# Excitation Functions
# for the Production of $^{90}$Nb and $^{88}$Y
# by Irradiation of Zirconium with Deuterons*

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Excitation functions for reactions induced by deuterons on natural zirconium and $^{90}$Zr targets have been measured radiochemically with the stacked foil technique between $\approx 9$ and 27 MeV. The observed reactions are $Zr(d, xn)^{90}$Nb, $Zr(d, \alpha xn)^{88}$Y, $^{90}$Zr$(d, 2n)^{90}$Nb and $^{90}$Zr$(d, \alpha)^{88}$Y. The excitation functions for the reactions $^{91}$Zr$(d, 3n)^{90}$Nb and $^{91}$Zr$(d, \alpha n)^{88}$Y have been deduced from the results mentioned above. Calculations of the excitation function for the $(d, 2n)$ reaction have been performed with two different treatments, each one taking into account two competitive mechanisms. The compound-statistical model plus Hittmair's stripping theory accounts quite well for the $(d, 2n)$ cross sections observed. However, the agreement obtained with Peaslee-Otozai's theory is excellent and the set of parameters used more reasonable. It has been assumed that the stripping mechanism can have no contribution to the $(d, \alpha)$ reaction. Accordingly, calculations for this reaction have been done using the compound-statistical model and the entire absorption process followed by the evaporation of an $\alpha$ particle. No good agreement is obtained with either theory.

## 1. Introduction

The compound-statistical process has been found to be important in deuteron-induced reactions involving the emission of more than one particle[1]. Owing to the loosely bound structure of the deuteron, the process in which the deuteron breaks into its components before interacting with the target is also probable. In this case, alternatively one or both of them penetrate, and a stripping or an entire absorption reaction is produced respectively.

Formation cross sections of residual nuclei produced by deuteron reactions vary with incident energy characteristically for the respective reaction process. It is then interesting to measure excitation functions and try to fit them theoretically to infer the relative contributions of the processes involved.

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1 Pement, F. W., Wolke, R. L.: Nucl. Phys. **86**, 429 (1966).

In this work, experimental excitation functions for the production of $^{90}$Nb and $^{88}$Y using natural zirconium and enriched $^{90}$Zr targets were determined radiochemically using the stacked foil technique. The deduced excitation functions for the $(d, 3n)$ and $(d, \alpha n)$ reactions produced by $^{91}$Zr$+d$ are also reported.

The results for the $^{90}$Zr$(d, 2n)^{90}$Nb reaction were analyzed in terms of two models: a) the compound-statistical theory and the stripping-evaporation theory of Hittmair[1,2], hereafter mentioned as CSH theory, and b) the theory of the deuteron reaction of Peaslee[3] modified by Otozai[4], P-O theory for short, in which the deuteron breaks up before entering the target leading to the two concurrent processes of stripping and entire absorption.

Assuming that the stripping mechanism can give no contributions for the production of a $(d, \alpha)$ reaction, experimental data from the $^{90}$Zr$(d, \alpha)^{88}$Y reaction were compared with calculations based on the compound-statistical theory and with the entire absorption theory.

## 2. Experimental Procedures

The production cross sections of $^{90}$Nb and $^{88}$Y were measured by the activation method using the stacked foil technique.

Target stacks were irradiated with the full energy of the external deuteron beam of the 180 cm diameter synchrocyclotron of the Comisión Nacional de Energía Atómica.

The first two irradiations were performed using very pure metallic targets of natural zirconium obtained from Koch-Light Ltd., England. For the third and last irradiation, metallic zirconium enriched in $^{90}$Zr at 97.68% was supplied by ORNL. Target foils were stacked with aluminium foils of high purity in order to obtain the excitation function in steps of about 1 MeV and with the purpose of using the $^{27}$Al$(d, \alpha p)^{24}$Na reaction for beam monitoring on account of its multiple known advantages[5].

Integrated beam intensities of 10, 3 and 3 µA for each of the irradiations respectively were calculated from the excitation function for the production of $^{24}$Na reported by Martens *et al.*[6] with an estimated error of 2.5%.

