Measurement of Proton-Induced Reaction Cross Sections in Ti, Ni and Zr near the Threshold

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Abstract. A stacked-foil method was used to study the cross section of the Ti(p,X)^{44}Ti, Ni(p,X)^{56}Ni and Zr(p,X)^{88}Zr reactions with energies up to 30 MeV. Natural targets of Ti, Ni and Zr were irradiated with a 30 MeV proton beam and the products were measured by residual activity using a germanium hyper-pure detector with energy resolution better than 2 keV. Due to the low irradiation energy, the (p,t) is considered the dominant channel for the formation of the final product. A good agreement between our results and other published data was found in all cases.

1. INTRODUCTION

The determination of the reaction cross sections with energies near the threshold offers new possibilities to study the structure of the nuclei given a better understanding about the reaction mechanism [1, 2] and the existence of clusters inside the nucleus [3, 4]. However, these data are, in several cases, very scarce in the literature, and a great lack of cross section data for some reactions can be found at low energies. Also, some published data for the excitation function show discrepant results or large values for the uncertainties. Specifically for (p,t) reactions at energies near the threshold in light and medium mass nuclides the reduced values of the cross section makes the greatest part of the data be concentrated at high energies.

The measurement of the cross section of (p,t) reactions is possible in online experiments or by residual activity [5, 6]. For proton energies up to 30 MeV and near the threshold, cross sections lower than 100 μb can be observed [5]. In this case an online measurement becomes a very difficult option. The aim of this work is to show the capability of our relatively simple experimental setup for the determination of reduced cross section values, establishing an optimized procedure for the study of rare reactions in very difficult experimental conditions.

2. EXPERIMENTAL METHOD

In Table 1 we present the main characteristics of the targets and products studied. The first and second columns contain, respectively, the main targets (with their isotopic abundances) and the final products. The third column show the (p,t) reaction Q values. The last two columns contain, respectively, the half-life and the main γ energies of the products with their branching ratio.

The irradiations were performed at the Cyclone-30 cyclotron of the Institute of Energetic and Nuclear Research (IPEN, Brazil). High purity foils of natural Ti and Ni, $50(1)$ μm thickness, and Zr, 0.259(5) mm thickness, were used as target. Foils of Al with various thickness were inserted between the samples for energy degradation. In front of each sample were placed Cu foils of $50(1)$ μm thickness for energy and current monitoring, as we will describe in subsection 2.1.

All products were determined by γ-ray analysis. The measurements were made using an hyper-pure germanium detector with an energy resolution of 1.69 keV for the 1332 keV transition of ^{60}Co. A covariant method [8, 9] was used to make the energy and efficiency calibration.

2.1. Determination of the Proton Beam Energy and Current

The energy and current of the proton beam were determined using Cu foils of $50(1)$ μm thickness put in front of the samples [10]. The method is based in the ratio of the activities of the nuclides ^{62}Zn and ^{65}Zn produced in the Cu by the reactions ^{63}Cu(p,2n)^{62}Zn and ^{65}Cu(p,n)^{65}Zn. In order to be clear, in this section we reproduce the formalism given in Ref. [10]. The activities can be expressed in terms of their cross sections,

$$R(E) = \frac{\sigma_1}{\sigma_2} = \frac{A_1 \tau_1}{A_2 \tau_2}, \qquad (1)$$

where the ratio $R(E)$ is a function of the energy of the incident protons, $\sigma_{1,2}$ are, respectively, the reaction cross sections for the ^{63}Cu(p,2n)^{62}Zn and ^{65}Cu(p,n)^{65}Zn reactions, $A_{1,2}$ are the ^{62}Zn and ^{65}Zn activities, respectively, and $\tau_{1,2}$ their mean-life time.

If we know the $R(E)$ function, the irradiation energy is obtained by a simple interpolation. Following the determination of the irradiation energy, the current of the

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TABLE 1. Main nuclear properties of the targets and products studied. The columns show the irradiated targets and their abundance, the products, the (p,t) reaction Q values, the half-life of the products and the γ energies with their branching ratio. The data were taken from [7].

