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Excitation Functions for the $^{11}B(^{18}O, pn)^{27}Mg$ and $^{32}S(^{18}O, t)^{47}V$ Reactions

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Abstract

In order to determine traces of boron and sulfur using Heavy Ion Activation Analysis (HIAA), yield curves and total cross sections for the $^{11}B(^{18}O, pn)^{27}Mg$ and $^{32}S(^{18}O, t)^{47}V$ reactions were determined in the 15 to 44 MeV ^{18}O and 27 to 44 MeV ^{18}O energy ranges respectively. The yields of characteristic γ-rays (^{27}Mg: E_γ = 843 keV and ^{47}V: E_γ = 511 keV) were detected either with a Ge(Li) detector or by coincidence measurements using two 3″ × 3″ NaI(Tl) scintillation detectors.

Introduction

The development of heavy ion beams with energies up to 2 – 3 MeV/amu have made possible the use of nuclear reactions in Heavy Ion Activation Analysis (HIAA) of light elements particularly [1, 2]. The knowledge of the excitation functions of these reactions is useful to determine the best experimental conditions for an analytical application to trace determination of the elements considered.

FALK *et al.* [3, 4] have studied the nuclear reactions induced by an ^{18}O ion beam in the energy range $12 \leqslant E_{lab} \leqslant 30$ MeV on boron, beryllium, and sodium. In order to discuss these reactions' mechanisms, they have determined the yield and the cross sections of all the reactions producing radionuclides by bombarding these three elements.

The goal of this work was to determine the excitation functions for the production of ^{27}Mg and ^{47}V via the $^{11}B(^{18}O, pn)^{27}Mg$ and $^{32}S(^{18}O, t)^{47}V$ reactions, respectively in a larger range of energy: $15 \leqslant E_{lab} \leqslant 44$ MeV. Given the results, this study could, thus, be applied analytically.

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 Swiss Federal Institute of Technology in Zürich, using enriched oxygen in the $Ca^{18}O$ solid form as an ion source.

The material used for the cross section measurements were boron powder and PbS powder (97% purity, FLUKA). Targets were prepared by pelleting these powders as small 13 mm diameter and 1 – 2 mm thick disks. In the case of the $^{32}S + ^{18}O$ reaction, PbS was chosen since the low melting point (117 °C) and the sublimation of pure sulfur do not allow its irradiation in the elementary form. All the targets were thicker than the range of the incident ion beam, whose intensity ranged from 20 to 100 nA. With these values, no target deterioration was observed.

The experimental irradiation set-up has been described in an earlier paper [5]. The level of vacuum in the irradiation chamber was 10^{-5} mm Hg. The diameter of the ^{18}O ion beam on the target was restricted to 8 mm by a couple of tantalum collimators. The number of ^{18}O ions striking the target was determined from the integrated charge on a Faraday cup.

The γ-rays were measured on a Ge(Li) detector (Ortec 8001-1020 V, 2.0 keV resolution for the 1.33 MeV ^{60}Co γ-ray), coupled with a multichannel analyzer (Canberra Series 80). Dead time corrections, when needed, were made during the data acquisition using the peak of a 50 Hz impulse generator. The spectra were transfered to a floppy disk recorder (Scientific Micro System D 222) 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.

An automatic sample changer for coincidence counting equipped with two 3″ x 3″ NaI(Tl) scintillation detectors (Quartz & Silice, Scintibloc 76/S/76) was used to measure the 511 keV γ-rays from the positron annihilation and to follow the decay curves. These curves were then deconvoluted using the CLSQ computer program [6]. The overall counting efficiency of the system was determined to be 4.4%.

Cross Section Calculation

KRASNOV *et al.* [7, 8] have defined a thick target reaction yield, Y, by the following equation:

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

where n – concentration of atoms from which radionuclide is formed (atom · mg^{-1}),
Φ – particle flow (particles · sec^{-1}),
$\sigma(E)$ – cross section for incident energy E (cm^2),
dE/dx – differential energy loss of the incident ions (MeV · mg^{-1} · cm^2)