2 Pement, F. W., Wolke, R. L.: Nucl. Phys. **86**, 417 (1966).
3 Peaslee, D. C.: Phys. Rev. **74**, 1001 (1948).
4 Otozai, K., Kume, S., Koyama, M., Mitsuji, T., Nishi, T., Fujiwara, I.: Nucl. Phys. **81**, 322 (1966).
5 Christaller, G.: European Colloquium on A.V.F. Cyclotrons, Eindhoven, 1965.
6 Martens, U., Schweimer, G.: Report KFK-1083, Kernforschungszentrum Karlsruhe (1969).

The initial energy of the deuteron beam was 27.2 MeV and its initial spread of about 0.3 MeV.

The error in the energy scale is not linear. The quadratic increase of range with particle energy leads to the formula

$$\Delta E(E) = \Delta E(E_0) \cdot E_0/E \tag{1}$$

where $E_0$ is the beam energy, $\Delta E(E_0)$ is the initial spread and $\Delta E(E)$ is the error at energy $E$.

Tables of reference [7] were used to obtain the energy of the beam particles along the foils in the stack. The mean energy in the middle of each foil was used as abscissa of the excitation functions. Corrections for the energy spread in each foil, due to the foil thickness and the energy degradation in the preceding foils, were not applied. They are small in comparison to the energy uncertainty due to the error in the beam energy.

No chemical separation was necessary because the activities of $^{90}$Nb and $^{88}$Y were measured through the highly energetic gamma radiations of 2.32 MeV and 1.84 MeV respectively. The corresponding efficiencies were determined experimentally and the error was estimated to be less than 3%. The gamma spectra were measured by means of a 2″ × 2″ NaI(Tl) crystal and a 400 channel analyser. Decay schemes, branching ratios, half-lives values and internal conversion and pair formation coefficients were taken from the most recent literature [8-18]. The intensity of the 2.32 MeV line of $^{90}$Nb was corrected for the presence of the 2.18 MeV line of the same nucleide which occurs with an intensity of 25% of that of the 2.32 MeV line [12]. This introduced an error of 3% in the determination of the $(d, 2n)$ cross sections.

7 Williamson, C. F., Boujot, J. P., Picard, J.: Report CEA-R3042, Commissariat a l'Energie Atomique, Saclay (1966).
8 Handbook of chemistry and physics, ed. Weast, R. C. Cleveland: The Chemical Rubber Co. 1969.
9 Lederer, C. M., Hollander, J. M., Perlman, I.: Table of isotopes, 6th. ed. New York: John Wiley & Sons 1967.
10 Lazar, N. H., O'Kelley, G. D., Hamilton, J. H., Langer, L. M., Smith, W. G.: Phys. Rev. 110, 513 (1958).
11 Petterson, H., Antman, S., Grunditz, Y.: Nucl. Phys. A 108, 124 (1968).
12 Tucker, A. B., Simmons, S. O.: Nucl. Phys. A 158, 83 (1970).
13 Metzger, F. R., Amaher, H. C.: Phys. Rev. 88, 147 (1952).
14 Wyatt, E. I., Reynolds, S. A., Handley, T. H., Lyon, W. S., Parker, H. A.: Nucl. Sci. Eng. 11, 74 (1961).
15 Siegbahn, K., du Toit, S.: Arkiv Fysik 2, 211 (1950).
16 Siegbahn, K.: Arkiv Fysik 4, 223 (1952).
17 Slätis, H., Siegbahn, K.: Arkiv Fysik 4, 485 (1952).
18 Lagoutine, F., LeGallic, Y., Legrand, J.: Intern. J. Appl. Radiation Isotopes 19, 475 (1968).

The contents of $^{24}$Na and $^{90}$Nb were measured some hours after the end of irradiation and during approximately five days. The $^{88}$Y production measurement began some weeks later and spectra were taken during approximately five months.

The reactions $^{27}$Al$(n, \alpha)$ $^{24}$Na and $^{90}$Zr$(n, p\ 2n)$ $^{88}$Y might be induced by neutrons produced in the foil stack and beam collimators. In order to measure these activities, thick aluminium and zirconium foils were placed behind the target beyond the deuterons range. It was found that the contribution due to neutrons was less than 1% of the total activity.

Thresholds of all reactions considered in this work were estimated using the Nuclear Reaction $Q$-values table of Maples *et al.*[19].

