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Excitation Functions for the $^{9}Be(^{18}O, 2\alpha)^{19}O$ and $^{9}Be(^{18}O, d)^{25}Na$ Reactions

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Abstract

In order to determine traces of beryllium by Heavy Ion Activation Analysis (HIAA), yield curves and total cross sections for the $^{9}Be(^{18}O, 2\alpha)^{19}O$ and $^{9}Be(^{18}O, d)^{25}Na$ reactions were determined in the 10 to 40 MeV energy range of incident ions. The yields of characteristic γ-rays (^{19}O: E_γ = 197 keV and ^{25}Na: E_γ = 397 keV) were used for this purpose.

Introduction

The quality- and purity control of new material at diverse steps of preparation and the institution of security norms concerning pollution have promoted rapid evolution of analytical techniques of trace elements. The nuclear reactions induced by heavy ion beams accelerated to energies up to 2 MeV/amu have played an important part in chemical analysis, especially of light elements [1]. Knowledge of the excitation functions of these reactions is useful in order to find out the best experimental conditions for an analytical application to trace determination.

The reactions induced by ^{18}O on beryllium, boron, silicon, sulfur and sodium have been described in earlier papers [2–4]. The physical mechanism of these nuclear interactions has been reported [2, 3] and cross sections have been calculated.

In the present work, the excitation functions of the nuclear reactions induced by ^{18}O on beryllium have been established for a large energy range ($E_{^{18}O}$ = 10 to 40 MeV). The results show the possibility of an application for the determination of traces of Be using radioisotopes with short half-lives: ^{19}O (T = 27.1 s) and ^{25}Na (T = 59.7 s).

Experimental

Beams of ^{18}O ions at various energies and charge states were obtained with the HV EC-EN Tandem Van de Graaff accelerator of the Institute for Medium Energy Physics at the Swiss Federal Institute of Technology in Zürich. The $^{18}O^{n+}$ ions were obtained by sputtering of an enriched oxygen $Ca^{18}O$ solid cone.

The targets used were pure metallic Be discs (99% Be, GOODFELLOW METALS Ltd) of 15 mm diameter and 1–2 mm thickness. They were thicker than the range of the incident ion beam, whose intensity ranged from 20 to 100 nA.

The experimental irradiation set-up, especially designed to determine the production of radionuclides with short half-lives, has been described in an earlier paper [5]. It allows cyclic irradiations and activity measurements without interruption of vacuum (10^{-5} mm Hg). Targets were mounted on a mobile holder and irradiated for typically 10 seconds. The target holder was then transferred to the counting position in less than 1 second and its radioactivity was measured with a Ge(Li) detector (ORTEC 8001-1020 V, 2.0 keV resolution at 1.33 MeV) through a thin plexiglass window for typically 30 seconds. The detector was linked to a multichannel analyzer (CANBERRA 80). When necessary, dead time corrections were made using the peak of a 50 Hz impulse generator. The beam current was monitored immediately after the sample activity measurement using a Faraday cup placed just behind the position of the irradiated target. The whole electronically controlled process (irradiation - activity measurement - beam monitoring) was repeated for 10 cycles. The experimental conditions have been determined with a computer program [6] which optimizes (a) the irradiation time, (b) the delay between the end of irradiation and the beginning of activity measurement, (c) the counting time and (d) the number of cycles. The spectrum obtained after each irradiation was automatically added to those already stored in the multichannel analyzer, thus providing better statistics and a higher precision of the specific activity. At the end of the final counting, the total spectrum was transferred to a floppy disc recorder (SCIENTIFIC MICRO SYSTEMS D222) for further analysis with a PDP 11/23 computer. Standard ^{152}Eu and ^{22}Na sources with the same geometry as the targets were used for energy and efficiency calibration of the counting system.

Cross section calculation

KRASNOV [7] has defined a thick target reaction yield, Y, by the following relation:

$$Y = n \int_{E}^{0} \sigma(E) \frac{dx}{dE} \, dE \qquad (1)$$

where n = concentration of atoms from which radionuclide is formed (at · g^{-1})

$\sigma(E)$ = cross section for incident energy E (cm^2)

$\frac{dx}{dE}$ = differential energy loss of the incident ions (MeV · g^{-1} · cm^2)

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This reaction yield was determined experimentally for each incident energy, using the equation:

$$Y = \frac{a_0\, t z}{6.24 \times 10^{12}\,(I t)\,(1-e^{-\lambda t})\,\epsilon u} \qquad (2)$$

where a_0 = counting rate at the end of irradiation (s^{-1})
t – irradiation time (s)
z = charge of the incident ion
$6.24 \times 10^{12}/z$ = beam current (I) and ion flow (ϕ) interrelation factor
It = integrated charge collected on target (μC)
$(1-e^{-\lambda t})$ = saturation factor
λ = decay constant (s^{-1})
ϵ = detector efficiency for the chosen γ-ray
u = abundance of the γ-ray of interest [9]

