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COLLEGE ON MEDICAL PHYSICS
AND
WORKSHOP ON
NUCLEAR DATA FOR SCIENCE AND TECHNOLOGY:
MEDICAL APPLICATIONS
(20 SEPTEMBER - 15 OCTOBER 1999)

"Charged Particle Beam Monitoring"

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Charged particle beam monitoring (important parameters, direct and indirect methods, monitor reactions and their use)

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Beam parameters

- The most important beam parameters
- Importance and requirements of different applications on CP beam monitoring
- Definition of beam parameters and methods of determinations for measurements of beam parameters

Applications of monitor reactions

- Basic equations and parameters for use of monitor reactions
- General and special conditions to monitor reactions and monitor targets
- Methods of use of monitor reactions
- Application field of monitor reactions
- Status of nuclear reaction data for CP monitor reactions
- List of the most important monitor reactions
- Compilations and evaluations of data for monitor reactions(references)
- Requirements to improve the data base and the applications

The most important beam parameters

Ion species

Charge state

The current(time dependence of the beam current)

> **Macropulse current**
> **Bunch current**
> **Average or mean current**

Beam profile(intensity distribution in transverse directions)

Emmittance and brilliance(defined on phase space)

Beam energy, beam energy spread

Beam pulse frequency, width

Importance and requirements of different applications on CP beam monitoring

Beam parameters	Applications		
	Accelarator technology	Isotope Production	Radiation therapy
Ion species	Yes	Yes	Yes
Charge state	Yes	Yes	Yes
The current	Yes	Yes	Yes
Macro	Yes	No	No
Bunch	Yes	No	No
Mean	Yes	Yes	Yes
Beam profile	Yes	Yes	Yes
Emmittance and brilliance	Yes	(Yes))	(Yes)
Beam energy, beam energy spread	Yes	Yes	Yes
Beam pulse frequency, width	Yes	No	No

Definition of beam parameters and methods of determinations for measurements of beam parameters

Parameter: Ion species

Definition: (Z,N)
Determination: by parameters of ion source, accelerators, bending magnets
Appl. of monitor reactions: possible

Parameter: Charge state

Definition: ionisation state
Determination: by parameters of ion source, accelerators, bending magnets
Appl. of monitor reactions: possible

Parameter: Current

Type: macropulse, bunch, mean current: DC or AC
Definition: time dependence of the beam current
Determination:
- Faraday cup
- Calorimetric meas.
- Beam current transformers
- Secondary particles (electrons, ions, neutrons)
- Appl. of monitor reactions: possible

Parameter: Beam profile

Definition: intensity distribution in transverse directions
Determination:
- Viewing screens(optical, thermo)
- Profile grids, scanners or harps
- Residual gas ionisation
- Slit+Faraday cup
- Monitor reactions

Appl. of monitor reactions: possible

Definition of beam parameters and methods of determinations for measurements of beam parameters(cont.)

Parameter: Emittance

Definition: in 2. Dimensional projected phase space dx_i dp_I, in transverse phase space
Angular divergence of all particles in dependence of their co-ordinate

Determination: slits, holes+current measuring device

Appl. of monitor reactions: no

Parameter: Brilliance, Energy, Energy spread

Definition: in 2. Dimensional projected phase space dx_i dp_I, in longitudinal phase space
Momentum(energy) spread of all particles in dependence their phase deviation
Beam energy, beam energy spread

Determination: Magnetic spectrometers
Telescopes
TOF technique(capacitive pick ups, coaxial cups, ..)
Monitor reactions

Appl. of monitor reactions: no

Parameter: Beam pulse frequency, width

Definition: see time structure of the beam intensity

Determination: Cups, pick cups, etc

Appl. of monitor reactions: no

Basic equations and parameters for use of monitor reactions

Method: Irradiation of a target sample. Measurement of the amount of reaction products via direct in beam counting or via their nuclear decay

$$A \sim N \sim \sigma(E,\theta)\ \Phi(t)\ n$$

Where

A	activity
N	number of produced nuclei
Φ	number of incident particles
σ	reaction cross section
n	number of target nuclei

The monitor reactions can be used to determine:

number of incident particles(fluence)
number of target nuclei(thickness)
energy
irradiation time

The monitor reactions can be used to determine:

One unknown parameter
Several parameters simultaneously

Applications of monitor reactions
General and special conditions

General conditions

(collected for activation technique , the in beam technique will be discussed separately)

