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Experimental techniques (Nuclear reaction data, estimation of uncertainties)

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Experimental techniques
(Nuclear reaction data, estimation of uncertainties)

The experimenter intends to produce a dataset that will provide improved information on the magnitude of certain physical parameters, usually cross sections, in a particular domain (*e.g.*, a range of energies).

The experimenter should have in mind an accuracy goal, so that the results of the work will have a significant impact in this field, and not simply add more data points to a crowded body of pre-existing results. The decision to focus on quality as opposed to quantity, or the converse, will be driven largely by the current status of the database for a particular reaction process.

If the experimenter has developed a measurement capability, not previously available in the field, that will permit the exploration of a physical process or domain where only theoretical results were available up to that time, it may be decided to focus on quantity rather than quality, in order to “scope out” the region, and by that means provide a test of the theoretical predictions. The uncertainties associated with theoretically determined values are generally rather large, so an extensive collection of experimental data of modest quality could be valuable.

On the other hand, if the experimenter is aiming to resolve a long-standing question concerning the magnitude of a physical quantity in a particular domain, and abundant (and unfortunately often discrepant) data are already available from the literature, the choice may be to perform an experiment to generate a few high-quality data points, *i.e.*, reliable values with small uncertainties, in an attempt to resolve the discrepancies.

Nuclear Data Sheets 113 (2012) 3006–3053

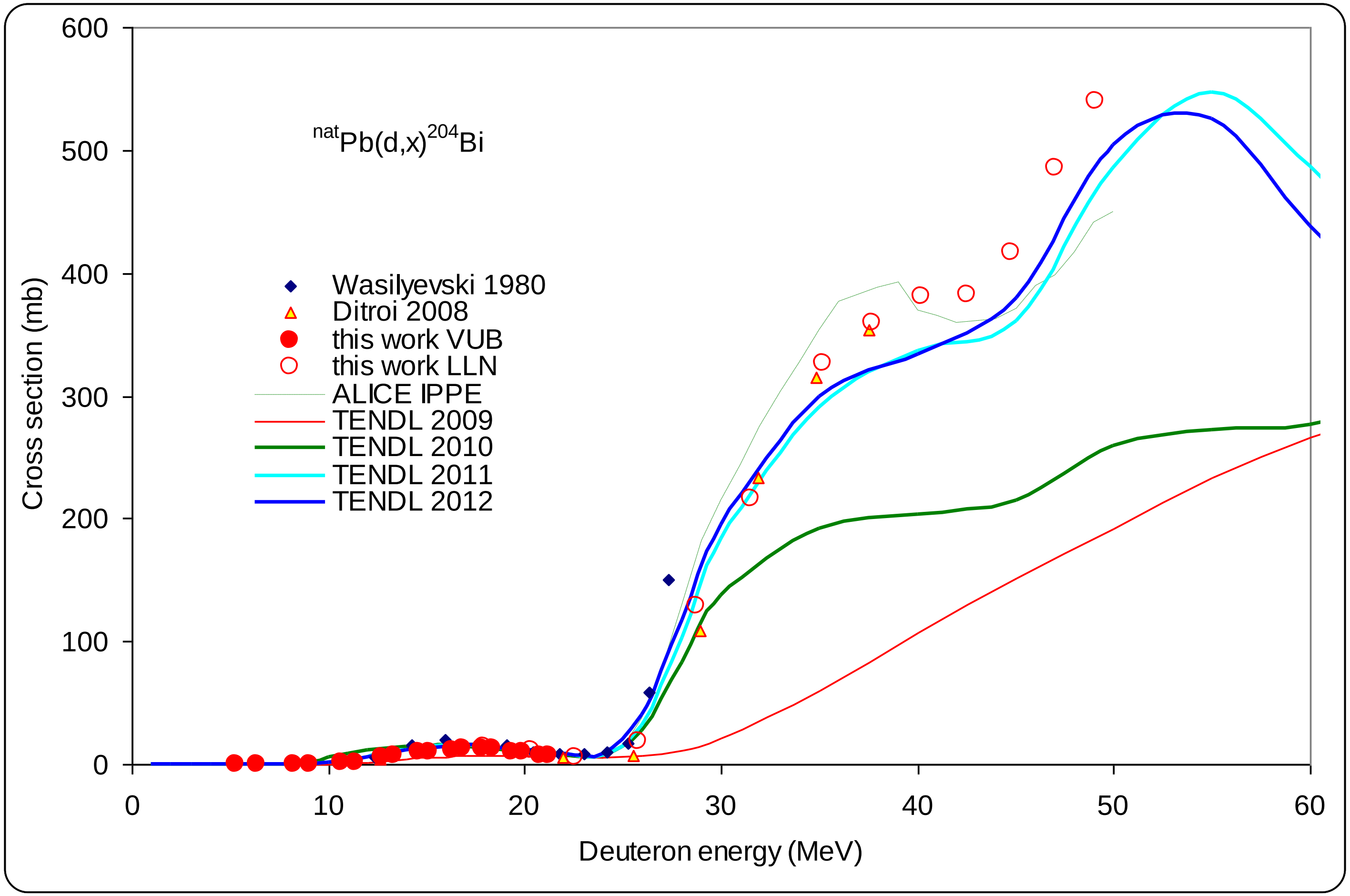
Overview

- **Main fields of the nuclear medicine**
- **Types of nuclear data**
- **Data needs for medical and connected applications**
- **Flow of measurement, processing and application of nuclear data**
- **Main parameters of nuclear reaction data**
- **Cross section data measurement (target, beam , irradiation,residual, emitted particles)**
- **Uncertainties**

