring the activity of ^{75}Ge (82 min). An isomer is also produced, but it decays entirely to the ground state with a half-life of 48 s, so that for counts starting $\sim$1 h after the end of the irradiation, the ^{75}Ge activity is proportional to the total ^{74}Ge cross section.

This is not the case for ^{76}Ge, because the metastable isomer ^{77}Ge^{m} (54 s) produced by neutron capture only partially (24%) decays to the ground state ^{77}Ge (11.3 h) and 76% of ^{77}Ge^{m} decays to ^{77}As (38.7 h) (Lederer *et al.* 1968) (see Fig. 1).

The activity of ^{77}As does not represent the sum of the activity of the two isomers due to the fact that its half-life is of the same order as the ^{77}Ge half-life.

If $\hat{\sigma}(\mathrm{m})$ and $\hat{\sigma}(\mathrm{g})$ are the effective cross sections to the metastable and ground state isomers, the saturation activity of ^{77}Ge and ^{77}As at the end of the irradiation, per atom of ^{76}Ge and neutron flux equal to one, can be expressed (see Appendix II) by

$$Q(^{77}\mathrm{Ge}) = \hat{\sigma}(\mathrm{g}) + fC_0\hat{\sigma}(\mathrm{m})$$

$$Q(^{77}\mathrm{As}) = \hat{\sigma}(\mathrm{g}) + B_0\hat{\sigma}(\mathrm{m})$$

where

$$B_0 = \frac{(1-f)C_1 + fC_3}{C_2}$$

f is the isomeric transition fraction and C_0, C_1, C_2, and C_3 are terms which depend on the decay constants (λ_1, λ_2, λ_3), the irradiation time (T), and the time elapsed from the end of irradiation (t).

If one allows for complete decay of the 54 s activity, the coefficients C_0 and C_1 become constants: $C_0 = \lambda_1/(\lambda_1 - \lambda_2)$ and $C_1 = \lambda_1/(\lambda_1 - \lambda_3)$. Figure 2 shows C_2, C_3, and B_0 calculated as a function of time.

The ^{76}Ge isomeric yield ratio is different for thermal and epicadmium capture, hence the cadmium ratio obtained by measuring ^{77}Ge gamma rays will be different from that obtained by measuring ^{77}As gamma rays.

The ratios of the bare to the cadmium covered activity obtained from ^{77}Ge, R_2, and ^{77}As, R_3, photopeaks can be expressed in terms of the cadmium ratio, R_{Cd}:

$$[1] \qquad R_2 - 1 = (R_{\mathrm{Cd}} - 1)\frac{1-\alpha(1-Y)}{1-\alpha(1-Y_1)}$$

$$[2] \qquad R_3 - 1 = (R_{\mathrm{Cd}} - 1)\frac{1-\beta(1-Y)}{1-\beta(1-Y_1)}$$

where $\alpha = 1 - C_0 f$ and $\beta = 1 - B_0$.

