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PROGRESS REPORT ON NUCLEAR DATA RESEARCH IN THE FEDERAL REPUBLIC OF GERMANY

for the Period April 1, 2000 to March 31, 2001

July 2001

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FOREWORD

As in previous years, this report has been prepared to promote exchange of nuclear data research information between the Federal Republic of Germany and other member states of OECD/NEA and IAEA. It covers progress reports from the research centres at Karlsruhe and Jülich, the universities of Dresden, Hannover, Köln and Mainz, as well as from the PTB Braunschweig. Each contribution is presented under the laboratory heading from where the work is reported. The names of other participating laboratories are also mentioned. The emphasis in the work reported here is on measurement, calculation, compilation and evaluation of nuclear data for applied science programmes, such as those relevant to reactor technology and safety, transmutation concepts, accelerator shielding and development, astrophysics research, cosmogenic and meteoritic investigations, radiation therapy, production of medically important radioisotopes, etc.

The coordination of nuclear data activities at the international level is done by two committees: the NEA-Nuclear Science Committee (NEA-NSC) and the IAEA-International Nuclear Data Committee (INDC). The present Editor has the privilege and the responsibility of representing Germany in both the committees. This report should therefore also serve as a background information to some areas of work of those committees.

Jülich, July 2001 S.M. Qaim

This document contains information of a preliminary nature. Its contents should be used with discretion.

CONTENTS

FORSCHUNGSZENTRUM KARLSRUHE
INSTITUT FÜR KERNPHYSIK

1. Low-Energy Resonances in $^{14}N(\alpha,\gamma)^{18}F$ and their Astrophysical Implications*

J. Görres[1], C. Arlandini, U. Giesen[1], M. Heil, F. Käppeler, H. Leiste[2], E. Stech[1], and M. Wiescher[1]

The strengths of low-energy resonances in $^{14}N(\alpha,\gamma)^{18}F$ at 573 keV and 1136 keV have been measured using an activation method. In addition, their relative strength and the energy of the lower resonance have been determined in a prompt γ-ray experiment. The results of these measurements are used to reevaluate the stellar reaction rate of $^{14}N(\alpha,\gamma)^{18}F$. The present reaction rate at temperatures of astrophysical interest is a factor of 2 smaller than previously reported.

*Phys. Rev. C62 (2000) 55801, 1-7

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[2] Forschungszentrum Karlsruhe, Institut für Materialforschung I

2. Stellar Neutron Capture Cross Sections of the Yb Isotopes*

K. Wisshak, F. Voss, C. Arlandini, F. Käppeler, L. Kazakov[1]

The neutron capture cross sections of ^{170}Yb, ^{171}Yb, ^{172}Yb, ^{173}Yb, ^{174}Yb, and ^{176}Yb have been measured in the energy range from 3 to 225 keV relative to the gold standard. Neutrons were produced at the Karlsruhe 3.75 MV Van de Graaff accelerator via the $^{7}Li(p,n)^{7}Be$ reaction by bombarding metallic Li targets with a pulsed proton beam, and capture events were registered with the Karlsruhe 4π Barium Fluoride Detector. Neutron capture in the even ytterbium isotopes is characterized by a strong population of isomeric states, leading to unrecognized systematic uncertainties in previous measurements. For the first time, partial cross sections to ground and isomeric states could be experimentally identified in neutron time-of-flight measurements for ^{172}Yb, ^{173}Yb, ^{174}Yb, and ^{176}Yb. The present overall uncertainties of 1-1.5% correspond to an improvement by factors of 4 to 10 compared to existing data. Maxwellian averaged neutron capture cross sections were calculated for thermal energies between kT = 8 keV and 100 keV. In four cases, the results differ by more than 15% from recent evaluations. The s-process analyses based on the present data provide further evidence in favor of stellar models for thermally pulsing low-mass AGB stars.

*Phys. Rev. C61 (2000) 65801, 1-16

[1]Institute for Physics and Power Engineering, Obninsk-Kaluga, Region, Russia

3. Neutron Capture Cross Section of ^{232}Th*

K. Wisshak, F. Voss, and F. Käppeler

The neutron capture cross section of ^{232}Th has been measured in the energy range from 5 to 225 keV at the Karlsruhe 3.7 MV Van de Graaff accelerator relative to the gold standard. Neutrons were produced via the ^{7}Li(p,n)^{7}Be reaction by bombarding metallic Li targets with a pulsed proton beam, and capture events were registered with the Karlsruhe 4π Barium Fluoride Detector. The main difficulty in this experiment is the detection of true capture events characterized by a comparably low binding energy of 4.78 MeV in the presence of the high-energy γ-background (up to 3.96 MeV) associated with the decay chain of the natural thorium sample. With the high efficiency and the good energy resolution of the 4π detector the sum energy peak of the capture cascades could be reliably separated from the background over the full range of the neutron spectrum, yielding cross section uncertainties of about 2% above 20 keV and of 4% at 5 keV. The clear identification of the various background components represents a significant improvement compared to existing data for which sometimes high accuracy was claimed, but which were found to be severely discrepant. A comparison with the evaluated files shows reasonable agreement in the energy range above 15 keV, but also severe discrepancies of up to 40% at lower neutron energies.