Target / Abundance (%)		Products	Q (MeV)	$T_{1/2}$	γ (keV)	γ (%)
^{46}Ti	8.0(1)	^{44}Ti	-14.238	62.3(5) y	1157.008(3)	99.9(1)
^{58}Ni	68.077(5)	^{56}Ni	-13.984	6.10(2) d	158.39(3)	98.8(20)
^{90}Zr	51.45(2)	^{88}Zr	-12.805	83.4(3) d	392.9(1)	97.30(10)

beam is determined from the activity and cross section of one of the mentioned products:

$$A = \frac{N\sigma I t_i}{\tau}, \tag{2}$$

where A is the activity of the product, N is the number of atoms of the target, σ is the reaction cross section, I is the beam current, t_i is the irradiation time and τ the product mean-life time. The required cross section values for ^{62}Zn and ^{65}Zn formation were taken from [10].

To determine the mean proton energy value on the foils, the necessary stopping powers, $\frac{dE}{dx}$ (E is the energy loss per unit of length x), were calculated using the program SRIM based on the work of Ziegler et al [11]. Determining $\frac{dE}{dx}$, it is possible to calculate the proton energy $E_n(x')$ at any depth x' of the foil considered as a superposition of n thinner foils of equal thickness. So, for n sufficiently large, the expression

$$\langle E \rangle = \frac{1}{\Delta x}\int_0^{\Delta x} E_n(x')dx', \tag{3}$$

gives a good approximation of the mean energy inside the foil, where Δx represent the total foil thickness.

2.2. Determination of the Cross Section

The cross section was determined by the measurement of the residual activities of the products, given by:

$$\frac{dN_P}{dt} = \lambda N_T \sigma I t_i, \tag{4}$$

where $\frac{dN_P}{dt}$ is the decay rate of the products, $\lambda = \frac{\ln 2}{T_{1/2}}$ is the decay constant, N_T is the number of atoms of the target per units of area. Here we have considered $t_i \ll \tau$.

The errors quoted for the cross sections include uncertainties in the determination of the proton flux, counting statistics and reproducibility of the photopeak integration, absolute detector efficiency, target thickness and half-life, branching ratios and decay and measurement times.

3. RESULTS AND DISCUSSION

The Ti irradiation was performed with an incident proton energy of 29.3(5) MeV and a total integrated current of 6.1(4) μAh.

The presence of ^{44}Ti was well established from the 1157.008(3) keV characteristic transition, despite the wide formation of ^{46}Sc, ^{48}V and ^{56}Co by more favored reactions. All foils were measured during 72 h. A total of three spectra were obtained from each foil for half-life control and products identification. The experimental results for the Ti(p,X)^{44}Ti are presented in fig. 1 with the values from Refs. [12, 13, 14].

As we can see in fig. 1, the results of Brodzinski et al [12] agree quite well with that of Michel et al [13, 14]. For energies below 30 MeV our result can be compared only with that of [13, 14], and they were compatibles, except for the point with energy $E_p = 21.3(4)$ MeV, where our result is compatible with that of [14] but not with [13] (the compatibility between [13] and [14] comes from the relatively large uncertainty for the proton energy in [14] for that point).

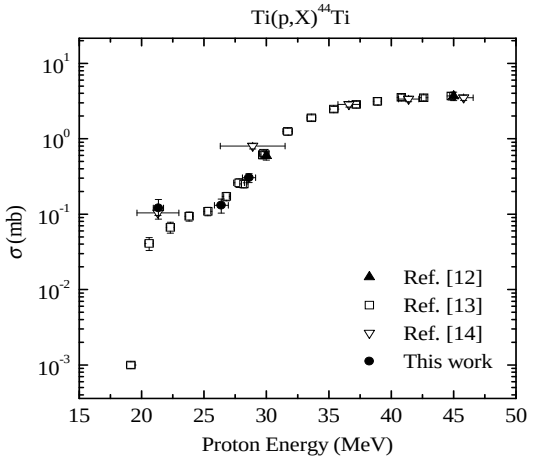

FIGURE 1. Excitation function of the Ti(p,X)^{44}Ti reaction.