Y is the isomeric yield ratio below the cadmium

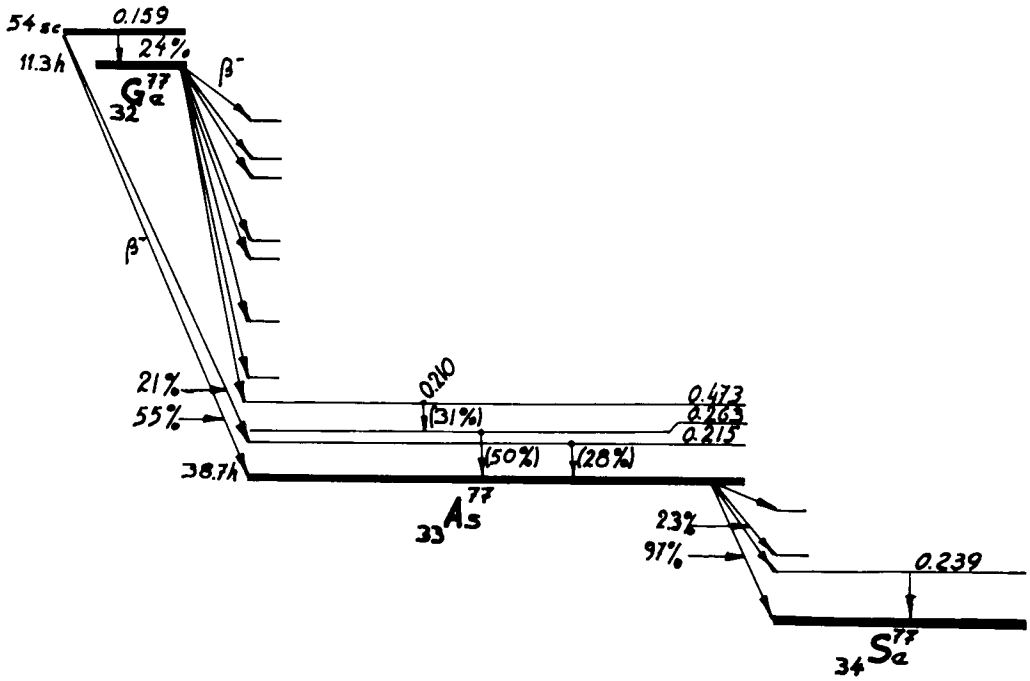

FIG. 1. ^{77}Ge decay scheme.

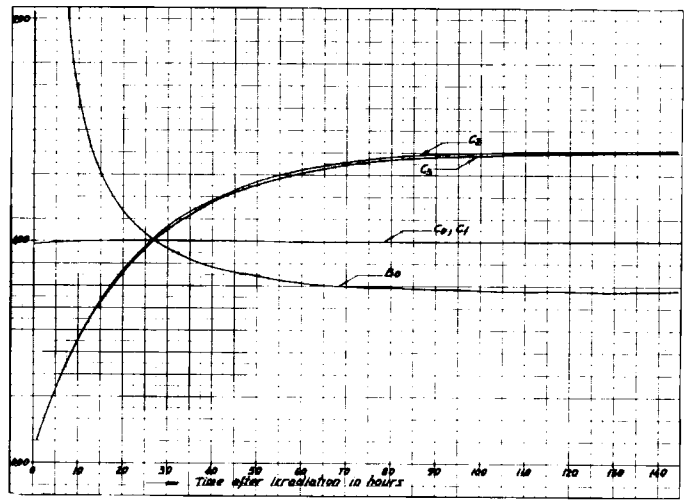

FIG. 2. Calculated coefficients as a function of time.

cutoff and equals the thermal isomeric yield ratio; Y_1 is the epicadmium isomeric yield ratio.

From the experimental values R_2 and R_3 and expressions [1] and [2], the cadmium ratio, R_{Cd}, can be obtained.

Assuming that the transmission of resonance neutrons in cadmium is equal to one ($F = 1$) and the cross section below the cadmium cutoff is $1/v$ ($g = 1$, $W = 0$), the reduced resonance integral I' can be deduced from the Westcott formalism (Westcott *et al.* 1958):

$$[3] \qquad \frac{I'G_r}{\sigma_0} = \frac{\sqrt{\pi}}{2}\,\frac{1 - R_{Cd}(1/K)(r\sqrt{T/T_0})}{(R_{Cd} - 1)(r\sqrt{T/T_0})}$$

where G_r is the resonance self-shielding correc-

tion; $r\sqrt{T/T_0}$ is the epithermal neutron index; $1/K = 0.462$, for $E_0 = 0.025$ eV, and $E_{Cd} = 0.60$ eV. The definition of the experimental resonance integral and its dependence on the reactor spectrum are discussed in Appendix I.

Resonance Self-Shielding Correction

The self-shielding correction, G_r, was calculated for every resonance using the parameters of Maletzki *et al.* 1968. The Doppler effect and resonance integral were calculated for every resonance. The narrow resonance approximation (Dresner 1960) was used to calculate self-shielding, because the neutron width was considerably narrower than the average decrement of the neutron energy per collision in the germanium resonances.

An experimental determination of the resonance self-shielding correction was made by measuring the cadmium ratio for two different sample thicknesses and $I'G_r$ was derived from them.