The target

- The target elements should be isotopicaly pure or disturbances of quantitative determination of reaction products are small
- The target material should be obtained without difficulty(price)
- The target should be prepared in final form in an easy way to get stable uniform thickness
- The target material, and the prepared target should stand normal laboratory circumstances without chemical or physical changes(recrystalisation, oxidation, etc)
- The target should be stable during irradiation. Targets having low melting points, chemical instabilities should be avoided
- Same type of target could be used for broad energy and flux range and for different bombarding particles
- The target should to have high thermal conductivity to allow higher intensities and effective cooling

Applications of monitor reactions
General and special conditions

The reaction cross section

- The absolute cross section should be known precisely in wide range of the energy of incident particles
- The effect of the secondary particles induced by the primary process should be small(cf. neutrons)
- The cross sections have to be "high" in the investigated energy region
- In case of energy measurements in the investigated energy range the cross sections should change sharply and several reaction channels have to be open with different slope of excitation functions
- In case of flux measurements the cross section should be constant or change slowly in the investigated energy range to minimize to uncertainty of the energy

The reaction products

- The emitted articles should be easy measurable(energy, intensity, type of irradiation, form of the reaction products)
- The reaction products(decay) has to remain in the irradiated sample(gas, recoil effects)

- The number of simultaneously produced other reaction products (not used in the monitoring process) should be small(background, overloading)
- The half life of the reaction products should be not too short and not very long as compared to irradiation time

The irradiation

- The irradiations should be done under controlled parameters concerning fix parameters ($\Phi(t)$, E, thickness).
- The monitor should be placed properly to the beam direction and to the region of interest

Review of standard monitor reactions

- The requirements are very complex
- The list of commonly used reactions continuously changed
- There are a lack of uniformity in the use of standard reactions
- The status of the available data base with few exceptions are very critical
- There are no recommended data for CP monitor reactions
- New evaluation are in progress for broad range of monitor isotopes
- Guidelines to use monitor reactions ear necessary

IAEA International Co-ordinated Research Program CP monitor reactions

Objectives To obtain verified reference data for the most important monitor reactions used for monitoring the p, d, ^{3}He and alpha particles up to 100 MeV energy

Participants: Seven laboratories

EVALUATION METHODOLOGY

1. **Compilation and collection of the data**
2. **New cross section measurements**
3. **Analysis of experimental data selection**
4. **Evaluation of the data**
5. **Integral Measurements. Collection of Integral Data**
6. **Selection of evaluated data**
7. **Publication of recommended data**
8. **Publication of independent laboratory data**

List of participating laboratories

No	Institution	Investigator	Profile
1	Free University Brussels, Belgium	A. Hermanne	compilation, selection, experiment
2	CNDC Beijing, China	Zhuang Youxiang	theory, calculation, fitting
3	INC Forschungszentrum Julich, Germany	S. M. Qaim	compilation, selection, experiment
4	INR HAS Debrecen, Hungary	F. Tárkányi	compilation, selection, experiment, fitting
5	NAC Faure, South Africa	M. Nortier, (H. Mills)	compilation, selection, experiment
6	IPPE Obninsk, Russia	Yu. Shubin	theory, calculation, fitting
7	LLNL Livermore, USA	M. Mustafa, (M. Blann)	theory, calculation, fitting

(Trieste99-Monitor-Tarkanyi)

Monitor reactions evaluated in the CRP

Particle	Reaction	Product half life	Emitted particle. Energy	Emitted particle Intensity
p	$^{27}Al(p,3p3n)^{22}Na$	2.6 y		
	$^{nat}Ti(p,x)^{48}V$	16.0 d		
	$^{nat}Ni(p,x)^{57}Ni$	1.5 d		
	$^{nat}Cu(p,x)^{56}Co$	77.7 d		
	$^{nat}Cu(p,x)^{62}Zn$	9.3 h		
	$^{nat}Cu(p,x)^{63}Zn$	38.1 min		
	$^{nat}Cu(p,x)^{65}Zn$	244.1 d		
d	$^{nat}Al(d,x)^{22}Na$	2.6 y		
	$^{nat}Ti(d,x)^{48}V$	16.0 d		
	$^{nat}Fe(d,x)^{56}Co$	77.7 d		
	$^{nat}Ni(d,x)^{61}Cu$	3.4 h		
^{3}He	$^{nat}Al(^{3}He,x)^{22}Na$	2.6 y		
	$^{nat}Ti(^{3}He,x)^{48}V$	16.0 d		
	$^{nat}Cu(^{3}He,x)^{66}Ga$	9.5 h		
	$^{nat}Cu(^{3}He,x)^{67}Ga$	3.3 d		
	$^{nat}Cu(^{3}He,x)^{65}Zn$	244.1 d		
α	$^{nat}Al(\alpha,x)^{24}Na$	14.7 h		
	$^{nat}Ti(\alpha,x)^{51}Cr$	27.7 d		
	$^{nat}Cu(\alpha,x)^{66}Ga$	9.5 h		
	$^{nat}Cu(\alpha,x)^{67}Ga$	3.3 d		
	$^{nat}Cu(\alpha,x)^{65}Zn$	244.1 d		