*Nucl. Sci. Eng. 137 (2001) 183-193

4. A 4 π BaF_2 Detector for (n,γ) Cross Section Measurements at a Spallation Neutron Source*

M. Heil, R. Reifarth, M.M. Fowler[1], R.C. Haight[1], F. Käppeler, R.S. Rundberg[1], E. H. Seabury[1], J.L. Ullmann[1], J.B. Wilhelmy[1], K. Wisshak

The quest for improved neutron capture cross sections for advanced reactor concepts, transmutation of radioactive wastes as well as for astrophysical scenarios of neutron capture nucleosynthesis has motivated new experimental efforts based on modern techniques. Recent measurements in the keV region have shown that a 4π BaF_2 detector represents an accurate and versatile instrument for such studies. The present work deals with the potential of such a 4π BaF_2 detector in combination with spallation neutron sources, which offer large neutron fluxes over a wide energy range. Detailed Monte Carlo simulations with the GEANT package have been performed to investigate the critical backgrounds at a spallation facility, to optimize the detector design, and to discuss alternative solutions.

* Nucl. Instr. Meth. A459 (2001) 229 – 246

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5. Neutron Cross Sections for Nucleosynthesis Studies*

Z.Y. Bao[1], H. Beer, F. Käppeler, T. Rauscher[2], F. Voss, K. Wisshak

Previous compilations of (n,γ) cross sections of relevance to neutron capture nucleosynthesis in the Big Bang and in the slow neutron capture process (s process) have been updated to encompass information available up to December 1998; data references include work in process then and published subsequently. The experimental results for nuclei between H and Bi were critically surveyed, renormalized to selected standard cross sections, and condensed into a set of recommended Maxwellian averaged cross sections for a thermal energy of kT=30 keV. Recent statistical model calculations of the capture cross sections done with the code NON-SMOKER are listed for comparison; these calculated cross sections are adopted in those cases where experimental information is still missing, e.g. for the majority of radioactive nuclei defining the s-process branchings. Maxwellian averages, normalized to our recommended 30 keV averages, were determined for a range of thermal energies between kT=5 and 100 keV. We have also included the calculated stellar enhancement factors due to thermally populated nuclear states as a function of temperature.

* Atomic Data Nucl. Data Tables 76 (2000) 70 – 154

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FORSCHUNGSZENTRUM KARLSRUHE
INSTITUT FÜR REAKTORSICHERHEIT

1. Benchmark for Sensitivity and Uncertainty Calculations Using EFF-3.1 ^{56}Fe Cross Section Data

U. Fischer, I. Kodeli[1], Ch. Konno[2], R. Perel[3]

A computational benchmark on probabilistic and deterministic sensitivity and uncertainty calculations has been conducted with the objective to check and validate the novel Monte Carlo technique for calculating point detector sensitivities as being implemented in the MCSEN code [1]. A suitable 14 MeV neutron benchmark problem on an iron assembly has been considered to this end. After removal of some minor problems in MCSEN, good agreement has been achieved for the calculated individual sensitivity profiles, the uncertainties and the neutron flux spectra as well. Uncertainties as calculated for the neutron flux integrals at the location of the detector are compared in Tables 1 and 2 for a 7.5 and a 28 cm thick spherical iron shell, respectively. Nuclear cross-sections and co-variance data were taken from the EFF-3.1 Fe-56 data file. It was concluded that the Monte Carlo technique for calculating point detector sensitivities and related uncertainties as being implemented in MCSEN is well qualified for applications in sensitivity and uncertainty analyses of fusion neutronics integral experiments [2].

Table 1. Uncertainties of neutron leakage flux integrals as calculated for a 7.5 cm thick iron spherical shell with the Monte Carlo (MCSEN) and the deterministic (ONEDANT/SUSD) approach.

E [MeV]	E<0.1	0.1 – 1	1 – 5	5– 7.4	7.4-10	10-13.84	E>13.84	Total
MCSEN	2.47	1.90	1.18	4.64	4.77	2.63	1.20	0.48
SUSD	2.46	1.90	1.18	4.76	4.64	2.67	1.22	0.49

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Table 2. Uncertainties of neutron leakage flux integrals as calculated for a 28 cm thick iron spherical shell with the Monte Carlo (MCSEN) and the deterministic (ONEDANT/SUSD) approach.