Flow chart of measurement, processing and application of nuclear data

- **Data measurement**
- **Compilation**
- **Critical analysis**
- **Selection**
- **Model calculation**
- **Evaluation**
- **Application**

Importance of experimental data



Nuclear data in (Nuclear) Medicine

- **Diagnostics with radioisotopes (SPECT, PET)**
- **Radiotherapy with:**
  - **external particles (X,γ,p,n,HI)**
  - **radioisotopes**
- **Research (nuclear analytic, biological studies)**
- **Dosimetry, radiation safety (space radiation effects, accelerator shielding)**
- **Other**
  - **Development of medical equipment (wear meas.)**
  - **Sterilization of medical equipments (radiation processing)**

Nuclear data-Classification

- **Nuclear decay data (decay schemes)**

  decay mode, half- life, energies, intensities of the transitions, etc.

- **Nuclear reaction data**

  Cross sections, energy spectra of emitted particle, etc.

  Induced by: γ, p, n, HI

- **Differential or integral data**

- ***Nuclear structure data (level schemes)***

  mass excess, energy, spin, parity, transition prob., life time, etc.

Nuclear data- Neutron therapy

- **Primary and secondary charged particle spectra for calculations of absorbed dose during the treatment**
- **Physics of neutron sources used for therapy**
- **Collimation and shielding**
- **Improvement the neutron transport calculation**
- **Kerma factors for the neutrons and partial and total neutron cross sections for biological important elements**

Nuclear data- Proton and heavy ion therapy

Mainly atomic data

- **Secondary charged particle spectra for calculations of absorbed dose during the treatment**
- **Collimation and shielding**
- **Kerma factors for the CP and partial and total cross sections CP for biological important elements**
- **Activation products in tissue**

Nuclear data-Medical isotope production

- **Decay data**
- **Reaction cross sections**
- **Production yields**
- **Shielding**
- **Dose calculation**

Main parameters of nuclear reaction data

- **Total cross sections**
- **Partial cross sections**
- **Differential data**
- **Integral data**
- **Secondary particle spectra**
- **Isotopic data**
- **Elemental data**
- **Production yields**
- **Activation data, residual activities**
- **Direct, cumulative**

Basic equation

(what to prepare, to control and to measure)

A(target) + b(beam**)= C(residual) + d(emitted)**

- **Target (preparation, stability, quality, stacked, single)**
- **Bombarding beam (energy, intensity, time structure)**
- **Irradiation (single, stacked)**
- **Residual product (through decay, mass)**
- **Emitted particle (spectrometers, differential, integrated data)**

Target (preparation, stability, quality, stacked, single)

A(target) + b(beam) = C(residual) + d(emitted)

- **Solid, gas, liquid**
- **Elemental, compound, alloy**
- **Enriched, natural**
- **Target preparation -solid:** rolling
  sedimentation
  electro deposition
  powder pressing
  vacuum deposition
- **Target preparation –gas:**
- gas cells
- **Target preparation –liquid**
- **Stability, toxicity, heat transfer, melting point, reaction product**
- **Beam-target interaction** melting
  evaporation
  diffusion
  compound dissociation
  gas density reduction
  liquid bubbling

Bombarding beam (parameters, direct and indirect methods)

A(target) + b(beam) = C(residual) + d(emitted)

- **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**

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)**
- **Emittance 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 Macro Bunch Mean	Yes Yes Yes Yes	Yes No No Yes	Yes No No 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

- **Definition: number of incident particles**
- **Type: macropulse, bunch, mean current: DC or AC, time dependence**
- **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
- **Appl. of monitor reactions: possible**

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

Parameter: Emittance

- **Definition:** **Angular divergence of all particles as function of their co-ordinate**
  In 2 dimensional phase space, dx_i dp_i, in transverse phase space
- **Determination:** **slits, holes + current measuring device**
- **Appl. of monitor reactions: no**

Parameter: Brilliance, Energy, Energy spread

- **Definition:** **Beam energy, beam energy spread**
  Momentum (energy) spread of all particles as function of their phase deviation
  in 2 Dimensional projected phase space, dx_i dp_i, in longitudinal phase space
- **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
Θ	emission angle

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

General requirements for monitor reactions

The target

- **The target elements should be isotopicaly pure or disturbances on 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 have high thermal conductivity to allow higher intensities and effective cooling**

General requirements for monitor reactions (cont)

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 the uncertainty of the energy

The reaction products

- The emitted particles 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 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 ($\Phi(t)$, E, thickness).
- The monitor should be placed properly to the beam direction and to the region of interest

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**
- **for relative measurements**
- **broad range of energy and intensity**
- **good accuracy for determination of the fluence**
- **the results could be corrected for changes of nuclear data**
- **nondestructive, the beam is passing trough, without significant changes**
- **the beam could be followed inside extended targets**