## 3. Experimental Results

In the irradiation with natural zirconium targets, the production of $^{90}$Nb and $^{88}$Y due to the interaction of the deuteron beam with the $^{92}$Zr,
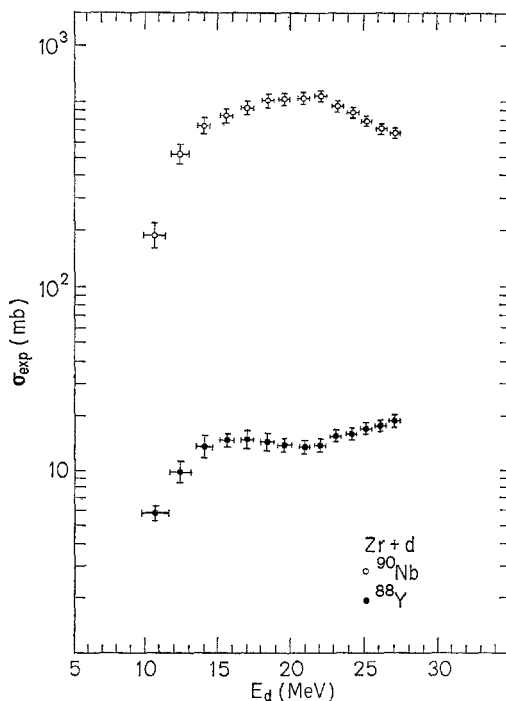


Fig. 1. Experimental excitation functions for the Zr+ *d* reactions

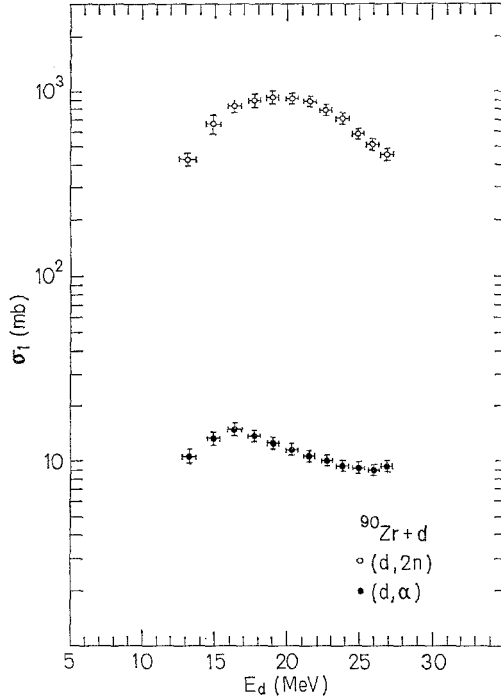19 Maples, C., Goth, G. W., Cerny, J.: Nucl. Data, Sect. A 2, 429 (1966).

Fig. 2. Experimental excitation functions for the $^{90}$Zr + d reactions

$^{94}$Zr and $^{96}$Zr isotopes has been neglected. Denoting the $^{90}$Zr$(d, 2n)$ or $^{90}$Zr$(d, \alpha)$ cross sections by $\sigma_1$, the $^{91}$Zr$(d, 3n)$ or $^{91}$Zr$(d, \alpha n)$ cross sections by $\sigma_2$ and the relative isotopic abundance of $^{90}$Zr and $^{91}$Zr by $f_1$ and $f_2$ respectively, Fig. 1 shows the experimental value $\sigma_{exp} = \sigma_1 + \sigma_2 f_2/f_1$ averaged over the first two irradiations vs. the incident deuteron energy.

In Fig. 2, the excitation functions for the production of $^{90}$Nb and $^{88}$Y through the reactions $^{90}$Zr$(d, 2n)$ and $^{90}$Zr$(d, \alpha)$ respectively are presented. As it was expected, below the $^{91}$Zr$(d, 3n)$ and $^{91}$Zr$(d, \alpha n)$ thresholds, the curves of Figs. 1 and 2 for the same nucleide agree within the estimated errors.