E [MeV]	E<0.1	0.1 – 1	1 – 5	5– 7.4	7.4-10	10-13.84	E>13.84	Total
MCSEN	3.64	1.00	1.43	12.1	7.46	5.73	4.35	0.72
SUSD	4.10	1.04	1.59	12.4	7.45	5.74	4.54	0.72

References

[1] R.L. Perel, J.J. Wagschal, and Y. Yeivin, "Monte Carlo calculation of point-detector sensitivities to material parameters", Nucl. Sci. Eng., **124** (1996), 197-209.

[2] U. Fischer, I. Kodeli, C. Konno, R. Perel, "Inter-comparison of Monte Carlo and S_N Sensitivity Calculations for a 14 MeV Neutron Benchmark", Int. Conf. Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, October 23-26, 2000, Lisbon, Portugal.

2. Intermediate Energy Activation Data File IEAF-2000

U. Fischer, A. Konobeyev[1], Yu. Korovin[1], U. v. Möllendorff, P.Pereslavtsev[1], A. Yu. Stankovsky[1]

Under a co-operation between the Forschungszentrum Karlsruhe and the Institute of Nuclear Power Engineering Obninsk, Russian Federation, a complete activation data library IEAF-2000 (Intermediate Energy Activation File) has been developed. The IEAF-2000 library includes 679 (stable and unstable) target nuclides from Z=1 (hydrogen) to 84 (polonium) with approximately 51000 excitation functions for neutron induced activation reactions up to 150 MeV. The European Activation File EAF-97 served as basis for the activation cross-section data below 20 MeV neutron energy. Threshold reaction cross-sections were evaluated on the basis of geometry dependent hybrid exciton and evaporation models using a modified version of the ALICE code. The principal changes applied to the code concern the incorporation of

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algorithms for describing pre-equilibrium cluster emission (d, t, ^{3}He, α), pre-compound γ-ray emission and the calculation of nuclear level densities according to the generalised superfluid model. IEAF-2000 is in standard ENDF-6 data format making use of the MT=5 (neutron, anything) option with the excitation functions stored on MF=3 and the product nuclide vectors on MF=6 (LAW=0). The IEAF-2000 library has been processed with NJOY/GROUPR in a 256 group structure to enable activation calculations for the IFMIF (International Fusion Irradiation Facility) neutron source. It can be used with activation codes capable of handling an arbitrary number of reaction channels. The IEAF-2000 library will be distributed both in pointwise and groupwise data format via the NEA data bank and the IAEA/NDS.

References

[1] Yu. Korovin, A. Konobeyev, P. Pereslavtsev, A. Yu. Stankovsky, U. Fischer, U. v.Möllendorff, "Data Library IEAF-2000 to study the activation of irradiated materials", Nuclear Applications in the New Millennium, November 11-15, 2001, Reno, NV, USA

[2] U. Fischer, P.P.H. Wilson , S. P. Simakov , U. v. Möllendorff, A. Konobeev, Yu. Korovin, P. Pereslavtsev, "Application of the IEAF-2000 Activation Library to the activation analysis of the IFMIF high flux test module", 10th International Conference on Fusion Reactor Materials, 14-19 October, Baden-Baden, Germany

INSTITUT FÜR NUKLEARCHEMIE FORSCHUNGSZENTRUM JÜLICH

1. Fundamental Investigations on Nuclear Reactions

S. Kastleiner, T.Stoll, K. Kettern, F. Cserpák*, S. Sudár*, N.Shubin†, S.M. Qaim

The on-going experimental and theoretical investigations on nuclear reactions were continued. The work during the period of this report consisted of measurements of excitation functions of the reactions $^{68}Zn(p,xn)^{67,66}Ga$, $^{68}Zn(p,2p)^{67}Cu$, $^{85}Rb(p,xn)^{85,83,82,81}Sr$ and $^{85}Rb(p,p'xn)^{84,83,82,81}Rb$ from their respective thresholds up to 70 MeV. To interpret the experimental data, nuclear model calculations were performed using the code ALICE-IPPE which is based on the hybrid model. It was found that most of the processes could be described well by the nuclear model calculations. Only in the case of the (p,2p) reaction some deviations were observed.