Main characteristics of beam monitoring via monitor reactions

Disadvantage:

- **moderate accuracy for determination of the energy**
- **highly dependent on the quality of the available nuclear data**
- **the accuracy of the recent data base is moderate**
- **no uncertainties on evaluated data**
- **no online information on the measured parameters**
- **it is difficult to install permanently at accelerators and beam lines (temporary installed)**
- **give only integral data (changes couldn't be followed)**
- **high doses during separation from target.**
- **choice dependent from the particle species and energy range**
- **the particles has to hit the monitor under well known conditions**
- **automation, feedback to control irradiation is impossible**

Main application fields of monitor reactions

- **Routine medical isotope production**
- **Parameters of accelerators**
- **Nuclear data measurement**
- **Irradiation for analytical purposes and thin layer activation technique**
- **Research work**

Guide to use monitor reactions

- **Data base for protons is more reliable**
- **For particles “d, ^{3}He, a” the status is poor**
- **No intercomparison, no validation**
- **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**

Irradiations for nuclear data measurements

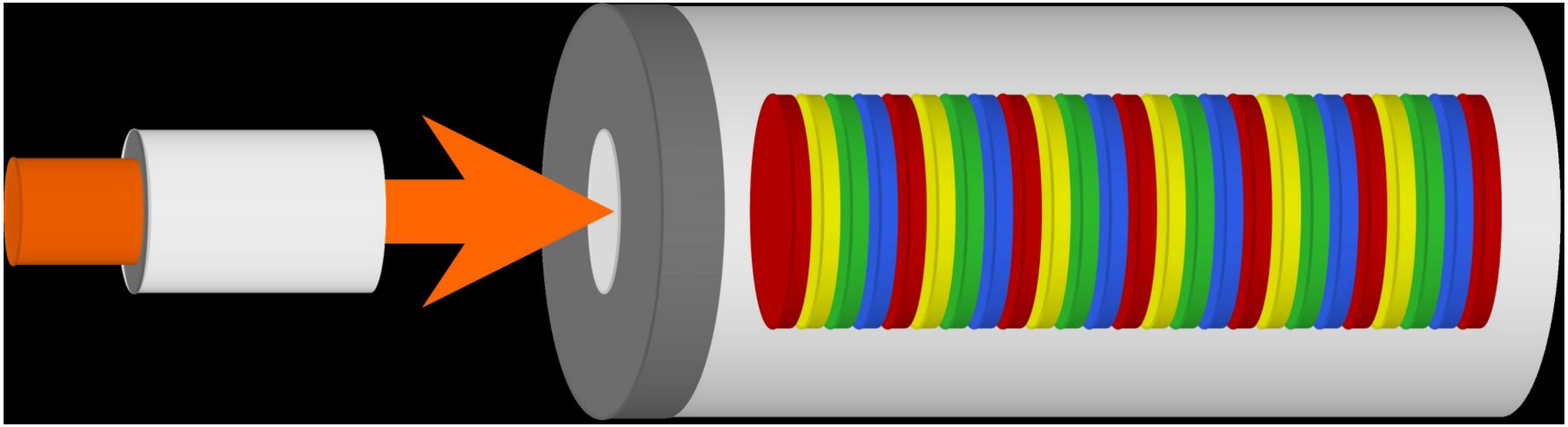
Cross sections

- single
- stacked
- thick target

