Progress Report of the Charged Particle Nuclear Data Group
of the Institute of Nuclear Research, (Atomki) Debrecen, Hungary
to the IAEA Technical Meeting
on the Network of Nuclear Reaction Data Centres
17 - 19 June 2003

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General

The Nuclear Data Group at the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI) is working within the Cyclotron Department.
The main activity of the nuclear data group in Debrecen is concentrated on the integral cross sections of light ion induced reactions. The investigated reactions are connected to the following application fields:

- nuclear reactions for production of diagnostic radioisotopes,
- **nuclear reactions for therapeutic radioisotopes**
- nuclear reactions for thin layer applications
- nuclear reactions to monitor beam parameters
- nuclear reactions connected to transmutation of radioactive waste

The investigations include experimental measurements, data compilations, data evaluations, data validations and data applications. The investigations are connected to several applications simultaneously. The experimental measurements and the data evaluations are done in international collaborations. The main partners for measurements of nuclear data for production of therapeutic radioisotopes: VUB Brussels, FZ Jüelich, CYRIC Tohoku University.

Recent Progress

We have continued the determination of experimental cross sections on various target materials bombarded with charged particle beams, as well as the compilation and the critical comparison of several selected processes used for production of medically important radioisotopes, for monitoring charged particle beams and for thin layer activation measurements.

In 2002 first priority was given to check, update and upgrade of the evaluated Reference Database for medical isotope production and monitoring light charged particle beams. The database including recommended cross-section data and the corresponding deduced yields was published in IAEA-TECDOC-1211 and also was placed on the world-wide-web. The results of the Co-ordinated Research Project for "Development of reference charged particle cross section database for medical radioisotope production" were reviewed and 11 nuclear reactions for positron emitters were updated with

experimental results not included in the primary data base.

A validation test and upgrading of the recommended cross-section database for production of PET radioisotopes in charged particle induced reactions was performed. Experimental microscopic cross section data published earlier or measured recently and not yet included in the earlier evaluation work were collected and added to the primary database in order to improve the quality of the recommended data. The newly compiled experimental data in some cases influenced the decision made earlier and resulted in new selected cross-section data sets. A spline fitting method was applied to the selected data sets an updated recommended data were produced in those cases. The integral thick target yields deduced from the new recommended cross sections were critically compared with experimental yield data available in the literature and were compared with the data of the frequently used compilation work of P.P. Dmitriev, (*Radionuclide Yield in Reactions with Protons, Deuterons, Alpha Particles and Helium-3, Moscow, Ehnergioatomizdat (1986), and INDC(CCP)-263/G+CN+SZ (1986)*).

The results of the upgrading work were summarized in an article and were sent for publishing to Nuclear Instruments and Methods in Physics Research B. New evaluation and fit was performed for 8 reactions to produced improved recommended cross section. Data validation was performed for all the 11 investigated reactions by collecting and comparing experimental thick target integral yields with the calculated ones deduced from the new recommended cross sections. Generally the available experimental yields support our new recommended yields with minor deviations. Computational error and/or sub-optimal fitting procedures were detected in the TECDOC published data which were also corrected. The recommended cross section values for the 11 investigated reactions were compiled in EXFOR entry D4111.

Good agreement was found between our data and the ones published by Dmitriev for the $^{14}N(p,\alpha)^{11}C$ and $^{69}Ga(p,2n)^{68}Ge$ reactions. In two cases, $^{16}O(p,\alpha)^{13}N$ and $^{18}O(p,n)^{18}F$, the agreement is good up to 16 and 8 MeV respectively but above these energy points Dmitriev's data are higher than our ones. For the $^{nat}Ne(d,x)^{18}F$ and $^{124}Te(p,n)^{124}I$ reactions the data agree within a few percent. In the case of $^{85}Rb(p,4n)^{82}Sr$ and $^{nat}Rb(p,x)^{82}Sr$ the values in compilation work of Dmitriev are too low and are in disagreement with the new recommended yield data. No data were published by Dmitriev for the $^{15}N(p,n)^{15}O$, $^{14}N(d,n)^{15}O$ and $^{nat}Ga(p,x)^{68}Ge$ reactions. The results of this part of the upgrading work are summarized in Table 1.

EXFOR compilation

As agreed earlier the Debrecen CP Nuclear Data Group collects and compiles charged particle experimental cross section data measured in Debrecen and Jüelich.
In the last year this activity was temporary slowed down, due to the overload by other program. By this time two TRANS were transmitted to NDS including 19 entries and 85 new subentries containing experimental data.