Owing to the cyclic mode and the summation of the 10 spectra, the counting rate at the end of irradiation had to be determined from the total number of counts, N_t, detected in the chosen photopeak, whereby the various adjustable experimental parameters were taken into account [6]. Furthermore, the short half-lives involved required a counting rate correction due to the decay during acquisition [10]. Thus:

$$a_0 = \frac{N_t\,\lambda\,(1-e^{-\lambda t_c})}{(1-e^{-\lambda \Delta t})\,e^{-\lambda t_D}} \left[n_c + \frac{1-e^{-\lambda n_c t_c}}{1-e^{-\lambda t_c}} \right]^{-1} \qquad (3)$$

where t_c = time separating one irradiation from the next (s)
Δt = counting time (s)
t_D = delay between the end of irradiation and the beginning of counting (s)
n_c = number of cycles

The experimental yield curve thus obtained was refined using a computer program [11]. The derivative of equation (1), $\frac{dY}{dE'}$, at a given energy leads to the cross section:

$$\sigma(E) = \frac{1}{n}\left(\frac{dY}{dE}\right)_E \left(\frac{dE}{dx}\right)_E \qquad (4)$$

Results and discussion

The Q-value and the Coulomb barrier of the two reactions are presented in Table 1 together with the characteristics of the produced radionuclides. The underlined γ-ray energies are used for determining the specific activities at the various energies. These low energies are particularly suitable for detection with a Ge(Li) detector. The absolute intensities of the γ-rays are given in parentheses. They correspond to the decay scheme factors.

Fig. 1 shows a typical γ-ray spectrum obtained by bombarding a thick beryllium target with a 17 MeV $^{18}O^{+3}$, 100 nA ion beam for 10 cycles. Owing to the low specific activities of ^{23}Ne, the latter has been discarded. The characteristic γ-rays from both ^{19}O and ^{25}Na appear clearly.

Table 1. Nuclear reactions and characteristics

Reaction	Q value (MeV)	Coulomb barrier (MeV)	Half-life (s)	γ-ray energies (keV)	
^{9}Be(^{18}O,d)^{25}Na	+6.8	19.6	59.7	390.7	(12.8%)
				585.9	
				975.2	
				1611.9	
^{9}Be(^{18}O,2α)^{19}O	+2.4	19.6	27.1	109.9	
				197.4	(97.0%)
				1375.6	
				1440.9	

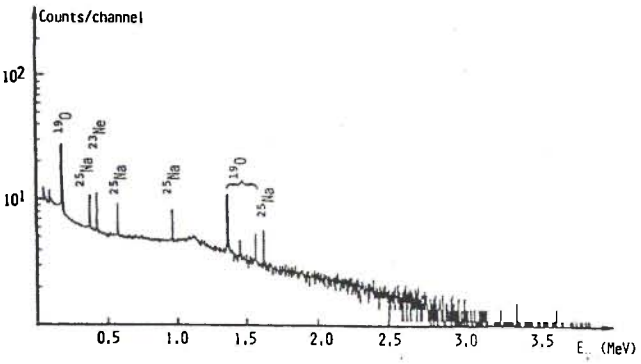

Fig. 1. γ-ray spectrum of irradiated beryllium ($E_{^{18}O}$ = 17 MeV, t = 10 s, t_D = 1 s, Δt = 30 s, n_c = 10).

Excitation function for the ^{9}Be(^{18}O,d)^{25}Na reaction

The reaction was studied between E_{lab} = 15 MeV and E_{lab} = 40 MeV ^{18}O. The charge state of the ^{18}O ions increased from +3 to +6 upon increasing the beam energy. The ^{25}Na production yield per incident particle is presented in Fig. 2a. The curve is a monotonically increasing