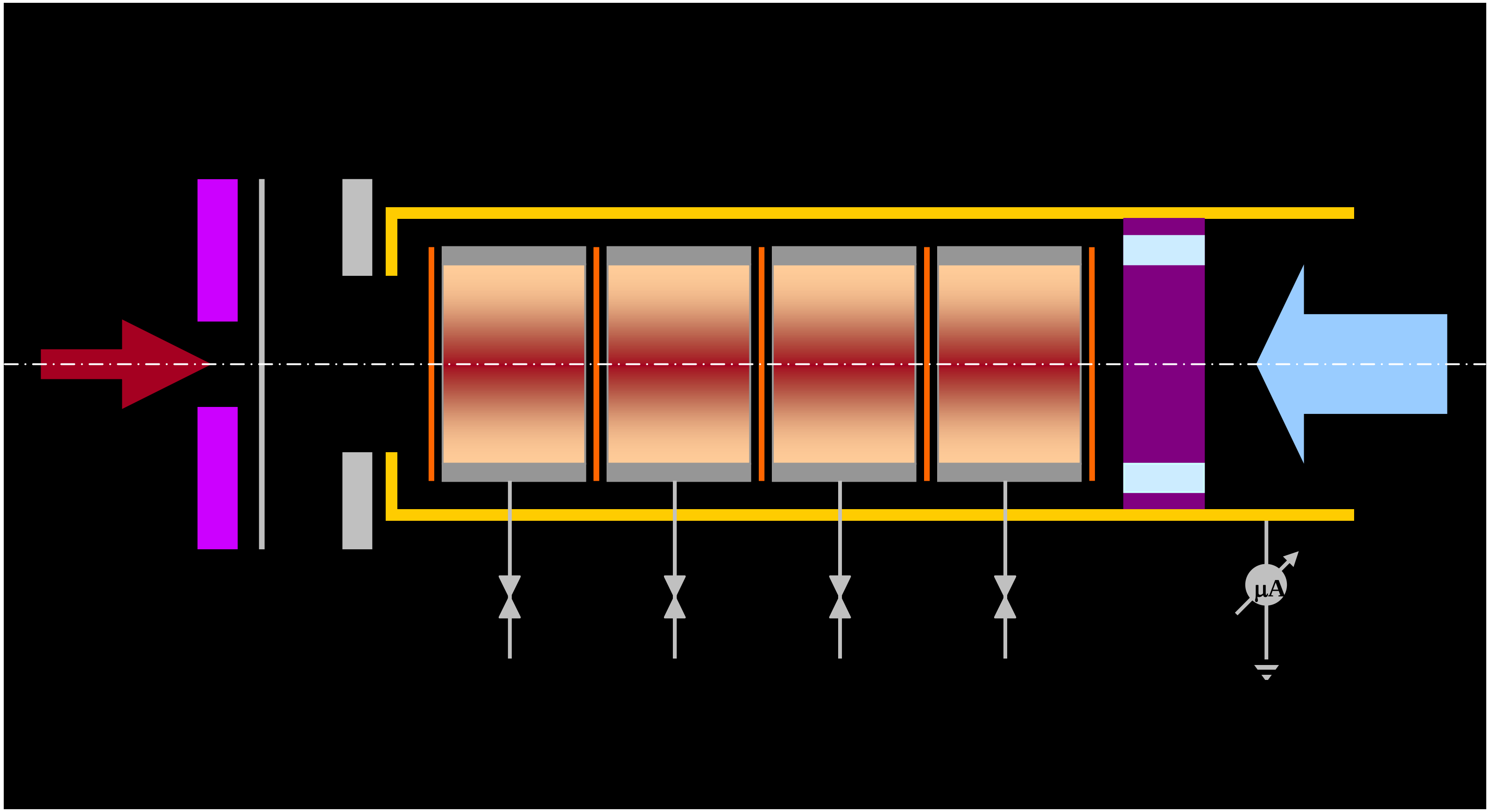
Yields

- thin
- thick
- differential
- integral
- production yield

Solid targets: stacked foils



The stacked gas cells



Investigation of beam broadening in stacked gas targets

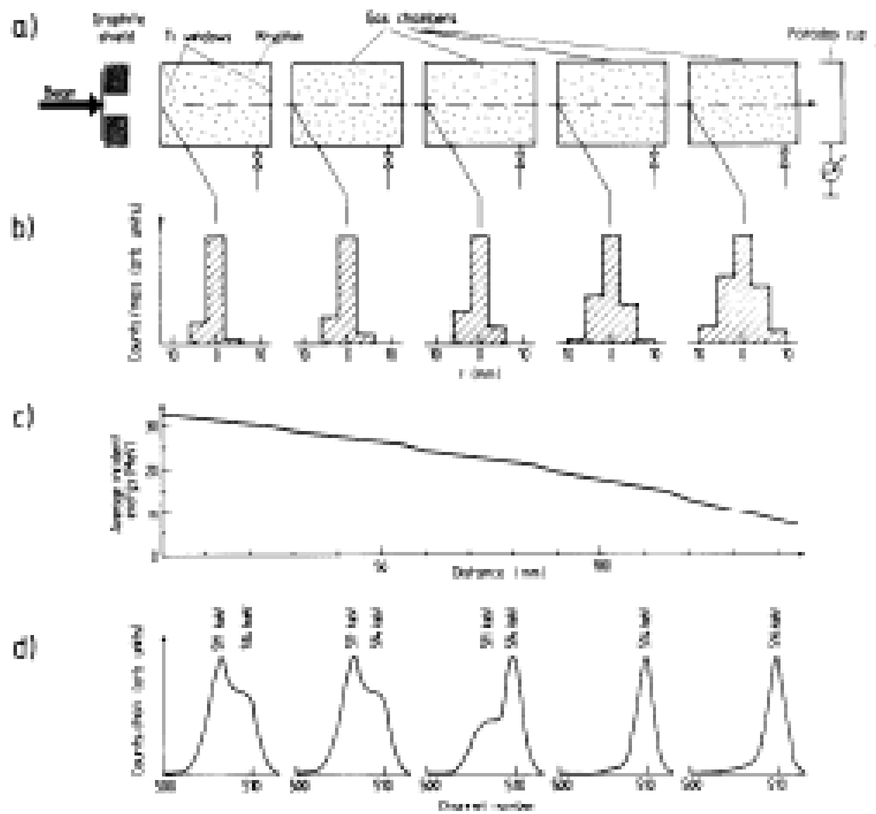
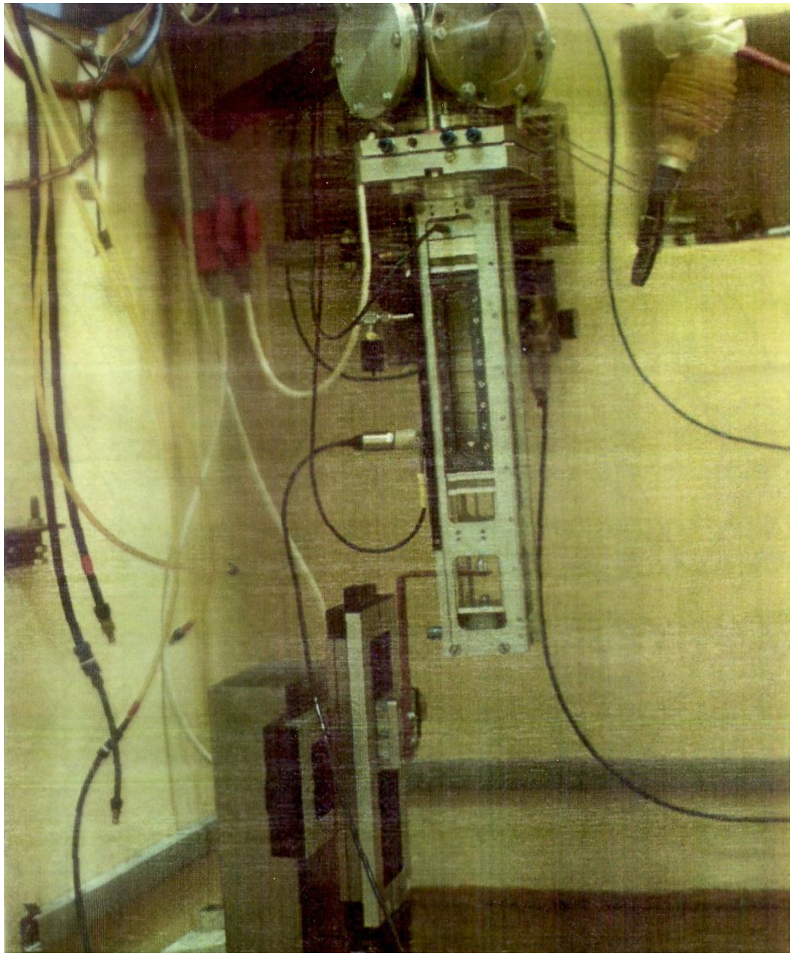
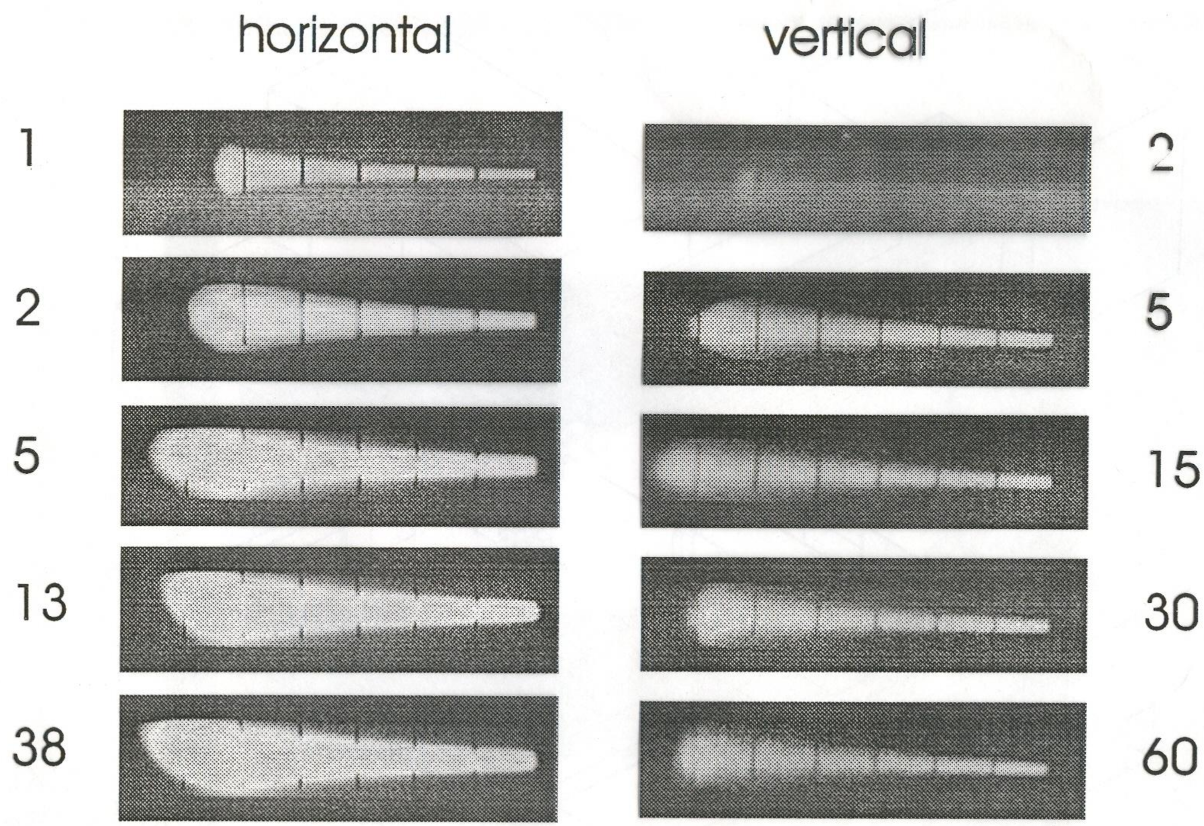


Fig. 1. (a) Schematic arrangement for irradiation of gas target chambers for excitation function measurements. (b) Radial activity distribution in the front window of each gas cell. The distribution reflects the beam profile. (c) Typical energy degradation along the successive gas chambers. (d) 511/514 keV gamma-line ratio at different bombarding energies.

