THE USE OF CROSS SECTION DATA FOR MONITORING CHARGED PARTICLE BEAM PARAMETERS

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Excitation functions of proton, deuteron, helium-3 and alpha particle induced reactions on ^{nat}Ti, ^{nat}Fe, ^{nat}Ni and ^{nat}Cu targets can be used to monitor the energy and intensity of charged particle beams. In order to develop a reliable cross section database for monitoring purposes critical evaluation of the available cross sections data and new measurements are needed. The investigated proton, deuteron, helium-3 and alpha-particle induced reactions on natural Ti, Fe, Ni and Cu are: ^{nat}Ti(p,x)^{48}V, ^{nat}Ti(d,x)^{48}V, ^{nat}Ti(^{3}He,x)^{48}V, ^{nat}Ti(α,x)^{51}Cr, ^{nat}Fe(p,x)^{56}Co, ^{nat}Fe(d,x)^{56,57}Co, ^{nat}Fe(α,x)^{58}Co,^{57}Ni ^{nat}Ni(p,x)^{57}Ni, ^{nat}Ni(d,x)^{57}Ni, ^{nat}Ni(^{3}He,x)^{55,58}Co,^{61}Cu, ^{nat}Ni(α,x)^{61}Cu,^{63,65}Zn, ^{nat}Cu(p,x)^{62,63,65}Zn, ^{nat}Cu(d,x)^{63,65}Zn, ^{nat}Cu(^{3}He,x)^{66}Ga and ^{nat}Cu(α,x)^{66,67}Ga.

1. Introduction

1.1 Status of monitor reactions

In some applications at cyclotron laboratories where the energy and/or current of the beam can not be measured directly one should monitor the beam by monitor foils. The use of monitor reactions is a simple method to determine the beam flux and can also provide a check of the calculated particle energy incident at a thin foil while assuring the necessary precision needed in different applications. From the activity of the foil induced by a charged particle beam and from the known cross section-energy relation of the reaction taking place in the monitor foil, the energy or the intensity of the bombarding beam can be calculated. The use of monitor reactions hence demands as prerequisite well-known and reliable excitation functions of the monitor reactions. The value of the beam parameters determined using monitor reaction are only be as good as the cross section values of the monitor reactions applied.

A survey [1] showed, that the status of the available experimental cross section data regarding the monitor reactions is not satisfactory. Even in the case of Cu+p reactions, for which many independent studies have been performed, some discrepancies exist which may not be solved clearly on the basis of available experimental data [2]. For incident beams different than protons, it seems that the experimental precision is not sufficient in all interested energy regions, or in some cases there is no experimental data at all. Therefore, in agreement with the recommendation of the Nuclear Data Section of the IAEA [3] our aim was:
- To measure reaction cross sections on selected target materials and to collect more precise experimental data to solve discrepancies existing among the available data sets.
- To search for new reactions and measure their excitation functions using the four light charged particle beams (p, d, ^{3}He and α) on the same type of target materials.

-To propose new monitor reactions to utilise the principles of simultaneous determination of the flux and energy.
-To provide a reliable data base after compilation and critical evaluation of the available experimental data for the reactions used for monitoring charged particle beams.

1.2 Requirements for monitor reactions

There are several criteria regarding monitor reactions and targets selection. These include the availability of the material, the physical and chemical characteristics of the target, the decay parameters of the produced nucleus, the shape and magnitude of the excitation function in the energy region in question, and the status of undesired interfering reactions. Among them the cross section is the most important signature that one should determine carefully to be able to use the appropriate reaction for monitoring.
Nuclear properties
- The reaction should have a high cross section.
- For flux determination a reaction having an excitation function with a flat plateau in the investigated energy region is more suitable because the derived flux value do not suffer much from the error of the energy determination.
- The reactions suitable for energy determination should have a steep cross section slope that provides good energy resolution in the investigated energy region.
- The isotope used for monitoring purposes must have suitable half-life compared to the irradiation time.
- The emitted gamma-photons should have a proper energy with no interference and with high relative intensity.
- The reaction product must remain in the monitor foil (low probability for volatilisation, evaporation or escape).
-Possibility to use the same material for monitoring different type of beams (p, d, ^{3}He, α) is an advantage.
Other necessary mechanical and chemical properties
- Chemical stability, chemical resistance.
- Good mechanical properties regarding thin foil production.

- Good heat and electrical conduction.
- Stability with regard to the energy dissipation of the beam.
- Resistance to mechanical deformations.
- Availability, low price.