The Ni irradiation was performed with an incident energy $Ep = 28.2(6)$ MeV and a total integrated current of 0.216(19) μAh. All the spectra (three for each Ni foil) were taken during 6 h. A large formation of ^{55}Co and ^{57}Ni was observed. The presence of ^{56}Ni could be detected in the foils with no ambiguity. The cross sections are presented in fig. 2. Although it exists a relatively wide set of cross section data [14, 15, 16, 17, 18, 19] (fig. 2)

given a very good idea of the excitation function behavior for energies up to 40 MeV, this information is more abundant for protons energies higher than 30 MeV. At low energies, especially very near the threshold, these data are scarce. For energies less than 20 MeV, besides our results, only three points could be found. Our results were consistent with all previous data for energies up to 27 MeV, contributing to a better knowing of this low energy interval.

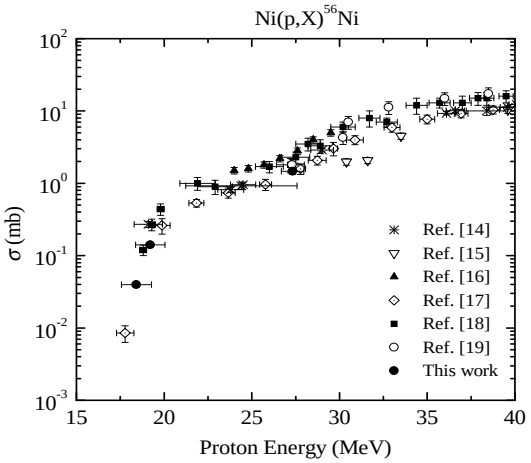

FIGURE 2. Excitation function of the Ni(p,X)^{56}Ni reaction.

The Zr irradiation was performed with an incident energy $Ep = 28.7(6)$ MeV and a total integrated current of $0.45(4)$ μAh. As in the other cases, three set of measurements were performed for all foils. The measurement time was $t_m = 12$ h. This time was enough to fit the 393 keV peak of the ^{88}Zr with a good statistic. In fig. 3 we show the cross section results for the Zr(p,X)^{88}Zr reaction. Only one excitation function was found for this reaction in this energy interval [14]. We can notice a very good agreement between both results,but as observed in other cases, it is still possible to obtain values much near the threshold.

All the cross section values determined in this work are presented in Table 2.

Even though we are dealing with (p,X) reactions, where X represents all the possibilities for the exit channel, we can discuss our results considering the (p,t) channel as the dominant reaction mechanism. In all cases exposed, it exists several stable isotopes that could contribute to the final product. We are considering that the probability of a (p,t) reaction is much greater than the other reactions. In all cases presented here we have (p,pjn) reactions, with $j \geq 2$, with a threshold greater than the incident energy. For $j = 2$ we have the ^{46}Ti(p,p2n)^{44}Ti with $Q = -22.719$ MeV, ^{58}Ni(p,p2n)^{56}Ni with

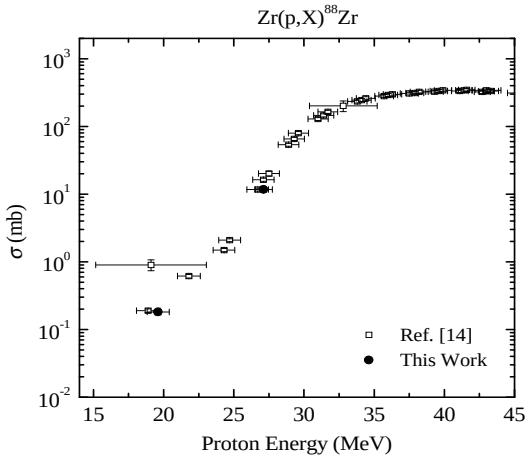

FIGURE 3. Excitation function of the Zr(p,X)^{88}Zr reaction.

TABLE 2. Excitation function for the Ti(p,X)^{44}Ti, Ni(p,X)^{56}Ni and Zr(p,X)^{88}Zr reactions determined in this work.