The infinite-dilution resonance integral was obtained by extrapolating the experimental values of $I'G_r$ to zero thickness using the calculated G_r as a parameter.

In cases where there is serious disagreement between calculated and experimental values of self-shielding this procedure is somewhat involved and may produce a 1% systematic error in the experimental resonance integral.

Experimental Details

In previous work (Ricabarra *et al.* 1968, 1970) most of the experimental details and analysis relevant to this kind of measure were given.

The irradiation place was the central graphite reflector of the Reactor Argentino 1 (RA1). The flux distribution and slowing down spectra in the site of irradiation were given in the papers mentioned above.

The Westcott epithermal index, $r\sqrt{T/T_0}$, was 0.0794 ± 0.0003 based on a gold-cadmium ratio of 1.674 ± 0.003 and a value of I'/σ_0 of 15.69.

Cadmium ratios were made for two foil thicknesses; foils of metallic germanium 406 mg/cm^2 thick and thin foils of 25 mg/cm^2 or 40 mg/cm^2 of germanium oxide deposited in plastic paper.

An activation analysis was made of the irradiated plastic paper to be sure that no undesirable activities were present in the gamma energy region of interest. The reproducibility of our germanium oxide deposits was checked and was found to be better than 10%.

To avoid problems of weight intercalibration each run was repeated for each pair of foils reversing the position of bare and cadmium-covered foils.

The foil activities were counted alternately in a Li-drifted Ge gamma-ray spectrometer to total around 10^6 counts. Dead time correction in the spectrometer multichannel analyzer system was controlled to be less than 0.5% and the multichannel analyzer was operated in the live-time mode.

^{74}Ge

Metallic germanium foils (406 mg/cm^2) were irradiated in the central graphite reflector.

The 190 keV gamma ray of ^{75}Ge (82 min) was measured 2 h after irradiation and the activity followed for about $1\frac{1}{2}$ h.

The average result from three experiments was

$$R_{Cd}(^{74}\text{Ge}) = 7.00 \pm 0.09$$

$$I'G_r/\sigma_0 = 1.383 \pm 0.021$$

Thin foils (40 mg/cm^2) of germanium oxide were irradiated bare and cadmium covered for 5 min and the 190 keV gamma-ray activity measured 1 h after irradiation. Eight runs were made with four pair of foils, reversing the cadmium box position for each pair.

The average result was

$$R_{Cd}(^{74}\text{Ge}) = 6.64 \pm 0.10$$

$$I'G_r/\sigma_0 = 1.497 \pm 0.027$$

By extrapolation of $I'G_r/\sigma_0$ as a function of the calculated G_r, as described before, the value of the ratio of the resonance integral to the thermal cross section for infinite dilution is obtained:

$$I'/\sigma_0 = 1.514 \pm 0.031$$

In Table 1 are summarized the results of the experiments and the experimental resonance self-shielding. The thermal cross section adopted for ^{74}Ge is the value recommended by Goldberg *et al.* (1966), $\sigma_0 = 0.45 \pm 0.08$ b.

From the experimental value of I'/σ_0 and $\sigma_0 = 0.45 \pm 0.08$ b, $I' = 0.681 \pm 0.123$ b is obtained. The calculated value is $I'_{calc} = 0.217$ and disagrees by a factor of three. This calculation

TABLE 1. Resonance integral and resonance self-shielding of ^{74}Ge

δ (mg Ge/cm^2)	G_r calculated	$I'G_r/\sigma_0$ measured	G_r experimental
406	0.7042	1.383	0.9135
28	0.9622	1.497	0.9888
0	1	1.514	1

TABLE 2. Resonance integral and resonance self-shielding of ^{76}Ge

δ (mg Ge/cm^2)	G_r calculated	$I'G_r/\sigma_0$ measured	G_r experimental
406	0.782	9.584	0.798
17	0.987	11.860	0.988
0	1	12.004	1

was made with the resonance parameters of Maletzki *et al.* (1968) from 2 keV to 60 keV and Dresner treatment of the unresolved resonance integral. This discrepancy is considered further in a separate section.