Considering the above requirements first of all the Al, Ti, Fe, Ni and Cu could be considered as appropriate candidates for monitor targets

Some applications might require the use of more than one monitor foil. If higher energy is available one can irradiate a thicker target and still wants to monitor the beam from the incident particle energy down to the threshold of the selected reaction. Thick targets can hence result in large uncertainty in the lower section of the energy scale. The problem of increased precision of the deduced energy scale in the low energy part can be solved by a method we proposed [4]. More than one monitor foil is used with the extra requirement that the monitor target must provide multiple reactions with overlapping energy regions for simultaneous flux and energy determination. Besides the generally accepted principles (knowledge of the cross sections of the applied monitor reactions, use of infinitely thin monitor foil and use of mono-energetic bombarding beam) two other principles are postulated for application of this modified method:

1. The beam intensity calculated from the activity of monitor foils at different position in the stack will give the same value only if the beam energy in each monitor foil was determined correctly and if no beam loss occurred in the target.

2. The energy calculated from one monitor foil but using different monitor reactions will give the same value only if the beam intensity in the foil is determined correctly.

Using these two extra assumptions the energy and the flux can be determined more accurately applying successive approximations. Choosing the most suitable reactions in a given monitor foil can decrease the uncertainty of the calculated flux or energy.

2. Experimental summary

In a series of systematic experiments the ^{nat}Ti(p,x) [5], ^{nat}Fe(p,x) [6], ^{nat}Ni(p,x) [7], ^{nat}Ti(d,x) [8], ^{nat}Fe(d,x) [9], ^{nat}Ni(d,x) [10], ^{nat}Cu(d,x) [9], ^{nat}Ti(^{3}He,x) [11], ^{nat}Ni(^{3}He,x) [12], ^{nat}Cu(^{3}He,x) [13], ^{nat}Ti(α,x) [13, 14], ^{nat}Ni(α,x) [13], ^{nat}Cu(α,x) [13, 15] reactions were investigated on metallic foils. The cross sections of reactions were (re)measured in well defined irradiation conditions, using a high resolution gamma spectrometry detection technique and reliable nuclear data for data analysis and evaluation. The excitation functions were calculated using the activation method and the stacked-foil technique in the energy range from threshold up to 41 MeV for protons, up to 21 MeV for deuterons, up to 36 MeV for ^{3}He-particles and up to 42 MeV for alpha particles.

The investigated reactions on natural Ti are: ^{nat}Ti(p,x)^{43,44m,44g,47}Sc,^{48}V, ^{nat}Ti(d,x)^{43,44m,44g,46,47,48}Sc,^{48}V, ^{nat}Ti(^{3}He,x)^{44m,44g,47,48}Sc,^{48}V and ^{nat}Ti(α,x)^{44m,44g,46,47,48}Sc,^{48}V,^{51}Cr. The proposed monitor reactions on Ti are those leading to the formation of ^{48}V for p, d and ^{3}He and for ^{51}Cr in the case of alpha particles.

The investigated reactions on natural Fe are: ^{nat}Fe(p,x)^{56}Co and ^{nat}Fe(d,x)^{51}Cr,^{52,54,56}Mn,^{55,56,57,58}Co. The proposed monitor reactions on Fe are leading to the production of ^{56}Co for protons, and ^{56,57}Co for deuteron particles.

The investigated reactions on natural Ni are: ^{nat}Ni(p,x)^{55,56,57}Co,^{57}Ni, ^{nat}Ni(d,x)^{55,56,57,58}Co,^{57}Ni,^{60,61}Cu, ^{nat}Ni(^{3}He,x)^{52}Mn,^{52,53}Fe,^{55,56,57,58}Co,^{56,57}Ni,^{60,61}Cu,^{62,65}Zn and ^{nat}Ni(α,x)^{57}Co,^{57}Ni,^{60,61}Cu,^{62,63,65}Zn. The proposed monitor reactions on Ni are leading to the production of ^{57}Ni for protons and deuterons, of ^{57}Ni, ^{55,58}Co and ^{61}Cu for ^{3}He and of ^{61}Cu and ^{63,65}Zn for alpha particles.

The investigated reactions on natural Cu are: ^{nat}Cu(d,x)^{64}Cu,^{62,63,65}Zn, ^{nat}Cu(^{3}He,x)^{61,64}Cu,^{63,65}Zn,^{66,67}Ga and ^{nat}Cu(α,x)^{61}Cu,^{63,65}Zn,^{66,67}Ga. The proposed monitor reactions on Cu are leading to the formation of ^{65}Zn for deuterons and to ^{66,67}Ga for ^{3}He and alpha particles. Intercomparisons between monitor reactions were performed and effects of secondary neutrons were investigated. The experimental cross section values were in several cases compared with results of nuclear model calculation. The proposed reactions were also evaluated as to their possible application for radioisotope production and thin layer activation.