Summary of available experimental data

Nuclear reaction	Responsible for compilation	Available data	New measurement	Selected data
		Proton monitors		
$^{27}Al(p,x)^{22}Na$	Faure	20 (-5)		10
$^{27}Al(p,x)^{24}Na$	Atomki	27		22 (5 not used)
$^{nat}Ti(p,x)^{48}V$	Atomki	16	Szelecsenyi (submitted)	9 (2 not used)
$^{nat}Ni(p,x)^{57}Ni$	Atomki	21	Sonck et al. (1997)	14
$^{nat}Cu(p,x)^{56}Co$	Faure	7		3
$^{nat}Cu(p,x)^{62}Zn$	Julich	13	Hermanne et al. (1999)	4
$^{nat}Cu(p,x)^{63}Zn$	Julich	24		9
$^{nat}Cu(p,x)^{65}Zn$	Julich	30		9
		Deuteron monitors		
$^{27}Al(d,x)^{22}Na$	Atomki	5	Takacs et al. (unpublished)	3
$^{27}Al(d,x)^{24}Na$	Atomki	15	Takacs et al. (unpublished)	12
$^{nat}Fe(d,x)^{56}Co$	Atomki	9	Takacs et al. (unpublished)	7
$^{nat}Ni(d,x)^{61}Cu$	Atomki	6	Takacs et al. (1997) Takacs et al. (unpublished)	4
		^{3}He-particle monitors		
$^{27}Al(^{3}He,x)^{22}Na$	Atomki	5		5
$^{27}Al(^{3}He,x)^{24}Na$	Atomki	6		5
$^{nat}Ti(^{3}He,x)^{48}V$	Atomki	4	Ditroi et al. (submitted)	4
		α-particle monitors		
$^{27}Al(\alpha,x)^{22}Na$	Atomki	13		10
$^{27}Al(\alpha,x)^{24}Na$	Atomki	17		13
$^{nat}Ti(\alpha,x)^{51}Cr$	Atomki	10	Hermanne et al. (1999)	7
$^{nat}Cu(\alpha,x)^{66}Ga$	Atomki	17	Tarkanyi et al. (submitted)	10
$^{nat}Cu(\alpha,x)^{67}Ga$	Atomki	14	Tarkanyi et al. (submitted)	8
$^{nat}Cu(\alpha,x)^{65}Zn$	Atomki	15	Tarkanyi et al. (submitted)	9

Preparation of recommended data

Methods

Obtained results

Conclusions

Other monitor reactions

Reaction	Half-life of reaction product	Energy range
$^{12}C(p,pn)^{11}C$	20.39 m	18 MeV- 2.8 GeV
$^{12}C(p,x)^{7}Be$		30 MeV-2 GeV
$^{27}Al(p,x)^{18}F$	1.83 h	40 MeV-2.8 GeV
$^{27}Al(p,x)^{11}C$	20.39 m	50 MeV-2.8 GeV
$^{27}Al(p,x)^{7}Be$	53.29 d	27 MeV-2.2 GeV
$^{65}Cu(p,pn)^{64}Cu$	12.70 h	12 MeV- 2.8 GeV
$^{197}Au(p,x)^{149}Tb$	4.15 h	600 MeV-2 GeV
$^{12}C(d,dn)^{11}C$	20.39 m	16-60 MeV
$^{27}Al(\alpha,x)^{18}F$	1.83 h	80- 900 MeV
$^{59}Co(p,pn)^{58}Co$	70.916 d	
$^{nat}Cu(p,x)^{61}Cu$	3.41 h	
$^{51}V(d,2n)^{51}Cr$	27.70 d	
$^{nat}Mo(p,x)^{96}Tc$	4.28 d	
$^{197}Au(d,2n)^{197}Hg$	2.67 d	
$^{nat}Mo(\alpha,x)^{97}Ru$	2.88 d	
....		