Reaction	E_p (MeV)	σ (mb)
Ti(p,X)^{44}Ti	21.3(4)	0.12(4)
	26.4(6)	0.13(3)
	28.6(5)	0.30(4)
Ni(p,X)^{56}Ni	18.4(9)	0.65(8)
	19.2(8)	0.56(7)
	27.3(6)	1.7(3)
Zr(p,X)^{88}Zr	19.6(8)	0.181(16)
	27.1(6)	11.6(9)

$Q = -22.465$ MeV and ^{90}Zr(p,p2n)^{88}Zr with $Q = -21.286$ MeV whose contribution should be small compared to the (p,t) reaction for energies below 29 MeV (or null for our lower energy results). Contribution to the cross section could be expected also from the (p,nd) and (p,3n) reactions. In the first case we have ^{46}Ti(p,nd)^{44}Ti with $Q = -20.495$ MeV, ^{58}Ni(p,nd)^{56}Ni with $Q = -20.241$ MeV and ^{90}Zr(p,nd)^{88}Zr with $Q = -19.062$ MeV. Their contribution is expected to be small due to proton energy very near (or below) the threshold and cross section smaller than that of the corresponding (p,t) reaction. In the second case we have ^{46}Ti(p,3n)^{44}V with $Q = -37.203$ MeV, ^{58}Ni(p,3n)^{56}Cu with $Q = -38.601$ MeV and ^{90}Zr(p,3n)^{88}Nb with $Q = -29.618$ MeV with threshold above incident energy. Finally we consider also small the contribution of ^{47}Ti(p,nt)^{44}Ti with $Q = -23.116$ MeV and ^{91}Zr(p,nt)^{88}Zr with $Q = -19.999$ MeV for incident energies near the threshold and expected low values of its cross section.

As we are interested in cross sections not greater than a few mb, the impurities analysis is very important, once a few ppm of these nuclides could constitute a considerable interference if other products can be formed with much greater cross sections. In the present work all the nuclides produced in the samples were identified by successive measurements. The only relevant impurity found, up to 10 ppm, was Fe in the Ti and Ni samples. Also a careful background analysis was made, once the low intensity peaks could be affected. As none of the gamma lines from the background could affect the peaks, no background subtraction was necessary.

With respect to the beam monitoring technique, we should notice that its precision depends on the adopted excitation function used as monitor. In the case of a stacked-foil sample composed by many foils, the use of one monitor sample for every one or two sample foils of the elements that are being studied is extremely recommended once the inverse proportional relation between the stopping power and the proton energy implies an increasing of the uncertainties estimation as the proton energy decrease. The method also allows the determination of the characteristics of the beam using products of other reactions in the same foils (if adequate excitation functions are available).

During the spectra analysis, it was possible to fit photopeaks with counting rates of about 2 cph. This fact allows the establishment of some limits in the experimental method used. Lets consider an hypothetical case where we are studying a (p,X) reaction in a sample with 50 μm thickness, irradiated with a total integrated current of 10 μAh with the reaction product having a half-life of about 1 y and a γ-ray of about 1200 keV and emission probability of 100%. If the photopeak can be fitted with an area corresponding to 1 cph, it is possible to estimate the value of 1 μb as the limit for a cross section determination. In practice, only in some very favored situations this limit can be attained, so a good previous estimative of the factors that affect the experiment (irradiation parameters, decay time, thickness of the targets, measurements geometry and possible impurities) should be made.

4. CONCLUSIONS

Several cross section values for the reactions Ti(p,X)^{44}Ti, Ni(p,X)^{56}Ni and Zr(p,X)^{88}Zr were determined at proton energies very close to the threshold by γ spectroscopy. Due to energy and reaction mechanism involved, the (p,t) is considered the dominant channel in all cases. Our results were compatibles with all previous published data up to 27 MeV, contributing to a better knowing of this low energy interval.

The appropriate fitting of photopeaks with areas corresponding to about 2 cph allow us to estimate as 1 μb the limit of our method for cross sections determination.

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