Similarly the experimental G_r in Table 1 disagrees with the calculated G_r. If one assumes that this discrepancy is due to a nonshielded contribution, P, to the resonance integral, then

$$G_r(\text{exp.}) = \frac{(\sum G_{ri}I_i)^{calc} + P}{(\sum I_i)^{calc} + P}$$

and P is about 0.5 b, which gives $I' = 0.72$ b, in better agreement with our experimental value of the resonance integral.

^{76}Ge

Thick foils of 406 mg/cm^2 of metallic germanium were irradiated for 3 h and measurement of the ^{77}Ge photopeaks started 24 h after irradiation to allow for complete decay of ^{75}Ge (82 min).

The bare and cadmium-covered samples were counted alternately and the decay of the 210, 215, and 263 keV of ^{77}Ge photopeaks (11.3 h) was followed for about 2 days.

Three irradiations were performed and the average result was

$$R_2 = 1.897 \pm 0.001$$

To obtain R_3 the activity of the ^{77}As (38.7 h) 239 keV gamma ray was counted. This is the strongest activity available because 97% of the decays go directly to the ground state. This activity was counted when the ^{77}Ge photopeak activity had decayed to the same order. Three irradiations were made and the foil activity was counted for about 10 h, from 117 to 127 h after the end of irradiation. The average result was

$$R_3 = 2.041 \pm 0.010$$

During the counting time, B_0 in expression [2] varies very slowly (0.12% in 10 h) and can be considered constant during the measurement, $B_0 = 0.7792$ at 122 h.

In expressions [1], [2], and [3], $Y = 0.339$ (Mannhart and Vonach 1968), $f = 0.24$ (Lederer *et al.* 1968). The results are

$$(R_{Cd} - 1) = 1.076 \pm 0.013$$

$$I'G_r/\sigma_0 = 9.58 \pm 0.12$$

Thin foils of 25 mg/cm^2 of germanium oxide were irradiated for 30 min. Three pairs of foils were used reversing the cadmium position for each pair; six runs in total were made.

The ^{77}Ge photopeaks were counted 24 h after the end of irradiation and the average was

$$R_2 = 1.731 \pm 0.007$$

Self-shielding which depends only on the total cross section at the resonances will equally affect both isomeric states and $R_2 - 1/R_3 - 1$ will not depend on the thickness. This ratio could be determined with better statistics for thick samples than for thin samples. Thus for thin samples only R_2 was determined and R_3 was obtained using the ratio of $R_2 - 1/R_3 - 1$ determined for thick samples.

A direct measurement of R_3 made on thin samples only in one run agreed within 1% with the value obtained by this method.

The values of R_{Cd} and $I'G_r/\sigma_0$ for thin foils are

$$(R_{Cd} - 1) = 0.877 \pm 0.011$$

$$I'G_r/\sigma_0 = 11.860 \pm 0.158$$

From $I'G_r/\sigma_0$ for two thickness, I'/σ_0 can be extrapolated as described in the Method section and the results are shown in Table 2. We then obtain

$$I'/\sigma_0 = 12.00 \pm 0.16$$

Using the thermal activation cross section for ^{77}Ge^m (54 s) recommended by Goldberg *et al.*

TABLE 3. ^{74}Ge cross section at 24[a] keV

References	Cross section (b) Calculated	Measured
Macklin *et al.* (1957)		0.057
Chaubey and Sehgal (1966)		0.020
Lakshmana Rao *et al.* (1970)		0.0896
Benzi (1969)	0.049	
Musgrove (1969)	0.033	
Dovbenko *et al.* (1969)	0.044	0.044
Average	0.042	0.053
Estimated cross section at 24 keV with Maletzki *et al.* (1968) parameters, with dispersion		
$\Delta E = \pm 1$ keV	0.016[b]	
$\Delta E = \pm 5$ keV	0.011[c]	

[a]Nominal Sb–Be source neutron energy.
[b]Estimated cross section varies 10% if calculated at 22 keV.
[c]Calculated cross section does not vary if calculated at 22 keV instead of 24 keV.