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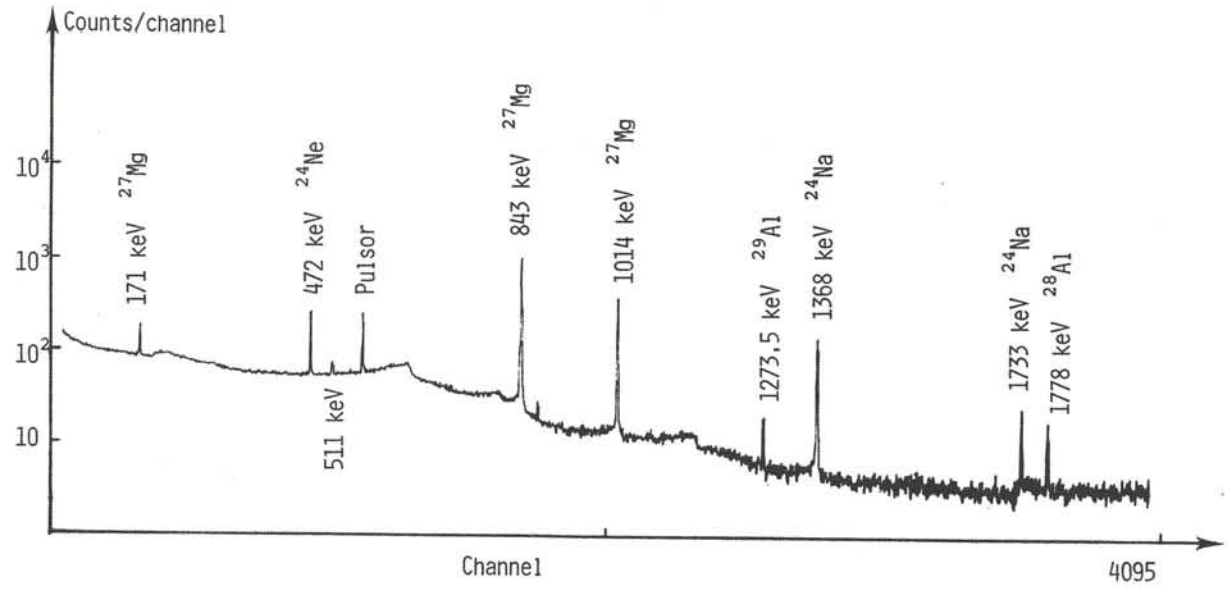

Fig. 1. γ-ray spectrum of irradiated boron ($E_{^{18}O^{+5}}$: 34 MeV, delay: 480 sec., counting time: 200 sec.)

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

$$Y/\Phi = \frac{a_0 \cdot t \cdot z}{S \cdot (\mathrm{It}) \cdot \epsilon \cdot u \cdot \zeta \cdot (6.24 \times 10^{12})} \qquad (2)$$

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

The experimental yield curve, thus obtained, given in Bq·particle^{-1} vs. MeV, was smoothed using a computer program [10], which took into account the errors on each separate value of $Y(E)$.

The derivative of equation (1) at a definite energy E_1 leads to the cross section:

$$\sigma(E_1) = \frac{1}{n \cdot \Phi} \left(\frac{dY}{dE}\right)_{E_1} \cdot \left(\frac{dE}{dx}\right)_{E_1} \qquad (3)$$

where the second term is the derivative of the reaction yield at the energy E_1 and the third term, the differential energy loss of the incident particle as given by NORTHCLIFF *et al.* [11].

Results and discussion

Excitation function for the $^{11}B(^{18}O, pn)^{27}Mg$ reaction

The kinematic parameters of the reaction have been previously given by FRIEDLI *et al.* [5]. FALK *et al.* [4] used enriched ^{10}B and ^{11}B powders to conduct their research. They have shown that the yields of ^{27}Mg are much greater with ^{11}B targets than with ^{10}B targets and a numerical calculation revealed that essentially all the yield for this product in the case of ^{10}B targets could be explained by the ^{11}B impurity. Thus, all the ^{27}Mg produced was linked to the $^{11}B + ^{18}O$ reaction.

Targets of natural boron were irradiated for 10 minutes, and a typical γ-ray spectrum is presented in Fig. 1. Of all the observed γ-rays arising from ^{24}Ne, ^{24}Na, ^{28}Al, ^{29}Al, and ^{27}Mg, the 843 keV transition from ^{27}Mg is the most intense, whatever the incident beam energy. The reaction was studied between E_{lab} = 15 and E_{lab} = 44 MeV by steps of 500 keV. The charge state of ^{18}O ions went up from +3 to +6 upon increasing the beam energy. The beam current was kept between 0.15 and 0.30 $\mu A \cdot cm^{-2}$. The counting rate at the end of irradiation was calculated from at least 5 measurements yielding a good estimation of the errors. The ^{27}Mg production yield per incident particle is presented in Fig. 2a. The curve is a monotonous increasing function from 15 to 30 MeV. It reaches a plateau above this value. The error for $Y(E)$ has been calculated to be about 10% when combining the errors of all parameters of the relation (2).