3. Results and discussion

Primary reactions that were recommended for monitoring purposes are listed in table 1 for different materials and particles. Table 1 summarises also the investigated energy range, the number of available different works published on each selected reaction and the status of the available experimental data. The reactions of light particles on Al, which in formation of ^{22,24}Na are also good reactions which in principle allow monitoring of beam parameters [1]. The Al and the produced isotopes ^{22,24}Na have excellent properties. Unfortunately, the reactions have relatively high Q values and can not be used for monitoring of the low energy beams mostly used in practice.

Proton reactions

Among the studied proton induced reactions the ^{nat}Ti(p,x)^{48}V; ^{nat}Fe(p,x)^{56}Co and ^{nat}Ni(p,x)^{57}Ni reactions were proposed for monitoring of proton beams. The reactions have high cross sections and the products ^{48}V, ^{56}Co and ^{57}Ni have convenient half-life to measure. On figure 1 the fitted excitation functions obtained from our measurements can be seen for these three reactions. One of the most frequently used reactions in the applied nuclear physics is the ^{nat}Fe(p,x)^{56}Co reaction, therefore detailed comprehensive literature survey, critical compilation and

recommended data set based on experimental evaluation given in [6]. The evaluation method consisting of successive weighted averaging and spline fitting of the critically selected experimental data sets allowing determination of a recommended data base for the reaction investigated was described in [16]. The $^{nat}Cu(p,x)^{63,65}Zn$ processes are also well studied. The minor drawback is that the ^{63}Zn has too short and the ^{65}Zn has too long half-life.
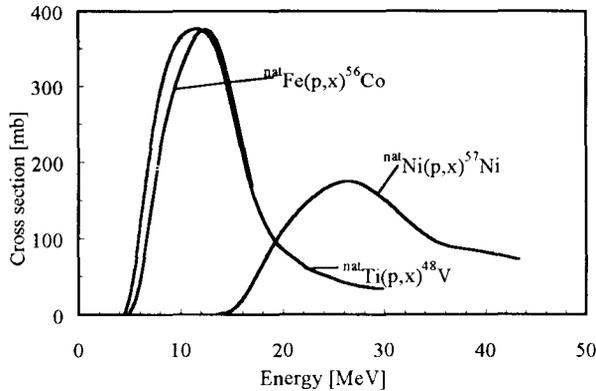

Figure 1 : Proton induced monitor reactions on Ti, Fe and Ni

Deuteron reactions

For monitoring low energy deuteron beams we have investigated the $^{nat}Ti(d,x)$ [8], $^{nat}Fe(d,x)$ [9], $^{nat}Ni(d,x)$ [10] and $^{nat}Cu(d,x)$ [9] processes and measured excitation functions from threshold up to 21.3 MeV energy (see also table 1). The beam current was monitored by a Faraday-cup. The experimental cross section data were compared to the data available in the literature for the reactions investigated and several disagreements (such as energy shift, position of maximum cross section value) were solved. For monitoring deuteron beams the $^{nat}Ti(d,x)^{48}V$, $^{nat}Fe(d,x)^{56,57}Co$, $^{nat}Ni(d,x)^{58}Co$ and $^{nat}Cu(d,x)^{65}Zn$ reactions were proposed (see figure 2). With these reactions the energy region was extended below the 15 MeV barrier where the deuteron beams can not be monitored with the $^{27}Al(d,x)^{24}Na$ reaction.