In addition to measurement of total cross section for a particular reaction channel, partial cross sections for the formation of isomeric states were also determined. The processes studied included $^{85}Rb(p,n)^{85m,g}Sr$, $^{85}Rb(p,p'n)^{84m,g}Rb$ and $^{nat}Sr(p,xn)^{87m,g}Y$ from threshold up to 70 MeV. The results were interpreted qualitatively in terms of the projectile energy and spins of the isomers concerned. Furthermore, the processes $^{107}Ag(n,\alpha)^{104m,g}Rh$ and $^{109}Ag(n,\alpha)^{106m,g}Rh$ were investigated over the neutron energy range of 7 to 12 MeV. Since some of the products were short-lived ($T_{1/2} \leq 1$ min) and pure β^- emitters, considerable care in activity measurement was needed. For a quantitative understanding of the isomer distribution, detailed nuclear model calculations were performed using the code STAPRE which is based on the statistical model and incorporates precompound effects. The model described the total (n,α) cross section well. In the case of isomeric states, a very careful selection of the input parameters, especially the level scheme, was mandatory.

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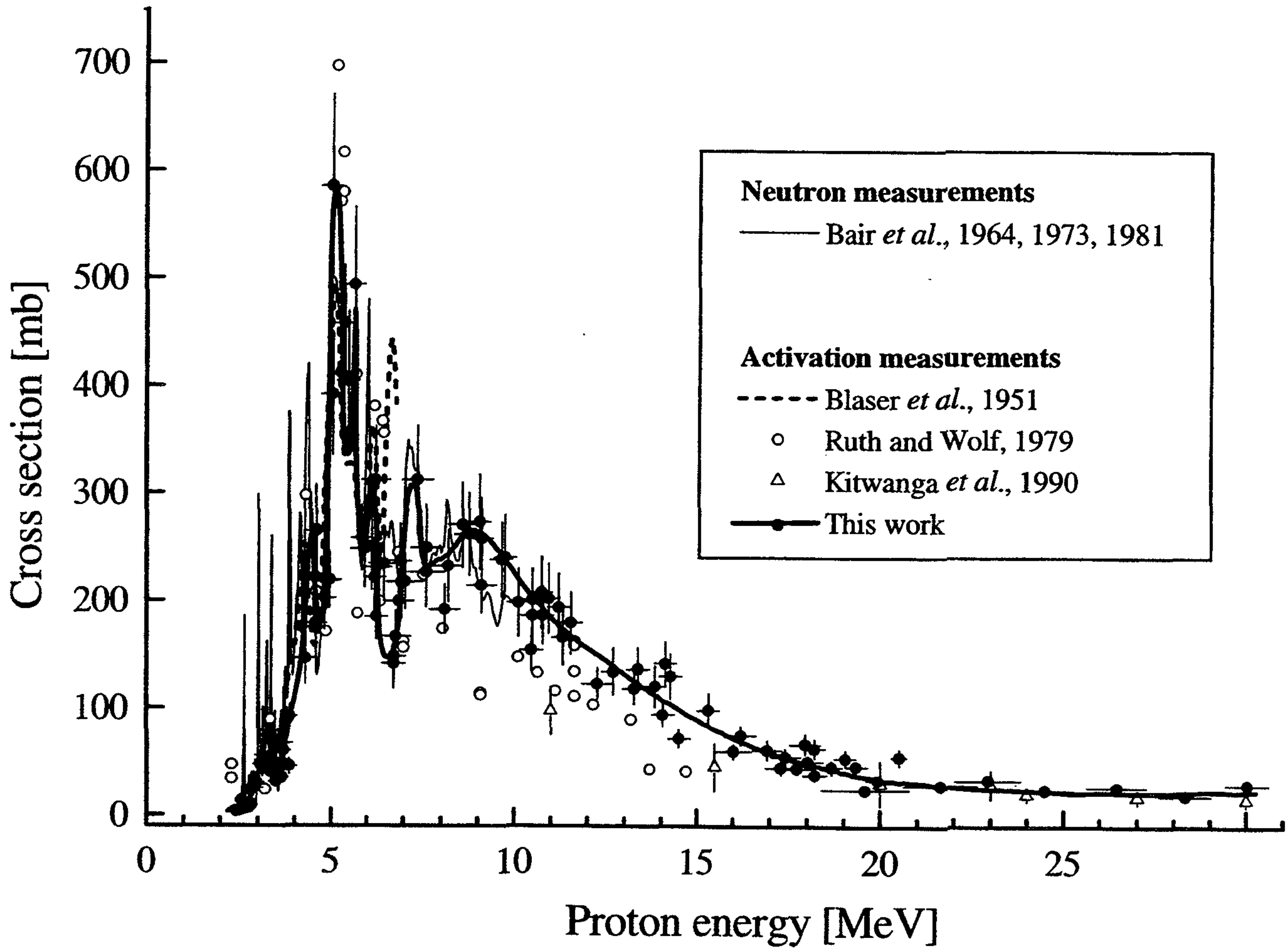

Fig. 1 Excitation function of the $^{18}O(p,n)^{18}F$ reaction. Results of both neutron and activation measurements are shown. The rather bold curve is an eye-guide to our activation data. For details see Ref [7].