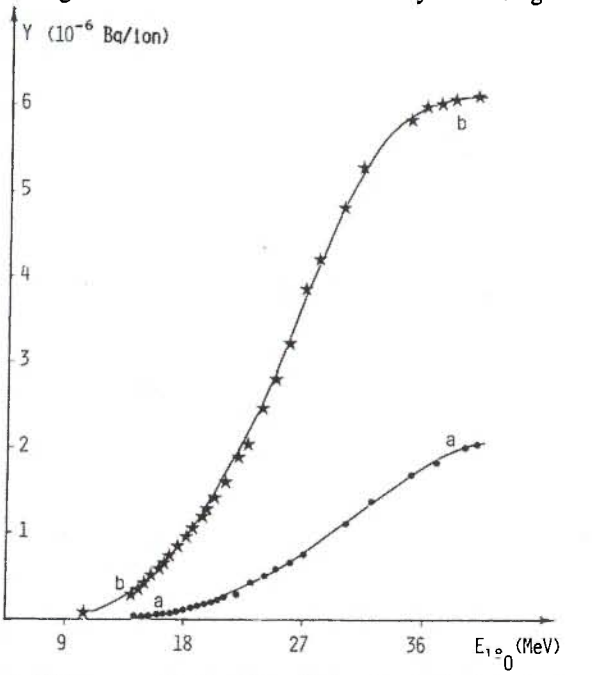

Fig. 2. Yield curves. (a) ^{9}Be(^{18}O,d)^{25}Na, (b) ^{9}Be(^{18}O,2α)^{19}O.

function throughout the whole energy range. The error on $Y(E)$ has been estimated to be about ± 8% when combining the errors of all parameters of relations (2) and (3).

The excitation function has been determined from these data and is presented in Fig. 3a. The errors on the cross sections are ± 11%. The calculated cross sections are of the same order of magnitude as those given by FALK *et al.* [3]; their maximum value was reported to be about 35 mb at 25 MeV ^{18}O, whereas our results show a maximum cross section of 23.6 ± 2.6 mb at 30 MeV. This difference could be explained by the narrow range of energy studied by these authors and by the method which they employed to determine the excitation functions.

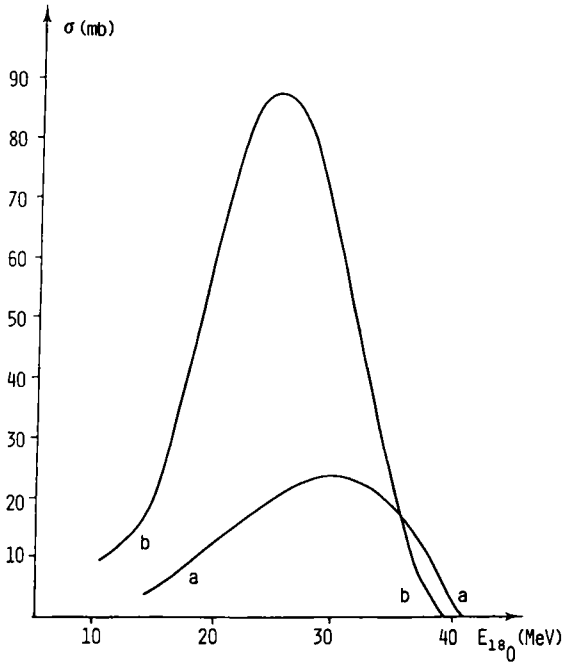

Fig. 3. Total cross sections. (a) $^{9}Be(^{18}O, d)^{25}Na$, (b) $^{9}Be(^{18}O, 2\alpha)^{19}O$.

Excitation function for the $^{9}Be(^{18}O, 2\alpha)^{19}O$ reaction

This reaction was studied between 10 and 40 MeV. The ^{19}O production yield per incident particle, presented in Fig. 2b, increases regularly from 10 to 35 MeV. It reaches a plateau above this energy.

Fig. 3b shows the excitation function calculated from these data. A maximum cross section of 90 ± 15 mb is obtained with a 25 MeV $^{18}O^{+4}$ beam. This value is in good agreement with that given by FALK *et al.* [3], although the function of these authors is flat at higher energies. Again, the observed difference could be explained by their experimental conditions.

Beryllium trace analysis

The maximum cross sections for both reactions are large enough to be utilized in analysis. The detection limits for beryllium have been calculated to be 110 ng with the $^{9}Be(^{18}O, d)^{25}Na$ reaction and 5 ng via ^{19}O.

In order to check the selectivity of the technique, a series of elements likely to produce either ^{19}O or ^{25}Na (or both simultaneously) in a ^{18}O induced nuclear reaction was tested. Among the 15 elements suspected for nuclear interference (identified with a computer program [12]), none produced ^{19}O and ^{25}Na simultaneously. For a bombarding energy of 25 MeV $^{18}O^{+4}$, only boron yields ^{25}Na and lithium ^{19}O, but their interference ratios remain very low (5% and 2% respectively).

In this way, a fast, non-destructive, selective and sensitive determination of beryllium is possible. The technique has already been applied successfully to metallic and biological specimens.

Acknowledgement

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