Lange and Munzel[20], analyzing experimental data of all known $(d, xn)$ reactions, have shown that the influence of charge and mass number of the target nucleus on characteristic data such as position,

20 Lange, J., Munzel, H.: Abschätzung unbekannter Anregungsfunktionen für $(\alpha, xn)$-, $(\alpha, pxn)$-, $(d, xn)$-, $(d, pxn)$- und $(p, xn)$-Reaktionen. Report KFK-797, Kernforschungszentrum Karlsruhe (1968).
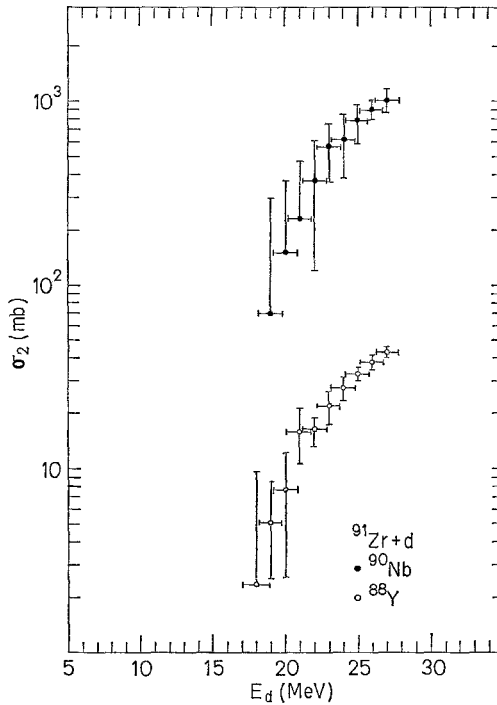
Fig. 3. Deduced experimental excitation functions for the $^{91}Zr(d, 3n)\,^{90}Nb$ and $^{91}Zr(d, \alpha n)\,^{88}Y$ reactions

heights and shape of the excitation function, can be explained by qualitative theoretical arguments. The $^{90}Zr(d, 2n)$ excitation function shown in Fig. 2 agrees quite well with their predictions.

The error bars shown on all cross sections values are the greatest deviations from the average of a series of determinations performed at different times after the end of irradiation. A systematic vertical error of 15% in the $^{90}Nb$ excitation function and 10% in the $^{88}Y$ excitation function appears as made up of the individual errors of the magnitudes involved in the determination of the cross section.

The error in the energy scale shown with horizontal bars on the experimental points was calculated with formula (1). Due to degradation, it grew up to 0.8 MeV at an energy of 10 MeV.

The contributions of the reactions $^{91}Zr(d, 3n)$ and $^{91}Zr(d, \alpha n)$ to the production of $^{90}Nb$ and $^{88}Y$ respectively were determined indirectly from data given in Figs. 1 and 2, and are shown in Fig. 3.

## 4. Discussion

### 4.1. Calculating Procedures

Experimental excitation functions were analyzed by two methods: the compound-statistical model plus Hittmair's stripping theory (CSH) and the Peaslee-Otozai theory of the deuteron reaction (P-O).

The method reported by Pement and Wolke[1,2] was followed in the first case. The values of 1.3 and 1.5 fm and A/15, A/18.2, A/20, A/30 and A/40 MeV$^{-1}$ were used for the two parameters involved, $R_0$ and the level density parameter $a$, respectively.

For the P-O calculations, Peaslee's theory[3] modified by Otozai *et al.*[4] was used. The main features of this theory have been summarized by the authors in Ref.[21].

The binding energy and the radius of the square-well potential of the deuteron were taken as 2.22 MeV and 2.8 fm respectively. Values of 1.5, 1.6 and 1.7 fm were used for the parameter $R_0$, while the para-
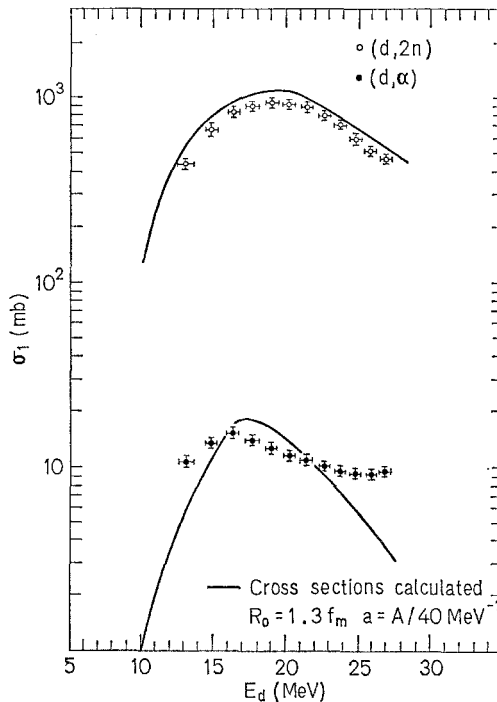