The excitation function has been determined from these data and is presented in Fig. 3a. The errors for the cross section values are ± 15%. The calculated cross sections are in good agreement with those given by FALK

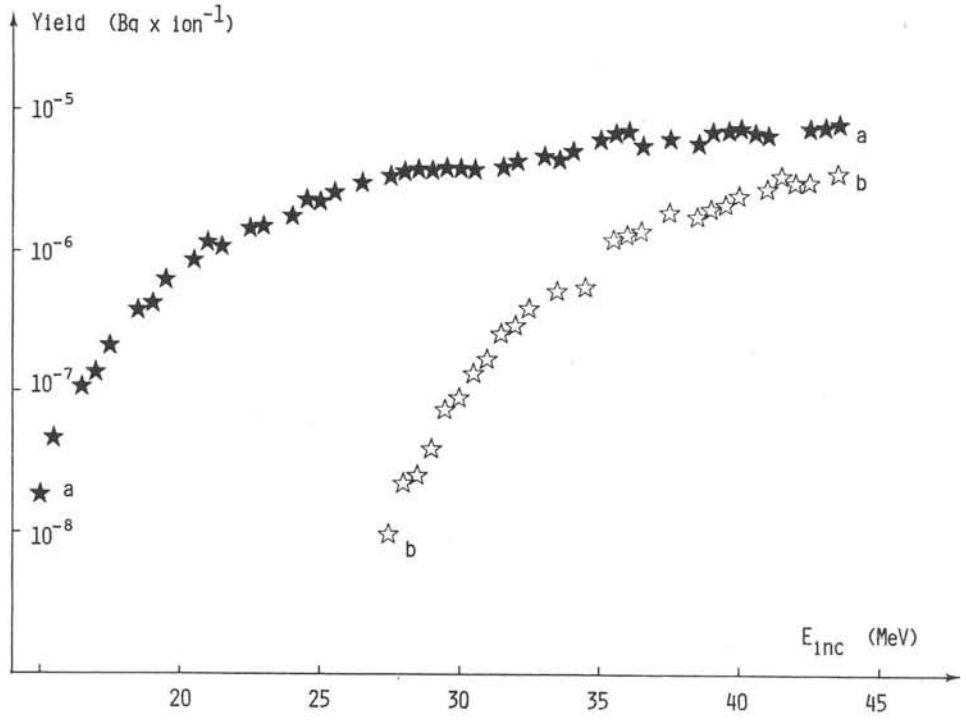

Fig. 2. Yield curves. a) $^{11}B(^{18}O, pn)^{27}Mg$ reaction b) $^{32}S(^{18}O, t)^{47}V$ reaction

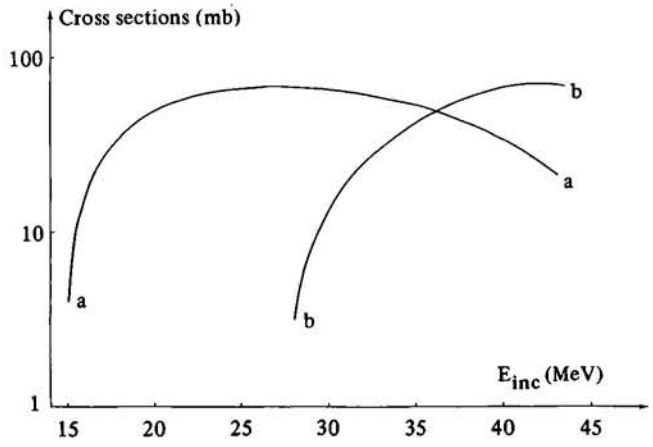

Fig. 3. Total cross sections. a) $^{11}B(^{18}O, pn)^{27}Mg$ reaction b) $^{32}S(^{18}O, t)^{47}V$ reaction

et al. [4], although a little higher at the lower energies. The maximum cross section was found to be 70 ± 10 mb corresponding to a 26.5 MeV $^{18}O^{+4}$ beam. This value is large enough to be utilized in an analytical application. With this purpose in mind a series of elements susceptible to produce ^{27}Mg through a nuclear reaction with ^{18}O ions were tested. Using the mass excess table of WAPSTRA *et al.* [13], these potential nuclear interferences were selected with a computer. The program [12] calculates the Q value, the threshold energy and the Coulomb barrier of any possible reaction with ^{18}O ions on target nuclei. Among the 15 elements tested, only 4 produced ^{27}Mg with ratios of specific activities given in Table 1. By decreasing the incident energy, the interferences due to carbon and aluminum disappear at 28 MeV, and that due to magnesium disappears at 25 MeV. As for nitrogen, the extent of interference decreases regularly with the energy of ^{18}O ions; however, at 25 MeV, the 11% interference still hinders the selectivity of the boron determination.