Nuclear data services

The group continue to supply compiled experimental charged particle data at low a medium energies for special request, needed mainly on non-energy related applications (medical isotope production, TLA, etc).

Staff

The staff consists of three physicists, working in different application areas at the Debrecen cyclotron. They work in-part time in different percentage on data measurement and compilations and other related work. The main problem is the lack of technical support for data input

Technical developments

New high speed computers were installed to increase the effectivity of data evaluation and data processing of experimental primary data. A high resolution scanner and simple but effective software were also put into operation to scan and digitize data given only in graphical form.

Planned new measurements to complete the available charged particle data

In collaboration with other laboratories we participate in a systematic study and measurements of CP cross sections data in low and medium energy range. The reactions are selected on the basis of the every day practice and requirements of the collaborating laboratories, and on the problems arising during compilation and evaluation of the available data. We continue to investigate the following processes and areas:

- Production of radioisotopes for medical diagnostic.
- Production of radioisotopes for therapy.
- Commonly used reactions for thin layer activation technique.
- Intercomparison of commonly used monitor reactions.
- We continue to work on the problems related to the Reference Database for medical isotope production and monitoring light charged particle beams.
- We continue to compile new entries in EXFOR from the papers published by the INC, Forschungszentrum Jüelich, Jüelich, Germany, and Institute of Nuclear Research, Debrecen, Hungary.

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Experimental work done on charged particle cross sections in 2002-2003

The following light charged particle induced nuclear reactions were investigated and cross sections were measured. Results were summarized in articles and were published or were sent to publisher.

$^{nat}Ti(p,x)^{48}V$
$^{nat}Ni(p,x)^{57}Ni$
$^{nat}Cu(p,x)^{62}Zn$
$^{nat}Cu(p,x)^{63}Zn$
$^{nat}Cu(p,x)^{65}Zn$
$^{85}Rb(p,4n)^{82}Sr$
$^{nat}Mo(p,x)^{96mg}Tc$
$^{nat}Mo(p,x)^{99m}Tc$
$^{nat}Mo(p,x)^{99}Mo$
$^{100}Mo(p,2n)^{99m}Tc$
$^{14}N(p,n)^{14}O$
$^{18}O(p,n)^{18}F$

$^{nat}Pd(d,xn)^{111}Ag$
$^{nat}Pd(d,xn)^{110m}Ag$
$^{nat}Pd(d,xn)^{104mg}Ag$
$^{nat}Pd(p,xn)^{104mg}Ag$
$^{103}Rh(d,x)^{103}Pd$
$^{nat}Zn(d,x)^{66}Ga$
$^{nat}Zn(d,x)^{67}Ga$
$^{nat}Zn(d,x)^{62}Zn$
$^{nat}Zn(d,x)^{65}Zn$
$^{nat}Zn(d,x)^{69m}Zn$
$^{nat}Zn(d,x)^{61}Cu$
$^{nat}Zn(d,x)^{64}Cu$
$^{nat}Zn(d,x)^{67}Cu$
$^{nat}Zn(d,x)^{58}Co$
$^{nat}Zr(d,x)^{88}Zr$
$^{nat}Zr(d,x)^{89}Zr$
$^{nat}Zr(d,x)^{95}Zr$
$^{nat}Zr(d,x)^{97}Zr$
$^{nat}Zr(d,x)^{86}Y$
$^{nat}Zr(d,x)^{87}Y$
$^{nat}Zr(d,x)^{88}Y$
$^{nat}Zr(d,x)^{90}Nb$
$^{nat}Zr(d,x)^{91m}Nb$
$^{nat}Zr(d,x)^{92m}Nb$
$^{nat}Zr(d,x)^{95}Nb$
$^{nat}Zr(d,x)^{96}Nb$
$^{nat}W(d,x)^{181}Re$
$^{nat}W(d,x)^{182mg}Re$
$^{nat}W(d,x)^{183}Re$
$^{nat}W(d,x)^{184g}Re$
$^{nat}W(d,x)^{186}Re$
$^{nat}W(d,x)^{187}W$
$^{78}Kr(d,\alpha)^{76}Br$

$^{nat}Fe(^{3}He,x)^{54}Mn$
$^{nat}Fe(^{3}He,x)^{55}Co$
$^{nat}Fe(^{3}He,x)^{56}Co$
$^{nat}Fe(^{3}He,x)^{57}Co$
$^{nat}Fe(^{3}He,x)^{58}Co$
$^{nat}Fe(^{3}He,x)^{56}Ni$
$^{nat}Fe(^{3}He,x)^{57}Ni$
$^{nat}Cu(^{3}He,x)^{66}Ga$
$^{nat}Cu(^{3}He,x)^{67}Ga$
$^{nat}Cu(^{3}He,x)^{63}Zn$
$^{nat}Cu(^{3}He,x)^{65}Zn$