Based on the data measured in this work, the integral yield of ^{18}F was calculated. Up to an energy of 8 MeV, the yield values are in good agreement with the literature data of Ruth and Wolf. Above that energy the yield becomes higher compared to the earlier data; at 14 MeV the difference is about 15 %. The yield above 14 MeV is reported for the first time.

The radionuclide **^{76}Br** ($T_{1/2}$ = 16.0 h) is an important longer-lived β^+ emitter. It is generally produced via the $^{76}Se(p,n)^{76}Br$ or $^{75}As(^3He,2n)^{76}Br$ reaction. We considered it worthwhile to investigate the $^{78}Kr(d,\alpha)^{76}Br$ reaction. The standard gas cell technique using 99.95 % enriched ^{78}Kr was applied. Though the reaction cross section could be measured from threshold up to 14 MeV, the yield was found to be rather low. This nuclear route is therefore not very suitable for production of ^{76}Br.

As mentioned in the last Progress Report, the radionuclide ^{83}**Sr** ($T_{1/2}$ = 32.2 h) is a positron emitting analogue of the therapy nuclide ^{89}Sr and appears to be well-suited for dosimetry and therapy planning. Measurements on the ^{85}Rb(p,xn)$^{85m,g,\ 83,82,81}$Sr reactions were now extended up to 100 MeV and completed. The reaction ^{85}Rb(p,3n)^{83}Sr over the energy range E_p = 37 → 30 MeV was found to be very suitable for production of ^{83}Sr. The measured cross sections were tested via an integral experiment. A thick target was irradiated (E_p = 35 → 30 MeV) at a low current and radiostrontium was radiochemically separated. The practical yield of ^{83}Sr was compared with the yield calculated from the excitation function. The results agreed within 10 %, adding confidence to our cross section measurements. The cross section data for an alternative production reaction, namely ^{82}Kr(^{3}He,2n)^{83}Sr, were also tested via an integral measurement involving a production gas target. The practical yield of ^{83}Sr obtained was in agreement within 20 % with the value deduced from the excitation function.

A comparison of the two routes developed for the production of ^{83}Sr is given in Table 1. The data were deduced from the measured excitation functions normalised to 100 % enrichment of the target. As one can see, the yield of ^{83}Sr is much higher for the proton induced reaction on highly enriched ^{85}Rb and the level of radioactive

Table 1: Comparison of production routes of ^{83}Sr under optimum conditions[a]

Production route	Energy range [MeV]	Yield of ^{83}Sr[b] MBq/µA·h	Impurities [%][b] ^{85g}Sr	^{82}Sr
^{85}Rb(p,3n)	37 → 30	142.53	0.24	0.75
^{82}Kr(^{3}He,2n)	18 → 10	5.12	-	1.37

[a] Values normalised to 1 hour irradiation, 1µA beam current, 100 % enriched targed.

[b] Deduced from measured excitation functions.

impurities is low (< 1 %). The $^{82}Kr(^{3}He,2n)$-process leads to a lower ^{83}Sr yield and higher impurities. The $^{85}Rb(p,3n)$-process is thus the method of choice for the production of ^{83}Sr, provided a 40 MeV cyclotron is available.

The radionuclide **^{90}Nb** ($T_{1/2}$ = 14.6 h) is a potentially interesting β^+ emitter. Its production cross sections were measured in collaboration with the University of Mainz. The details are given in a report submitted by that University (see page 31).

The β^+ emitting radionuclide **^{124}I** ($T_{1/2}$ = 4.18 d) is both of diagnostic and therapeutic use. In recent years its importance has been enhancing. After having investigated the $^{124}Te(p,n)^{124}I$ and $^{125}Te(p,2n)^{124}I$ processes, studies were started last year on the $^{124}Te(d,2n)^{124}I$ reaction. This nuclear route has been commonly used for production purposes but the available data were discrepant. The results of our extensive studies are depicted in Fig. 2. The $^{124}Te(d,n)^{125}I$ reaction has been investigated for the first time. For the $^{124}Te(d,2n)^{124}I$ process, an experimental measurement (Firouzbakht et al, 1993, BNL) and a theoretical calculation (Shubin, 2001, Obninsk) have been reported in the literature. Fig. 2 shows that the literature experimental data are about an order of magnitude smaller than our values but the results of the nuclear model calculation agree with our data.