Table 1. *Relative extent of nuclear interferences for boron determination*

Element	Ratio of specific activities at			
	34 MeV	30 MeV	28 MeV	25 MeV
C	0.01	0.03	0	0
N	0.19	0.14	0.13	0.11
Mg	0.01	0.01	6×10^{-3}	0
Al	1×10^{-4}	1×10^{-4}	0	0

Excitation function for the $^{32}S(^{18}O, t)^{47}V$ reaction

To evaluate the contribution of each isotope of natural sulfur for ^{47}V production, two parameters were taken into account: (1) the isotopic abundance, and (2) the values of the threshold energy and of the Coulomb barrier. These data are given in Table 2. They show that ^{32}S is probably the only isotope to react with an ^{18}O ion beam. For the others, the threshold energies and/or their isotopic abundances are such that their participation in producing ^{47}V is unlikely.

PbS targets were irradiated for 30 minutes in a 0.1 to 0.4 $\mu A \cdot cm^{-2}$ beam current. The reaction was studied between 27.5 and 43.5 MeV ^{18}O. A typical γ-ray spectrum is shown in Fig. 4. The 511 keV γ-rays were measured on

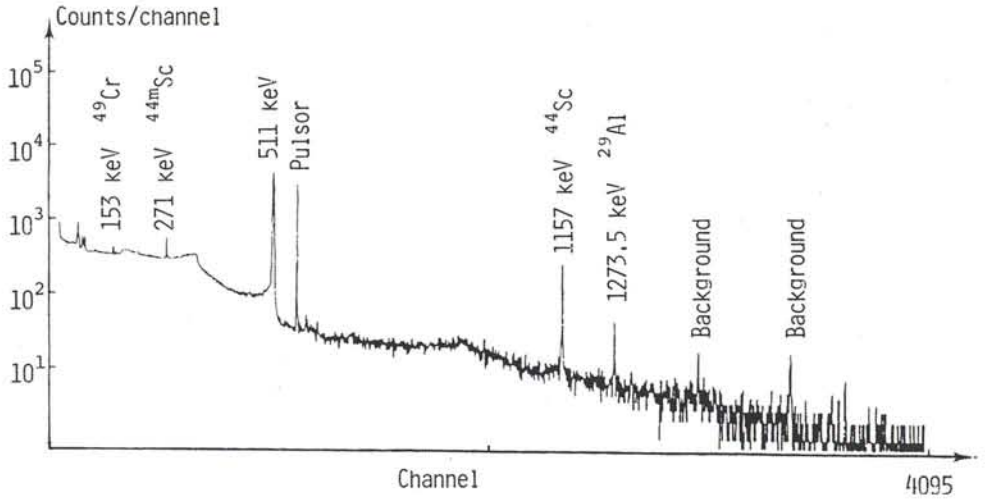

Fig. 4. γ-ray spectrum of irradiated PbS ($E_{^{18}O^{+6}}$: 39 MeV, delay: 20 min., counting time: 15 min.)

Table 2. *Isotopic abundance and kinematic parameters of the* S + ^{18}O *reactions*

Reaction	Isotopic abundance (%)	Kinematic parameters: Q (MeV)	Threshold (MeV)	Coulomb barrier (MeV)
^{32}S(^{18}O, t)^{47}V	95.02	+ 0.25	0	21.2
^{33}S(^{18}O, tn)^{47}V	0.75	− 8.39	13.0	21.1
^{34}S(^{18}O, t2n)^{47}V	4.21	−19.80	30.3	20.9
^{36}S(^{18}O, t4n)^{47}V	0.02	−36.68	55.0	20.7

the γ-γ coincidence system, and the decay curves were deconvoluted using the CLSQ program [6]. This program allows the half-lives of the different β^+ emitters produced and their activities at the end of irradiation to be calculated. The detected radionuclides were ^{47}V (half-life, $t_{1/2}$ = 32.6 min.), ^{44}Sc ($t_{1/2}$ = 3.92 h), ^{44m}Sc ($t_{1/2}$ = 2.44 day), and ^{45}Ti ($t_{1/2}$ = 3.08 h).

The yield curve, $Y = f(E)$, presented in Fig. 2b, increases regularly in the energy range studied here. Due to the limits of the accelerator performance higher energies could not be reached.

Fig. 3b shows the excitation function calculated with the relation (3). A maximum cross section of 70 ± 14 mb is obtained with a 42 MeV $^{18}O^{+6}$ beam. Thus, this reaction could be applied analytically.

Of the six potential nuclear interfering elements, as selected by the computer program [12], none produce ^{47}V. The detection limit for sulfur non-destructive determination has been calculated to be 3 ppm in the case of biological samples. The technique has already been applied successfully to metallic, ceramic and biological specimens [14].

Acknowledgement

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