(Trieste99-Monitor-Tarkanyi)

Main characteristics of beam monitoring via monitor reactions

Advantage

- simple and cheap
- require small space
- local monitor
- the number of incoming nuclei is controlled
- any beam shape could be monitored
- both absolute and relative measurements
- broad range of energy and intensity
- good accuracy for determination of the fluence
- the results could be corrected with changes of nuclear data
- nondestructive, the beam is passing trough, without significant changes
- The beam could be followed extended targets inside

Main characteristics of beam monitoring via monitor reactions

Disadvantage

- moderate accuracy for determination of the energy
- highly depend on the quality of the available nuclear data
- the quality of the recent data base is very poor
- no online information on the measured parameters
- it is difficult to install at accelerators and beam lines(temporary installed)
- give only integral data(changes couldn't be followed
- high doses during installation and separation.
- Not independent from the particle species, from energy their range, etc
- The particles has to hit the monitor under well known conditions
- Automation, feedback to control irradiation is impossible

Main application fields of monitor reactions

- **Medical isotope production**
- **Parameters of accelerators**
- **Nuclear data measurement**
- **Irradiation for analytical purposes and thin layer activation technique**
- **Research type of works**

Guide to use monitor reactions

- Data base for protons is more reliable
- For particles “d, ^{3}He, α” the status is poor
- No intercomparison, no validation
- Definition of the used cross sections
- To place in proper position (E, geometrically,..)
- Uniform monitor foils
- Irradiation time
- Effect of time variation of the fluence(integral)
- Effect of finite thickness(integral)
- Low energy gamma-rays, background lines
- Effect of energy spread of the beam
- Comparison of results of monitor reaction and other direct beam current measurement
- Cumulative effects
- Correction for recoils
- Secondary particles

(Trieste99-Monitor-Tarkanyi)

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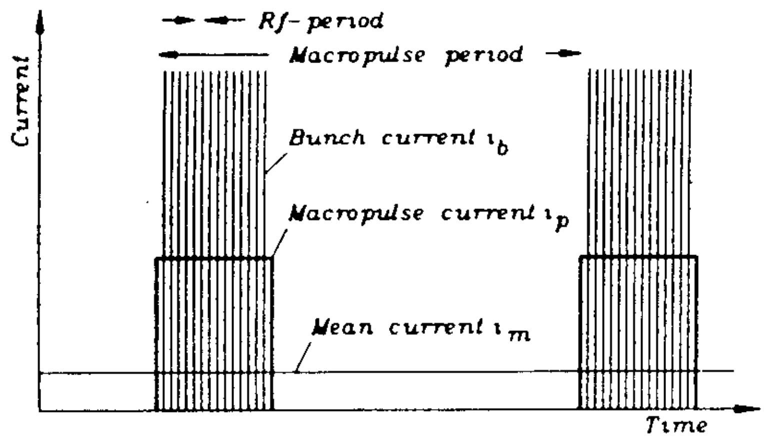
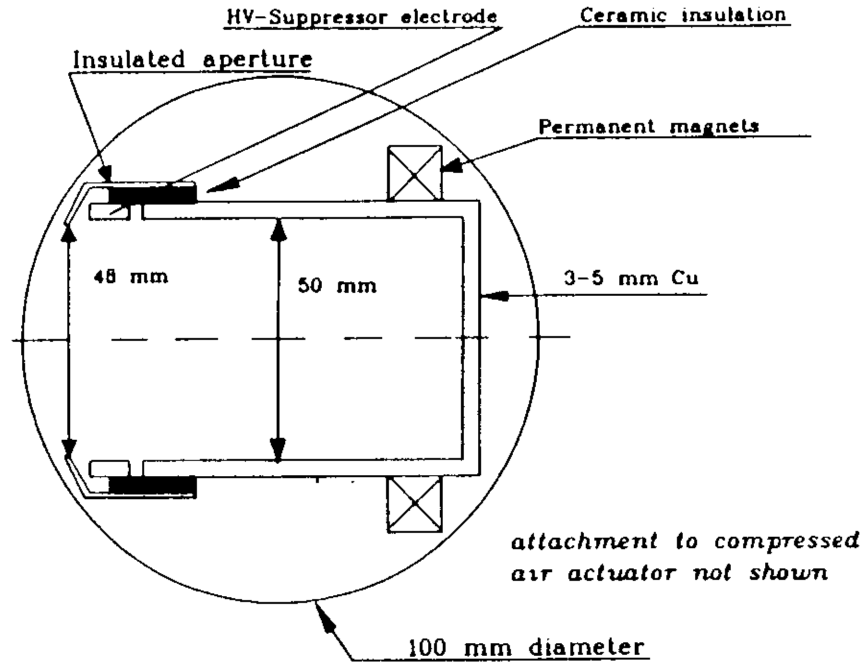


Various types of beam currents



Scheme of a uncooled Faraday cup