The yields of ^{124}I and associated impurities (^{123}I and ^{125}I) in the three nuclear routes, viz. $^{124}Te(p,n)$, $^{124}Te(d,2n)$ and $^{125}Te(p,2n)$, deduced from the detailed excitation functions measured in our laboratory, showed that the $^{124}Te(p,n)$-route provides ^{124}I of the highest purity. This route can be utilized even at a low energy cyclotron. The $^{125}Te(p,2n)$-reaction gives about four times higher yield than the other two processes. From the viewpoint of ^{125}I impurity, the $^{124}Te(d,2n)^{124}I$ reaction is the worst.

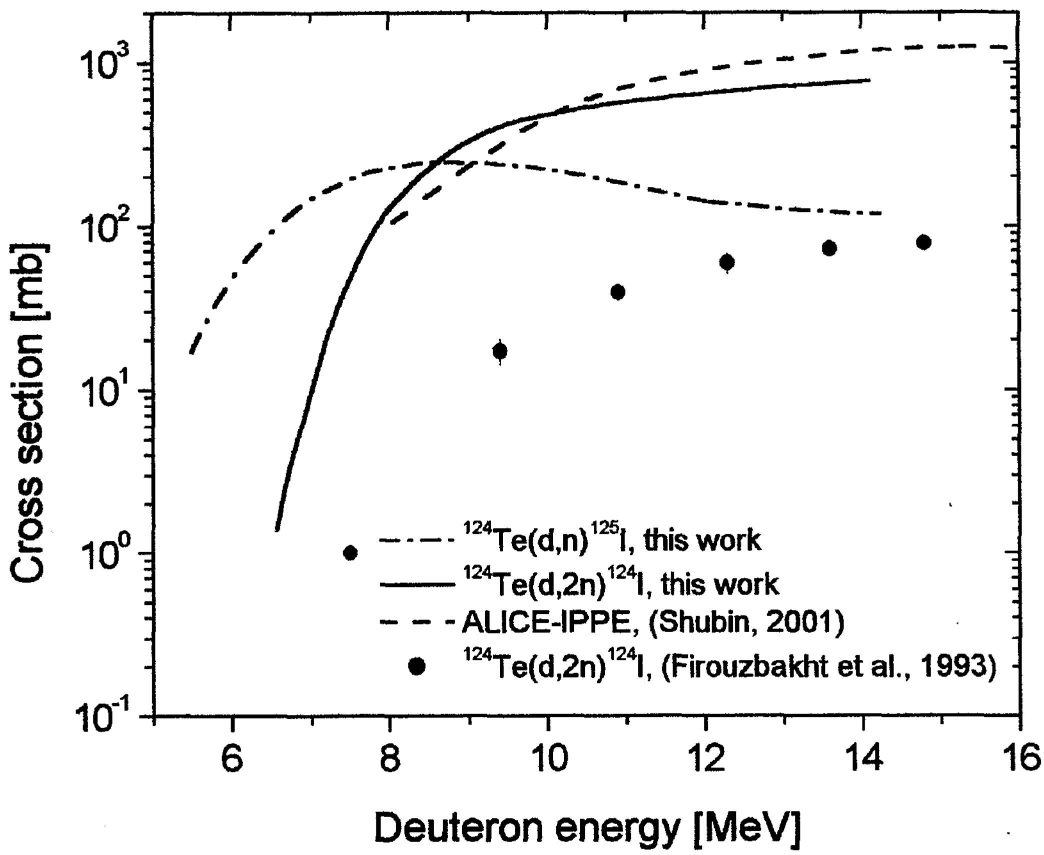

Fig. 2 Excitation functions of ^{124}Te(d,xn)^{124,125}I reactions. For simplicity the results are shown here only as curves. Detailed data are given in Ref. [9].

b) Cross sections and yields of therapy related and other radionuclides (^{67}Cu, ^{88}Y and ^{103}Pd)

The radionuclide ^{67}**Cu** ($T_{1/2}$ = 61.9 h) is of great interest in systemic endoradiotherapy. It is produced via several routes but is not readily available. A commonly used method at medium-energy cyclotrons is the ^{68}Zn(p,2p)^{67}Cu-reaction. Since the cross sections for this process were not known well, we thought it worthwhile to study it in detail. A serious problem arose due to the very similar half-lives and γ-ray energies of ^{67}Ga and ^{67}Cu. Since ^{67}Ga is formed in much higher yields, measurements on ^{67}Cu could be done only using radiochemical techniques.

During the period of this report extensive radiochemical studies were performed up to 70 MeV, and the cross section data base for the ^{68}Zn(p,2p)^{67}Cu reaction was established. Furthermore, the data base for the production of ^{67}Ga and ^{66}Ga via $^{68}Zn(p,2n)$ and $^{68}Zn(p,3n)$ reactions, respectively, was extended up to 70 MeV.