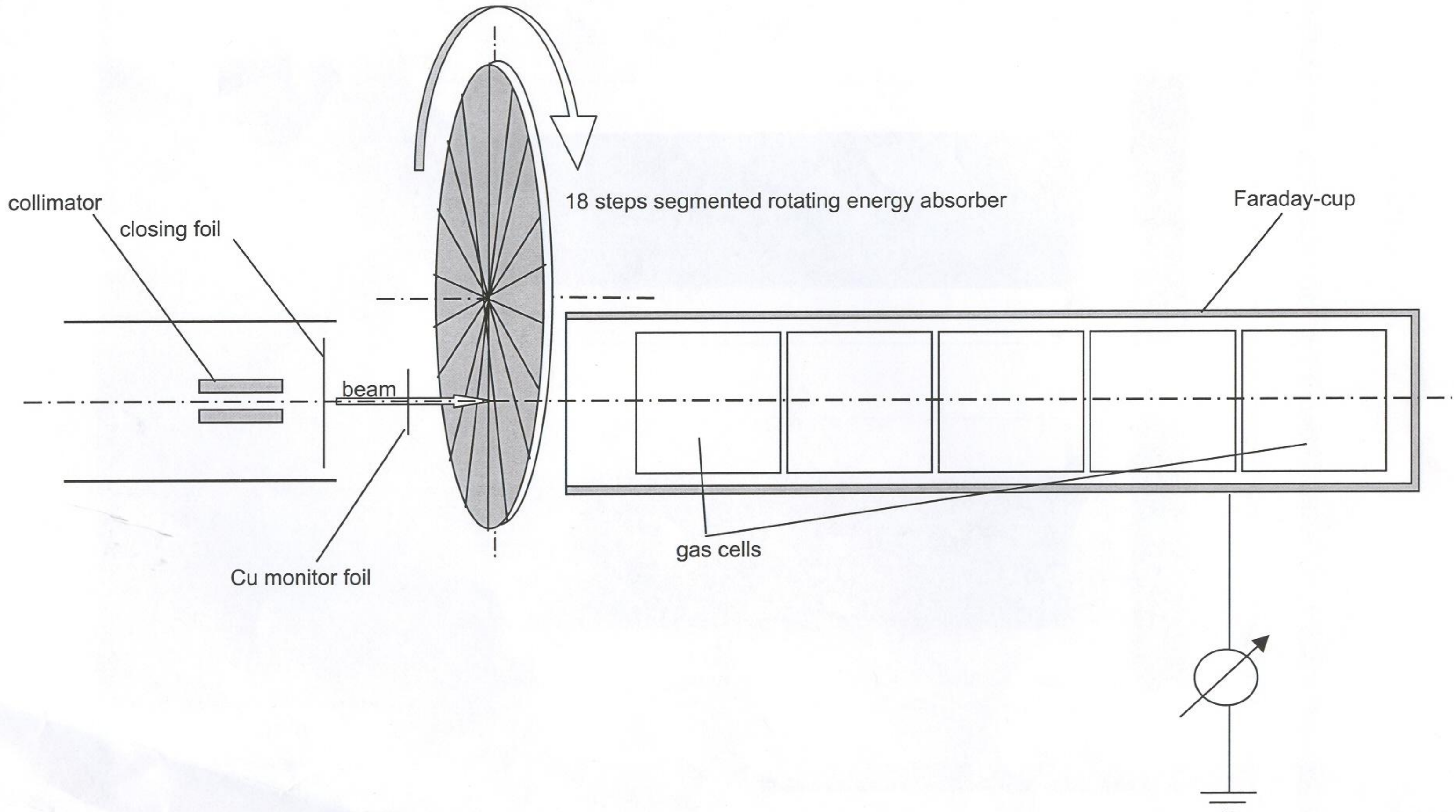
Investigation of gas density reduction



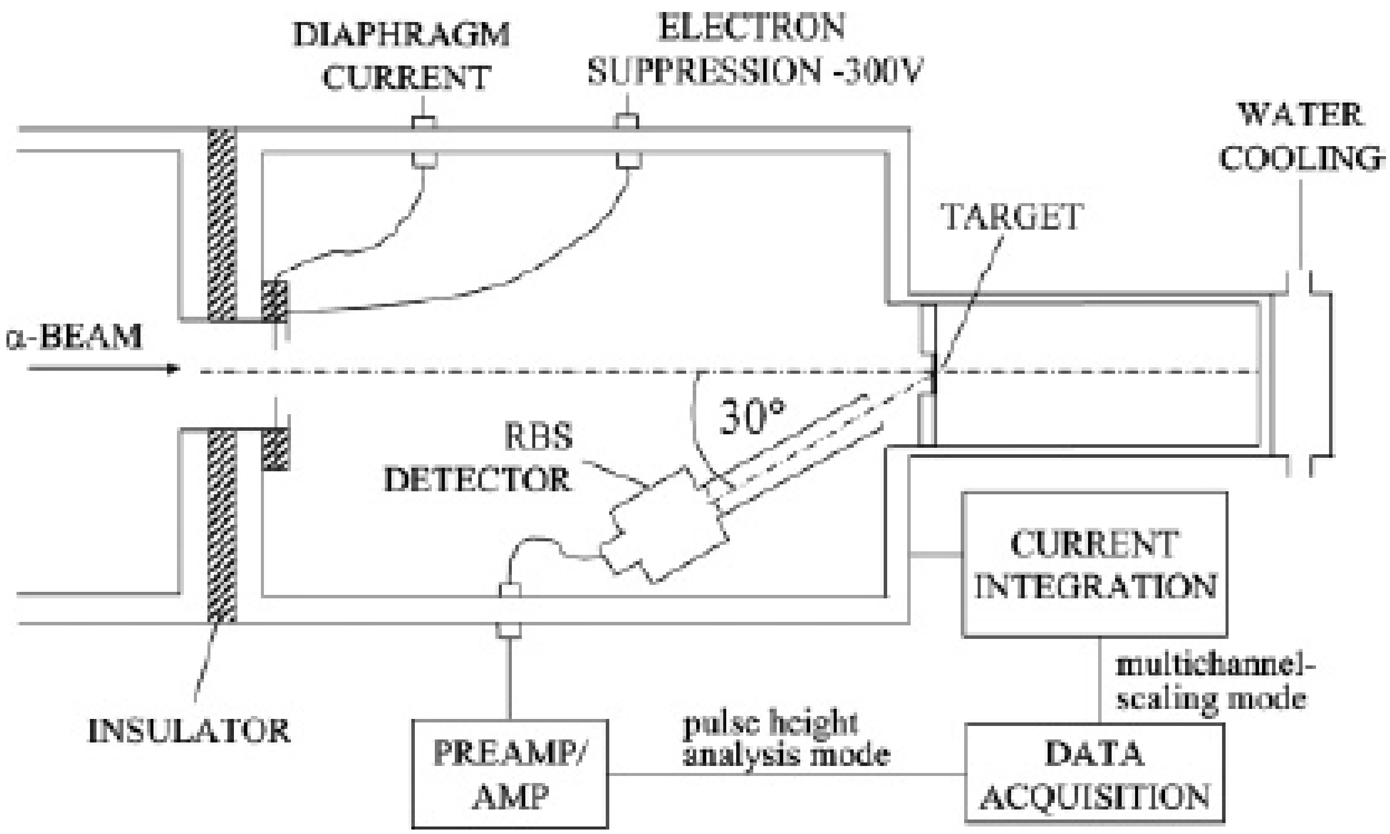
Distribution of charged particle beam in gas