(1966), $\sigma_0(m) = 0.11 \pm 0.02$ b, and the thermal isomeric yield ratio $Y = 0.339 \pm 0.020$ (Mannhart and Vonach 1968), one obtains $\sigma_0 = 0.166 \pm 0.030$ b.

With $I/\sigma_0 = 12.00 \pm 0.16$ and $\sigma_0 = 0.166 \pm 0.030$ b we obtain

$$I = 1.992 \pm 0.359$$

Using the neutron resonance parameters given by Maletzki *et al.* (1968), the calculated value is $I = 1.20$ b which seriously disagrees with the experimental value.

Evaluation of ^{74}Ge keV Neutron Radiative Capture Cross Section and Resonance Integral

Early measurements of ^{74}Ge neutron activation cross sections were made by Macklin *et al.* (1957) and Lyon and Macklin (1959) at 24 and 197 keV. New activation cross section measurements at 24 keV were made by Chaubey and Sehgal (1966) and Lakshmana Rao *et al.* (1970).

Tolstikov *et al.* (1967) and Dovbenko *et al.* (1969) made a differential activation cross section measurement from 10 keV to 3 MeV and obtained a good fit with their calculated statistical model curve and a reasonable agreement with Macklin measurements.

There are also measurements in the MeV energy region by Hughes *et al.* (1953) and Pasechnik *et al.* (1958).

In addition to these low resolution measurements there are the previously quoted neutron resonance and resonance parameter measurements from 2 keV to 60 keV, made by transmission and capture technique with enriched ^{74}Ge samples (Maletzki *et al.* 1968).

Furthermore, there are two semi-empirical statistical model calculations for ^{74}Ge by Benzi and Reffo (1969) and Musgrove (1969).

We estimated from Maletzki neutron resonance parameters the average activation cross section at 24 keV with energy dispersion of ± 1 keV ($\Delta E = 2$ keV) as recommended for Sb–Be sources (Pauw 1970) and of ± 5 keV ($\Delta E = 10$ keV) as quoted by Dovbenko *et al.* (1969).

Examination of Table 3 shows that Maletzki neutron resonance parameters seriously underestimate neutron captures at 24 keV.

This discrepancy may be due to neglect of *p*- and *d*-wave neutron captures according to the statistical model calculations of Dovbenko *et al.* (1969) and Musgrove (1969).

We may now proceed to evaluate the neutron radiative capture resonance integral from the ^{74}Ge cross sections quoted previously. The unresolved part of the reduced resonance integral from 60 keV to 10 MeV was evaluated by Dresner treatment (Dresner 1960) using Maletzki *et al.* (1968) average resonance parameters; by numerical integration of the resonance integral using the statistical model calculated cross section (Benzi and Reffo 1969); and

TABLE 4. Calculation of ^{74}Ge unresolved resonance integral (60 keV $< E \leqslant$ 10 MeV)

References	Resonance integral (b)	
	$1/E$ spectrum	Reactor spectrum[a]
Dresner formalism[b]	0.002	
Benzi (1969)	0.058	0.161
Tolstikov *et al.* (1967) and Dovbenko *et al.* (1969)	0.055	0.150

[a]54 group diffusion reactor spectrum calculation.
[b]With Maletzki *et al.* (1968) parameters.

TABLE 5. Evaluation of ^{74}Ge resonance integral in the reactor spectrum[a]

References	I' (b)		
	2–10 keV	10–60 keV	60 keV–10 MeV
Maletzki *et al.* (1968)[b]	0.231	0.013	0.005
Tolstikov *et al.* (1967) and Dovbenko *et al.* (1969)[c]		0.116	0.150
Benzi (1969)[d]		0.126	0.161
Experimental value $I' = 0.68 \pm 0.12$			

[a]Multigroup diffusion calculation.
[b]Breit–Wigner calculation and Dresner formalism for unresolved resonance integral.
[c]Low resolution differential activation cross section measurement.
[d]Semi-empirical statistical model cross section.

finally, by using differential activation cross sections (Tolstikov *et al.* 1967; Dovbenko *et al.* 1969). These numerical integrations were made both for a $1/E$ spectrum and a reactor spectrum obtained from a 54 group diffusion code (Boix and Solanilla 1967). The results are shown in Table 4.