The importance of the β^+ emitting ^{86}Y ($T_{1/2}$ = 14.7 h) in therapy planning and quantitative dosimetry with regard to the β^- emitting therapy nuclide ^{90}Y ($T_{1/2}$ = 64.1 h) is well established. However, for studying slow biokinetics, the radionuclide $\mathbf{^{88}Y}$ ($T_{1/2}$ = 106.6 d) appears to be more suitable. Cross sections were therefore measured for the $^{nat}Sr(p,xn)^{88}Y$ process up to 25 MeV. The suitable energy range for the production of ^{88}Y was deduced to be $E_p = 14 \rightarrow 9$ MeV.

The X-ray and Auger electron emitting radionuclide $\mathbf{^{103}Pd}$ ($T_{1/2}$ = 16.96 d) is of immense importance in endoradiotherapy. It is produced routinely via the $^{103}Rh(p,n)$-reaction. As mentioned in the last Progress Report, we performed detailed studies on $^{103}Rh(p,xn)^{103,101,100}Pd$ reactions up to 40 MeV, using X-ray and γ-spectrometry. Furthermore, the alternative routes $^{102}Ru(^3He,2n)^{103}Pd$ and $^{100}Ru(\alpha,n)^{103}Pd$ were also investigated. The data analysis is in progress.

c) Dissemination of knowledge on nuclear data for medical applications

The final report of the IAEA-CRP on "Standardisation of Nuclear Data for the Production of Medically Important Radioisotopes" was published as IAEA-TECDOC-1211 (2001). S.M. Qaim chaired the CRP and the institute contributed actively to the effort.

A special issue of the international journal *Radiochimica Acta* dealing with all aspects of "Nuclear Data for Medical Applications" was published (Vol. 89, pages 189-355 (2001)). It was edited by S.M. Qaim.

4. Decay Data

K. El-Azoney, H.H. Coenen, S.M. Qaim

The β^+/EC ratio in the decay of ^{124}I ($T_{1/2}$ = 4.18 d), i.e. the β^+ emission intensity ($I_{\beta}{}^+$), is rather uncertain: values between 23 and 26 % have been reported in the literature. We determined the intensity using a highly pure ^{124}I source, which was produced by irradiation of 99.9 % enriched ^{124}Te with 14 MeV protons, followed by a chemical separation of radioiodine. Both γ-ray and X-ray spectrometry were applied. In the former case a comparison of the intensity of the annihilation radiation with that of the 603 keV γ-ray of ^{124}I was done, and in the latter with that of the K_α or K_β X-ray of the daughter tellurium. Our measurements lead to a value of 23 ± 0.5 % for the $I_{\beta}{}^+$ of ^{124}I.

Publications (During the Period of the Progress Report)

[1] A.T.J. Klein, F. Rösch and S.M. Qaim
Investigation of ^{50}Cr(d,n)^{51}Mn and ^{nat}Cr(p.x)^{51}Mn processes with respect to the production of the positron emitter ^{51}Mn
Radiochimica Acta **88** (2000) 253

[2] F. Sudbrock, U. Herpers, S.M. Qaim, J. Csikai, P.W. Kubik, H.-A. Synal and M. Suter
Cross sections for the formation of long-lived radionuclides ^{10}Be, ^{26}Al and ^{36}Cl in 14.6 MeV neutron-induced reactions determined via accelerator mass spectrometry (AMS)
Radiochimica Acta **88** (2000) 829

[3] M. Ibn Majah, A. Chiadli, S. Sudár and S.M. Qaim
Cross sections of (n,p), (n,α) and (n,2n) reactions on some isotopes of zirconium in the neutron energy range of 10 to 12 MeV and integral tests of differential cross section data using a 14 MeV d (Be) neutron spectrum
Appl. Radiat. Isot. **54** (2001) 655

[4] S.M. Qaim
Nuclear Data for medical applications: an overview
Radiochimica Acta **89** (2001) 189

[5] S.M. Qaim
Nuclear data relevant to the production and application of diagnostic radionuclides
Radiochimica Acta **89** (2001) 223

[6] S.M. Qaim
Therapeutic radionuclides and nuclear data
Radiochimica Acta **89** (2001) 297

[7] E. Hess, S. Takács, B. Scholten, F. Tárkányi, H.H. Coenen and S.M. Qaim
Excitation function of the $^{18}O(p,n)^{18}F$ nuclear reaction from threshold up to 30 MeV
Radiochimica Acta **89** (2001) 357