Measurements thick target yields by using thin targets



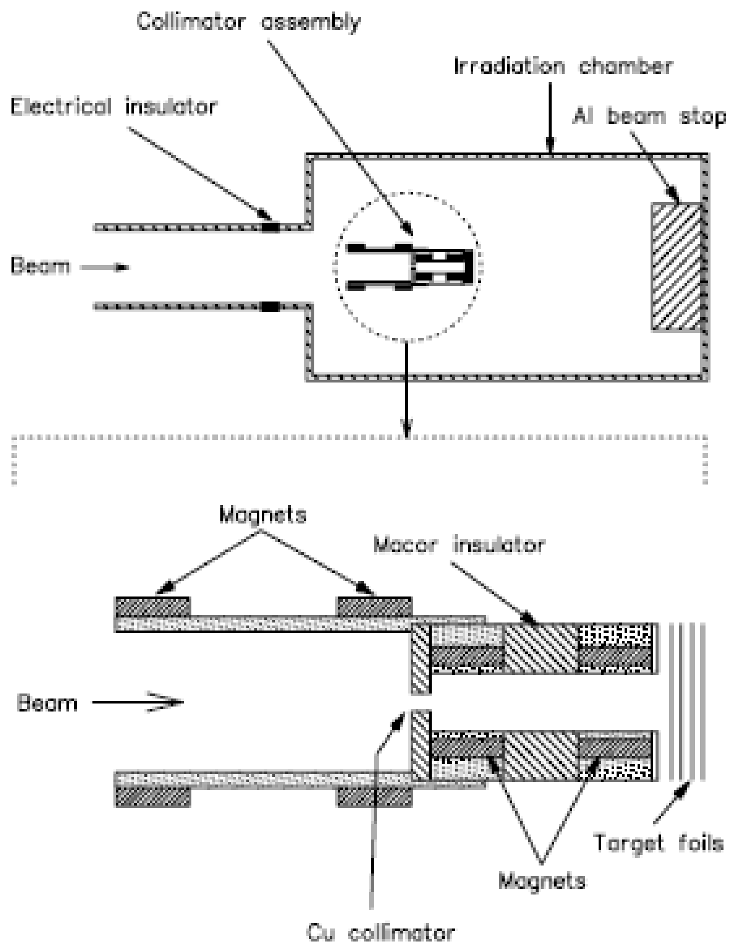
Single foil irradiation



e FIG. 3. Schematic view of the ATOMKI target chamber.