³He reactions
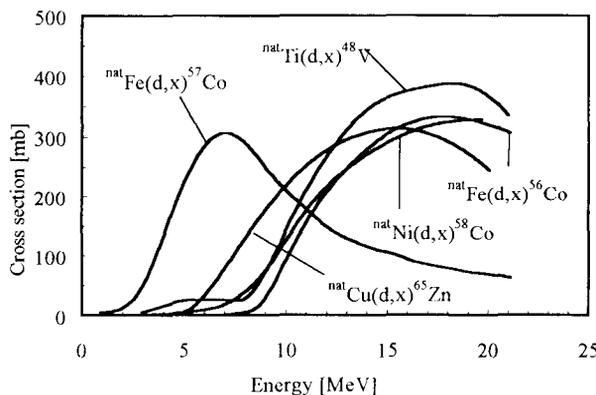
Cross sections of ^{3}He induced reactions on ^{nat}Ti, ^{nat}Ni and ^{nat}Cu were measured. The proposed reactions are shown in figure 3. As among the suggested primary reactions the $^{nat}Ti(^{3}He,x)^{48}V$ has the highest cross section this is the most suitable for monitoring ^{3}He beams. The $^{nat}Ni(^{3}He,x)$ processes were investigated for the first time. Among the studied thirteen reaction products the excitation functions for production of ^{56}Co is one of the suitable ones for monitoring ^{3}He particle beam. The use of the excitation function of ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co, ^{65}Zn and ^{61}Cu may allow simultaneous determination of flux and energy although they have lower cross sections in the studied energy region. The $^{nat}Fe+^{3}He$ reactions are under evaluation.
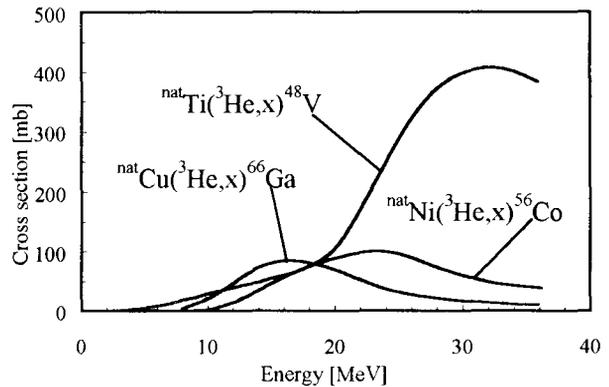

Figure 3 : ^{3}He particles induced monitor reactions on Ti, Ni and Cu

Alpha reactions

Cross sections of alpha particle induced reactions on ^{nat}Ti, ^{nat}Ni and ^{nat}Cu were measured. The fitted cross sections of the reactions proposed for monitoring of alpha particle beams are shown in figure 4. Among the investigated target materials the $^{nat}Cu(\alpha,x)^{65}Zn$ reaction has the highest cross section. Using the $^{nat}Ti(\alpha,x)^{51}Cr$ reaction the alpha beams can be monitored from about 8 MeV to 25MeV. The $^{nat}Fe+\alpha$ reactions are under evaluation.

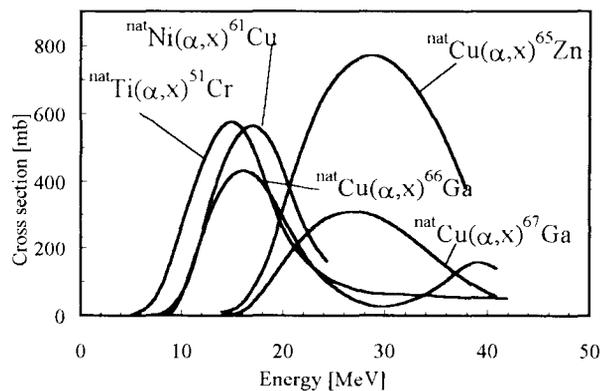**Figure 2** : Deuteron induced monitor reactions on Ti, Fe, Ni and Cu

Figure 4 : Alpha particles induced monitor reactions on Ti, Ni and Cu

4. Conclusion

Excitation functions of proton, deuteron, helium-3 and alpha particle induced reactions on ^{nat}Ti, ^{nat}Fe, ^{nat}Ni and ^{nat}Cu targets were investigated in order to increase the availability of cross section data for monitoring the energy and/or intensity of charged particle beams. One of the aims of the work was to show that the use of the same, easy available target material is possible for monitoring all the four light particle beams. The compilation and critical evaluation of the available other works in connection with the investigated reactions already has been started in the frame of an international project co-ordinated by the International Atomic Energy Agency. The aim is to establish a reliable charged particle cross section database for the reactions applied in production of medically important radioisotopes and the reactions used for monitoring the production processes [3]. The collected and critically evaluated experimental data including our results were fitted experimentally and were also supplied to theoretical evaluators to produce recommended data sets for the selected reactions. Evaluation of all experimental data showed that in some cases additional experiments are required to be able to solve the discrepancies found among the data presented by different authors. In some cases the extension of the energy range of the available experimental cross section data is also necessary.