One may observe in this table that the Dresner formalism which assumes equally spaced s-wave neutron resonances underestimates by a factor of 70 the unresolved resonance integral of ^{74}Ge. This underestimation is significant for isotopes with wide average level spacing ($\sim$keV), where the unresolved resonance integral is comparable with the contribution of the first or second keV main s-wave resonances; thus some unresolved resonance integrals may have been incorrectly calculated in previous evaluations (Persiani 1963; Schmidt 1966; Connolly *et al.* 1968; Walker 1969; Müller 1970).

In addition it can be observed that about half of the unresolved resonance integral comes from the 1 MeV region where the slowing down spectrum of a thermal reactor is not $1/E$. This fraction is about 10% of the experimental resonance integral ($I' \cong 0.68$) and may be enhanced (by a factor of two or three) in partial resonance integrals for the production of high-spin isomers. This shows that high-spin isomers may not be adequate indicators of keV neutron flux.

In Table 5 an evaluation of the reduced resonance integral of ^{74}Ge is made by different procedures.

It can be seen that the Maletzki *et al.* (1968) neutron resonance parameters seriously underestimate captures between 10 and 60 keV and this is consistent with our evaluation of ^{74}Ge neutron capture cross section at 24 keV and the unresolved resonance integral.

A second observation is that the disagreement between the ^{74}Ge experimental activation resonance integral and that calculated with neutron resonance parameters will be reduced if the data

from differential activation cross section of Dovbenko *et al.* (1969) are used to calculate the resonance integral from 10 keV to 10 MeV.

Therefore, the present evaluation of the ^{74}Ge resonance integral suggests that about one third of the activation resonance integral comes from neutron captures in the main *s*-wave neutron resonances, another one third comes from energies higher than 60 keV, and the remaining part can be ascribed to *p*- and *d*-wave neutron resonances which have not been resolved between 3 keV and 60 keV.

A comment may be added about the discrepancy in ^{76}Ge. The calculated resonance integral for the 550 eV resonance of ^{76}Ge is around 1 b and the contribution of keV energy resonances is 200 mb.

If the discrepancy of 800 mb between experimental and calculated ^{76}Ge resonance integral is assigned to the keV energy region, the calculated contribution of 200 mb in this energy region would be in error by a factor of four, in qualitative agreement with the results of ^{74}Ge.

Final Remarks

This measurement of ^{74}Ge and ^{76}Ge activation resonance integrals confirms previous results which showed that neutron captures in the keV energy region by isotopes with wide average resonance spacing were seriously underestimated by Breit–Wigner resonance integral calculations.

A critical analysis and evaluation of neutron radiative capture cross sections showed that an important fraction of neutron captures comes from energies higher than 10 keV.

This makes ^{74}Ge and ^{76}Ge and similar detectors like ^{80}Se and ^{64}Zn studied in our previous work (Ricabarra *et al.* 1968, 1969) unsuitable for neutron detection in the keV energy region because only a minor fraction of the activity comes from neutron captures in the lowest keV energy resonances, and shows that there is still much work and investigation to be done in order to find a convenient foil detector for neutron flux in the keV energy region.

Finally, previous evaluation suggests that for isotopes with wide average resonance spacing ($\sim$keV), differential activation or semi-empirical statistical model neutron cross sections may give a better description of neutron captures in the range of 10 keV to 100 keV than that obtained from resolved resonance parameters.

Appendix I

We may remind the reader that the value of the experimental resonance integral given in this paper may be defined as the integral reaction rate above the cadmium cutoff normalized to the slowing down flux at the standard resonance energy.

In previous work (Ricabarra *et al.*, 1968, 1969, 1970) a correction for the small deviation of the reactor spectrum relative to the $1/E$ spectrum has been applied to our experimental value and this correction is accurate if it is assumed that activation comes mainly from one or two low energy resonances. In this case the spectral correction will not be dependent on the assumed resonance parameters.