$^{nat}Fe(\alpha,x)^{56}Mn$
$^{nat}Fe(\alpha,x)^{55}Co$
$^{nat}Fe(\alpha,x)^{56}Co$
$^{nat}Fe(\alpha,x)^{57}Co$
$^{nat}Fe(\alpha,x)^{58}Co$
$^{nat}Fe(\alpha,x)^{61}Co$
$^{nat}Fe(\alpha,x)^{56}Ni$
$^{nat}Fe(\alpha,x)^{57}Ni$
$^{nat}Ta(\alpha,xn)^{184mg}Re$
$^{nat}Ta(\alpha,xn)^{183}Re$
$^{nat}Ta(\alpha,xn)^{182mg}Re$
$^{nat}Ta(\alpha,xn)^{181}Re$
$^{nat}Nb(\alpha,x)^{96mg}Tc$
$^{nat}Nb(\alpha,x)^{95mg}Tc$
$^{nat}Nb(\alpha,x)^{94g}Tc$
$^{nat}Nb(\alpha,x)^{95mg}Nb$
$^{nat}Nb(\alpha,x)^{92m}Nb$

Table 1.: Experimental data summary for upgraded diagnostic positron emitters.

Nuclear reaction	Number of data sets (σ) in the CRP	Selected data sets (σ) in the CRP	Additional works (σ) in this work	Integral data (TTY, PY) in this work	New evaluation in this work	Reason	Agreement with Dmitriev's data
$^{14}N(p,\alpha)^{11}C$	13	9	2	10	no		good
$^{16}O(p,\alpha)^{13}N$	11	10	0	8	no		good below 16 MeV
$^{15}N(p,n)^{15}O$	5	5	2	3	yes	better fit	no data
$^{14}N(d,n)^{15}O$	9	5	0	3	yes	better fit	no data
$^{18}O(p,n)^{18}F$	6	4	2	14	yes	new data	good up to 8 MeV
$^{nat}Ne(d,x)^{18}F$	6	3	0	3	no		acceptable
$^{69}Ga(p,2n)^{68}Ge$	3	2	0	3	yes	better fit	good
$^{nat}Ga(p,x)^{68}Ge$	3	2	0	3	yes	better fit	no data
$^{85}Rb(p,4n)^{82}Sr$	1	1	2	8	yes	new data	bad
$^{nat}Rb(p,x)^{82}Sr$	3	2	3	11	yes	new data	bad
$^{124}Te(p,n)^{124}I$	8	2	0	5	yes	better fit	acceptable

Publications in 2002-2003

The new experimental cross section and yield data measured by our group were published in different papers and presented at different conferences. Here we give the list of publications appeared in the last two years or were submitted for publication in a scientific journal.

Hermanne A., Sonck M., Takács S., Tárkányi F., Shubin Yu. N.:
Study on alternative production of ^{103}Pd and characterisation of contaminants in the deuteron irradiation of ^{103}Rh up to 21 MeV.
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms ***187*** *(2002)3.*

Takács S., Tárkányi F., Sonck M., Hermanne A.:
New cross-sections and intercomparison of proton monitor reactions on Ti, Ni and Cu.
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms ***188*** *(2002)106.*

Takács S., Tárkányi F., Sonck M., Hermanne A.:
Investigation of the ^{nat}Mo(p,x)^{96mg}Tc nuclear reaction to monitor proton beams: New measurements and consequences on the earlier reported data.
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms ***198*** *(2002)183.*

Tárkányi F., Ditrói F., Takács S., Al-Abyad M., Mustafa M. G., Shubin Yu. N., Zhuang Y.: New data and evaluation of ^{3}He-induced nuclear reactions on Cu.
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms ***196*** *(2002)215.*

Hermanne A., Takács S., Tárkányi F., Bolbos R.:
Cross section for the charged particle production of the therapeutic radionuclide Ag-111 and its PET imaging analogue Ag-104g.
Annales Universitatis Turkuensis, Seria D ***499*** *(2002)14.*

Hermanne A., Sonck M., Takács S., Tárkányi F., Shubin Yu. N.:
Deuteron bombardment of ^{103}Rh: A new promising pathway for the production of ^{103}Pd.
Journal of Nuclear Science and Technology, Supplement ***2*** *(2002)1286.*

Qaim S. M., Tárkányi F., Oblozinsky P., Gul K., Hermanne A., Mustafa M. G., Nortier M., Scholten B., Shubin Yu. N., Takács S., Zhuang Y.: Charged-particle cross section database for medical radioisotope production.
Journal of Nuclear Science and Technology, Supplement ***2*** *(2002)1282.*

Scholten B., Hess E., Takács S., Kovács Z., Tárkányi F., Coenen H. H., Qaim S. M.:
Cross section measurements on gas targets relevant to the production of the positron emitting radionuclides ^{14}O, ^{18}F and ^{76}Br.