Table 1 : Proposed primary reactions to monitor the parameters of p, d, ^{3}He and α particle beams using Ti, Fe, Ni and Cu monitor foils. The main reaction, the investigated energy region and number of different experiments (No.) is listed.

	proton	deuteron	^{3}He	α
Ti	^{nat}Ti(p,x)^{48}V	^{nat}Ti(d,x)^{48}V	^{nat}Ti(^{3}He,x)^{48}V	^{nat}Ti(α,x)^{51}Cr
	4.5 - 29.98 MeV	2.95 - 21.26 MeV	4.3 - 35.8 MeV	8.58 - 38.42 MeV
	comp., eval. (No. 17)	comp., eval. (No. 4)	comp., eval. (No. 4)	comp., eval. (No. 11)
Fe	^{nat}Fe(p,x)^{56}Co	^{nat}Fe(d,x)^{56}Co		
	4.9 - 17.5 MeV	6.93 - 21.32 MeV	under evaluation	under evaluation
	comp., eval. (No. 13)	comp., eval. (No. 8)		
Ni	^{nat}Ni(p,x)^{57}Ni	^{nat}Ni(d,x)^{57}Ni	^{nat}Ni(^{3}He,x)	^{nat}Ni(α,x)^{61}Cu
	13.6- 43.48 MeV	2.3 - 20.15 MeV	2.1 - 35.0 MeV	5.9 - 24.3 MeV
	comp., eval. (No. 20)	comp., eval. (No. 5)	(No. 1)	comp., eval, (No. 10)
Cu	^{nat}Cu(p,x)^{62,63,65}Zn	^{nat}Cu(d,x)^{65}Zn	^{nat}Cu(^{3}He,x)^{66}Ga	^{nat}Cu(α,x)^{66,67}Ga,^{65}Zn
	meas. by other groups	10.48 - 20.24	12 - 35 MeV	11. - 37.3 MeV
	comp., eval.(No. 46)	comp. (No. 4)	comp. (No. 7)	comp., eval. (No. 24)

References

[1] O. Schwerer, K. Okomoto, IAEA-Report INDC(NDS)-218/GZ, Vienna, Austria, 1989

[2] A. Hashizume, Proc. of IAEA Consultant's Meeting on Data Requirements for Medical Radioisotope Production, Tokyo, Japan 20-24 April, 1987, Ed. K. Okomoto, IAEA, Vienna, 1988, p.44

[3] F. Tárkányi, P. Oblozinsky: Proc. of Int. Conf. on Nucl. Data for Sci. and Technology. Trieste, 19-24 May, 1997. 59. Ed.: G. Reffo, A. Ventura, C. Grandi. Bologna, Italian Physical Society Vol. 2(1997)1629.

[4] F. Tárkányi, F. Szelecsényi and S. Takács, Acta Radiologica. Supplementum 376 (1991) 72

[5] P. Kopecky, F. Szelecsényi, T. Molnár, P. Mikecz, F. Tárkányi, Proc. of 6th Symp. on Medical Appl. of Cyclotrons, June 1-4, 1992, Turku, Finland, Ed. L.M. Voipio-Pulkki, U. Wegelius, (1992) p.23.

[6] S. Takács, L. Vasváry, F. Tárkányi NIM **B89**(1994) 88

[7] F. Tárkányi, F. Szelecsényi, P. Kopecky, Appl. Radiat. Isot., **42** (1991) 513

[8] S. Takács, M. Sonck, B. Scholten, A. Hermanne, F. Tárkányi, Applied Radiation and Isotopes **48** (1997) 657

[9] S. Takács, F. Tárkányi, M. Sonck, A. Hermanne, S. Sudár, Proc. of 14th Int. Conf. on Applications of Accelerators in Research and Industry, Denton, Texas, 1996, p. 659.

[10] S. Takács, M. Sonck, A. Azzam, A. Hermanne, F. Tárkányi, Radiochimica Acta **76** (1997) 15

[11] F. Tárkányi, F. Szelecsényi, P. Kopecky, Proc. of Int. Conf. on Nuclear Data for Science and Technology, Jülich, Germany, 13 -17 May 1991, Ed. S.M. Qaim, Sringer-Verlag, Berlin, (1992), p.529

[12] S. Takács, F. Tárkányi, A. Fessler, Z.B. Alfassi, S.M. Qaim, Applied Radiation and Isotopes **46** (1995) 249

[13] F. Tárkányi, F. Szelecsényi, P. Kopecky, Proc. of Int. Conf. on Nuclear Data for Science and Technology, Jülich, Germany, 13 -17 May 1991, Ed. S.M. Qaim, Sringer-Verlag, Berlin, (1992), p.529

[14] F. Tárkányi, S. Takács, F. Szelecsényi, M. Sonck, A. Hermanne, Will be published in NIM **B**

[15] A. Hermanne, M. Sonck, S. Takács, F. Tárkányi, Will be published in NIM **B**

[16] F. Szelecsényi, T.E. Boote, S. Takács, F. Tárkányi, E. Tavano, Appl. Radiat. Isot. **49**(1998)1005