Fig. 4. Comparison between the cross sections calculated with the CSH theory and the experimental ones

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21 Otozai, K., Kume, S., Okamura, H., Mito, A., Nishi, T., Fujiwara, I.: Nucl. Phys. A **107**, 427 (1968).

meter $a$ took the same variable values that in CSH method. The values of 0.8 and 1.0 were chosen for the sticking probability $\xi_p$ and the values of 1.0 and 2.2 fm for the entire absorption parameter $\rho$.

All the calculation in this work have been performed with the aid of the IBM System/360 model 50 computer of La Plata National University.

### 4.2. Comparison of Calculations with Experiment

The best fits to experiment are shown in Figs. 4 and 5. In Fig. 4, experimental data are shown together with curves calculated using CSH method. It can be noted that the $(d, 2n)$ cross sections can be reproduced approximately using the values of 1.3 fm for $R_0$ and A/40 MeV$^{-1}$ for the level density parameter $a$.

Calculations using the P-O method yielded the curves shown in Fig. 5 for the best fit-values of the parameters: $R_0 = 1.7$ fm, $a = A/18.2$ MeV$^{-1}$, $\xi_p = 0.8$ and $\rho = 1.0$ fm. These curves account for the $(d, 2n)$ experimental data in a very good way over all the energy range. The set of parameters used is a very reasonable one. According to the literature, the value
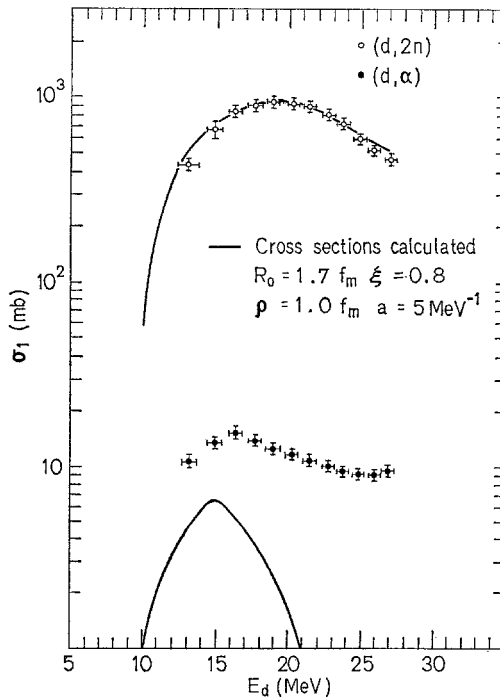


Fig. 5. Comparison between the cross sections calculated with the P-O theory and the experimental ones

A/18.2 MeV$^{-1}$ = 5 MeV$^{-1}$ for the level density parameter $a$ is better than the value A/40 MeV$^{-1}$ needed to obtain a good fit with the CSH mechanism.

In spite of using various sets of parameters, no good fit to experimental $(d, \alpha)$ excitation function could be obtained with any of the two theories. This fact is also observed in previous works[4,21], and suggests that the theories used are oversimplified ones in that they are not so sensible to account for the $(d, \alpha)$ cross sections which are two orders in magnitude smaller than the $(d, 2n)$ ones. An improved theory of reaction mechanism is needed.

The value $\rho = 1.0$ fm used in the P-O calculations agrees with the predictions of Mito et al.[22] for the neutron excess corresponding to our case.

Contributions of competitive mechanisms in the $(d, 2n)$ reaction according to CSH and P-O methods were also calculated using the same set of parameters of Figs. 4 and 5 respectively. It could be noted that the stripping mechanism plays a more important role in P-O theory than in CSH theory.

22 Mito, A., Komura, K., Mitsugashira, T., Otozai, K.: Nucl. Phys. A **129**, 165 (1969).

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