PHYSICAL REVIEW C **74**, 025805 (2006)

Irradiation of stacked foils



Nucl. Instr. and Meth. in Phys. Res. B 240 (2005) 625–637

Residual product (decay, emitted particles mass)

A(target) + b(beam)= C(residual) + d(emitted)

Through decay

Through emitted particles: X, γ, α, β

- **X**
  - **special detectors**
  - **Self absorption**
  - **Available intensities**
  - **Resolution**
  - **Complex low energy spectra**
  - **Same X-ray for same Z, contributions**
- **Gamma, positrons**
  - **Simultaneous many isotopes**
  - **Available intensities**
  - **Resolution**
  - **Complex low energy spectra**
- **Beta particles**
  - **continuous spectra**
  - **Solid state detectors Si**
  - **Liquid scintillators**

Trough atomic mass

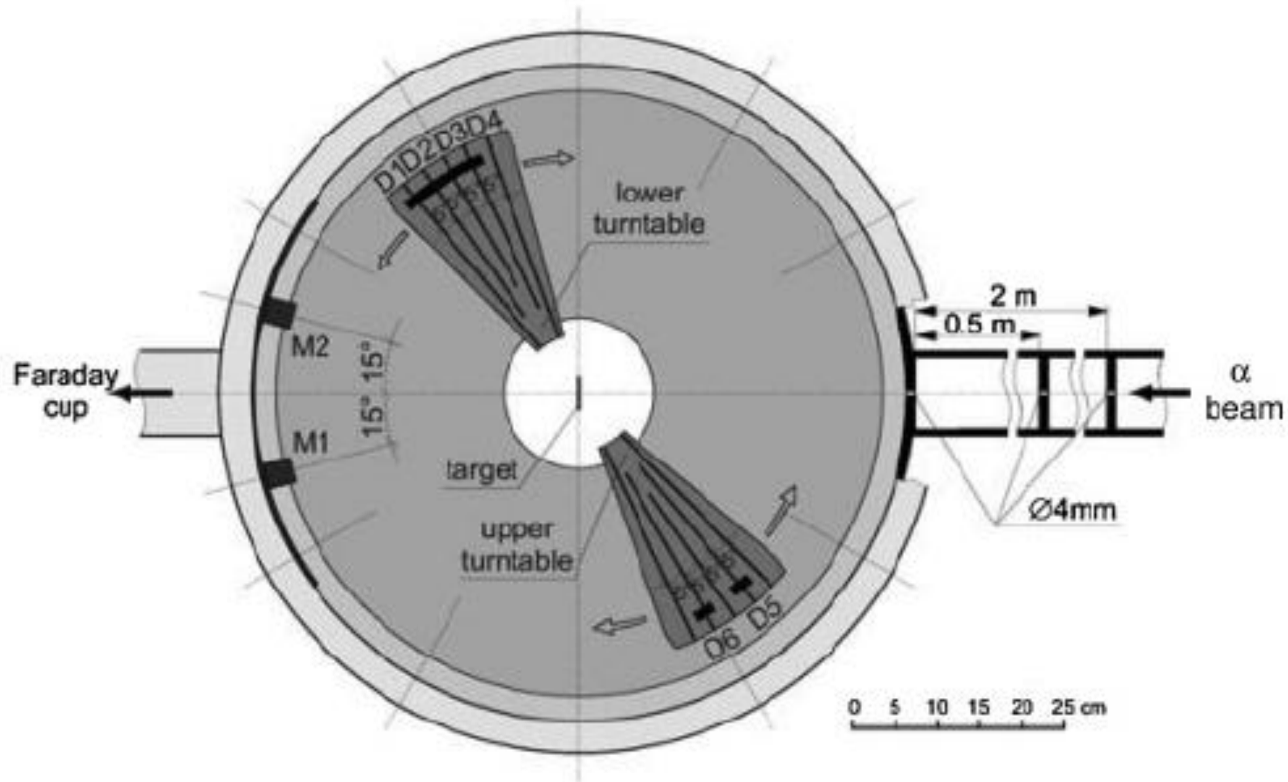
- **stable isotopes**
- **long half life**
- **mass spectrometers**

Emitted particles (spectrometers, differential, integrated data)

A(target)+b(beam)= C(residual)+d(emitted)

- **The residual product is not radioactive, or has long half life**
- **In case of differential (E, Θ) or total cross section data**
- **Rare in case of medical isotope production**

Nuclear reaction chamber at ATOMKI



PHYSICAL REVIEW C **83**, 065807 (2011)

Uncertainties

Energy

- **Primary beam average, distribution**
- **Determination of the target thickness**
- **Target uniformity**
- **Beam energy straggling**
- **Surface density change during irradiation**
- **Cumulative effects**

Uncertainties

Cross sections

- **Detector efficiency**
- **Spectrum evaluation**
- **Statistics**
- **Dead time**
- **Coincidence losses**
- **Self absorption**
- **Nuclear data (intensities, half life, transition probabilities)**
- **Separation of cumulative effects**
- **Standard sources**
- **Standard monitor reactions**
- **Beam intensity, time structure**
- **Chemical separation**

Publication of the experimental results

- List of uncertainty components and their values
- Degree of correlation between various components
- Detailed description of the experiment for full understanding of the measuring and data evaluation process.