*Journal of Nuclear Science and Technology, Supplement **2** (2002)1278.*

Tárkányi F., Takács S., Andó L., Vera-Ruiz H., Shubin Yu. N., Hermanne A.:
Status of the database for production of medical radioisotopes of ^{103}Pd ^{123,124}I, ^{201}Tl by using Rh, Te and Tl targets.
*Journal of Nuclear Science and Technology, Supplement **2** (2002)1318.*

Ido T., Hermanne A., Ditrói F., Szûcs Z., Mahunka I., Tárkányi F.:
Re-measurement of the excitation function of the ^{85}Rb(p,4n)^{82}Sr nuclear reaction near the threshold: relevance to the production of a ^{82}Sr(^{82}Rb) generator system with a medium energy cyclotron.
*Journal of Nuclear Science and Technology, Supplement **2** (2002)1310.*

Tárkányi F., Ditrói F., Szelecsényi F., Sonck M., Hermanne A.:
Measurement and evaluation of the excitation functions for alpha particle induced nuclear reactions on niobium.
*Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **198** (2002)11.*

Ido T. , Hermanne A., Ditrói F., Szûcs Z., Mahunka I., Tárkányi F.:
Excitation functions of proton induced nuclear reactions on ^{nat}Rb from 30 to 70 MeV. Implication for the production of ^{82}Sr and other medically important Rb and Sr radioisotopes.
*Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **194** (2002)369.*

Kovács Z., Scholten B., Tárkányi F., Coenen H. H., Qaim S. M.:
Cross section measurements using gas and solid targets for production of the positron-emitting radionuclide O-14.
*Radiochimica Acta **91** (2003)185.*

F. Tárkányi, S. Takács, A. Hermanne, F. Ditrói, L. Andó, S. -J. Heselius and J. Bergman
New experimental data on excitation functions for practical applications of alpha induced nuclear reactions on Ta up to 30 MeV, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, In Press, Corrected Proof, Available online 28 May 2003,*

F. Tárkányi, F. Ditrói, S. Takács, F. Szelecsényi, A. Hermanne and M. Sonck
Activation cross-sections of alpha induced nuclear reactions on iron up to 40 MeV, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, In Press, Corrected Proof, Available online 17 May 2003,*

F. Tárkányi, S. Takács, F. Szelecsényi, F. Ditrói, A. Hermanne and M. Sonck
Excitation functions of deuteron induced nuclear reactions on natural tungsten up to 50 MeV, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, In Press, Uncorrected Proof, Available online 17 May 2003,*

F. Tárkányi, F. Ditrói and S. Takács
Excitation functions of ^{3}He-particle induced nuclear reaction on iron, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, In Press, Uncorrected Proof, Available online 15 May 2003,*

S. Takács, F. Tárkányi, A. Hermanne and R. Paviotti de Corcuera
Validation and upgrading of the recommended cross section data of charged particle reactions used for production of PET radioisotopes, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, In Press, Uncorrected Proof, Available online 24 April 2003,*

F. Tárkányi, A. Hermanne, S. Takács, F. Ditrói
Excitation functions for production of radioisotopes of niobium, zirconium and yttrium by irradiation of zirconium with deuterons
Submitted to: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,*

F. Tárkányi, S. Takács, F. Ditrói, A. Hermanne and M. Sonck
Excitation functions of deuteron induced nuclear reactions on natural zinc up to 50 MeV
Submitted to: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,*

S. Takács, Z. Szűcs, F. Tárkányi, A.Hermanne, M. Sonck
Evaluation of Proton induced reactions on ^{100}Mo: New cross sections for production of ^{99m}Tc and ^{99}Mo,
In press at: Radioanalytical and Nuclear Chemistry

A. Hermanne, M. Sonck, **S. Takács.** and F. Tárkányi:
Monitoring of proton beams: a practical application of an Evaluated Charged Particle Database. Submitted to: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*

A. Hermanne, S. Takács, F. Tárkányi, R. Bolbos
Cross sections for charged particle production of the therapeutic radionuclide ^{111}Ag and its PET imaging analogue ^{104mg}Ag
Submitted to: *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*