In this paper our experimental data has not been corrected as in previous ones, because to do this would imply knowledge of the distribution of neutron captures in function of energy which was *a priori* not known and is one of the results of this investigation.

However, only 10% of the activation experimental resonance integral of ^{74}Ge comes from neutron captures in the MeV region, where the flux in the reactor is not "nearly" $1/E$, and only this fraction would significantly change for a cadmium-covered sample irradiated in a more thermalized spectrum. This fraction may be easily estimated with the knowledge of the fast flux and activation cross section of ^{74}Ge at 1 MeV.

Appendix II

The activity of ^{77}Ge and ^{77}As per atom, in a germanium sample that has been exposed to a flux equal to one, during a time T, and measured at a time t, after the end of the irradiation is

$$A(^{77}\mathrm{Ge}) = a_0\hat{\sigma}(\mathrm{g}) + fa_1\hat{\sigma}(\mathrm{m})$$

$$A(^{77}\mathrm{As}) = (1-f)b_0\hat{\sigma}(\mathrm{m}) + b_1\hat{\sigma}(\mathrm{g}) + fb_2\hat{\sigma}(\mathrm{m})$$

where $\hat{\sigma}(\mathrm{g})$ and $\hat{\sigma}(\mathrm{m})$ are the effective cross sections for the production of the ground and metastable isomers, and the coefficients a_0, a_1, b_0, b_1, b_2, depend on the decay constants λ_1,

λ_2, λ_3 of $^{77}Ge^m$, ^{77}Ge, and ^{77}As, the irradiation time, and the time of the measurement.

Extrapolating to the end of the irradiation and dividing by $(1-\exp(-\lambda T))$, we have the saturation activities

$$Q(^{77}\mathrm{Ge}) = \frac{A(^{77}\mathrm{Ge})\, e^{\lambda_2 t}}{1-e^{-\lambda_2 T}}$$

$$Q(^{77}\mathrm{As}) = \frac{A(^{77}\mathrm{As})\, e^{\lambda_3 t}}{1-e^{-\lambda_3 T}}$$

which can be expressed as

$$Q(^{77}\mathrm{Ge}) = \hat{\sigma}(\mathrm{g}) + fC_0\hat{\sigma}(\mathrm{m})$$

$$Q(^{77}\mathrm{As}) = (1-f)C_1\hat{\sigma}(\mathrm{m}) + C_2\hat{\sigma}(\mathrm{g}) + fC_3\hat{\sigma}(\mathrm{m})$$

or

$$Q(^{77}\mathrm{As}) = \hat{\sigma}(\mathrm{g}) + B_0\hat{\sigma}(\mathrm{m})$$

$$B_0 = \frac{(1-f)C_1 + fC_3}{C_2}$$

From well-known expressions for radioactive decay we have

$$C_0 = \frac{e^{\lambda_2 t}}{1-e^{-\lambda_2 T}}\left[\frac{\lambda_2}{\lambda_2-\lambda_1}(1-e^{-\lambda_2 T})\,e^{-\lambda_1 t} - \frac{\lambda_1}{\lambda_2-\lambda_1}(1-e^{-\lambda_1 T})\,e^{-\lambda_2 t}\right]$$

C_1 has the same form with λ_3 instead of λ_2, and C_2 is similar, replacing λ_2 with λ_3 and λ_1 with λ_2.

$$C_3 = \frac{e^{\lambda_3 t}}{1-e^{-\lambda_3 T}}\left[\frac{\lambda_3}{\lambda_3-\lambda_2}\left(1-\frac{\lambda_2}{\lambda_2-\lambda_1}e^{-\lambda_1 T}+\frac{\lambda_1}{\lambda_2-\lambda_1}e^{-\lambda_2 T}\right)e^{-\lambda_2 t}\right.$$
$$\left. - \frac{\lambda_2}{\lambda_3-\lambda_2}\left(1-\frac{\lambda_3}{\lambda_3-\lambda_1}e^{-\lambda_1 T}-\frac{\lambda_1}{\lambda_3-\lambda_1}e^{-\lambda_3 T}\right)e^{-\lambda_3 t}\right]$$

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