[8] A. Hohn, F.M. Nortier, B. Scholten, T.N. van der Walt, H. H. Coenen and S.M. Qaim
Excitation functions of $^{125}Te(p,xn)$-reactions from their respective thresholds up to 100 MeV with special reference to the production of ^{124}I
Appl. Radiat. Isot. **55** (2001) 149

[9] Th. Bastian, H. H. Coenen and S.M. Qaim
Excitation functions of $^{124}Te(d,xn)^{124,125}I$ reactions from threshold up to 14 MeV: comparative evaluation of nuclear routes for the production of ^{124}I
Appl. Radiat. Isot., in press

[10] S.M. Qaim
Cross section data for production of diagnostic and therapeutic radionuclides
Proc. Advisory Group Meeting on "Long Term Needs for Nuclear Data Development", IAEA, Vienna, 28 November – 01 December 2000, in press

INSTITUT FÜR KERN- UND TEILCHENPHYSIK TECHNISCHE UNIVERSITÄT DRESDEN

1. Integral Activation Experiment with SiC and Li_4SiO_4*

R. A. Forrest[1], H. Freiesleben, V. D. Kovalchuk[2], D. V. Markovskij[3], D. Richter, K. Seidel, V. I. Tereshkin[2], S. Unholzer

The radioactivity induced by neutrons in fusion reactor materials is a focus of investigations dedicated to safety and environmental assessments of fusion power. The greatest part of the radioactivity is produced by two components of the neutron flux spectrum, the thermal neutrons and the D-T fusion neutrons. The component, connected with the 14 MeV neutrons, is investigated in the present work for the advanced structural material SiC and for the breeding material Li_4SiO_4 [1].

In a calculation with the European Activation System (EASY-99, [2]) the materials were taken to be irradiated with 14 MeV neutrons at a flux density corresponding to the power of 1.0 MW, for a period of one year, to estimate the activation under reactor conditions. The results obtained for the contact dose rate as a function of the decay time after irradiation (t_C) are shown in Fig. 1. The dominant radionuclides, mainly produced from Si, have short half-lives. Radionuclides originating from impurities of the materials determine the dose rate already for $t_C > 1$ h. At about one year, the recycling limit is reached. For $t_C > 100$ y, more than 99% of the dose rate comes from ^{26}Al ($T_{1/2} = 7.2 \cdot 10^5$ y) produced by the $^{27}Al(n,2n)$-reaction.

The short- and long-term activities were experimentally investigated in separate runs.

Small pieces of the materials were irradiated at the high-intensity D-T neutron generator SNEG-13 at Sergiev Posad for 30 min with a fluence of the order of 10^{11} neutrons/cm² and for 17 h with a fluence of the order of 10^{14} neutrons/cm². Gamma-spectra of the samples were measured with a Ge(Li)-spectrometer several times during decay, and nuclide activities were derived. For each of the measured values the activity was calculated with EASY-99, and calculated-to-experimental values (C/E) were determined.

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* Work supported by the European Fusion Development Activity Programme (Task TTMN-002) and by the German Bundesministerium für Bildung und Forschung (Projekt RUS-564-98)

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The C/E-values for ^{27}Mg, ^{28}Al and ^{29}Al in short irradiations were presented in the previous Progress Report [3]. The measured sum of the activities of the three nuclides is in very good agreement with the calculated sum, as shown in Fig. 2. The rest of the total activity at short decay times, as calculated with EASY-99 and not measured, is shown with a dashed line.

After the long irradiation, the activities of ^{24}Na, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co ^{89}Zr and ^{92m}Nb were measured for SiC, and the activities of ^{24}Na, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{58}Co and ^{92m}Nb for Li_4SiO_4. The sum of these activities is compared in Fig. 3 with the result of the corresponding calculation, based on elemental compositions of the samples as determined by glow discharge mass spectroscopy and by X-ray fluorescence analysis, respectively. The underestimation of the total activity of SiC at the first and the second t_C of Fig. 3 is mainly due to the ^{24}Na activity, produced by the $^{27}Al(n,\alpha)^{24}Na$ reaction. Using the C/E obtained for ^{24}Na, the Al content of the material was estimated. With the same factor, the dose rate for $t_C > 100$ y increases, compared to the expected (Fig. 1) value. The ^{92m}Nb activity was underestimated by a factor of about 0.03 for SiC; in Li_4SiO_4 it was not expected, but found in the experiment. The small values have no significant influence on the long-term radioactivity induced by 14 MeV neutrons. For thermal neutrons the situation may be changed, as ^{94}Nb has a $T_{½}$ of $2{\cdot}10^4$ y. Several other values of the impurity content in the SiC and in the Li_4SiO_4 samples were determined by the 14 MeV neutron activation, and the effect on the total dose rate was estimated [4]. The uncertainties of both depend on the nuclear data uncertainties.

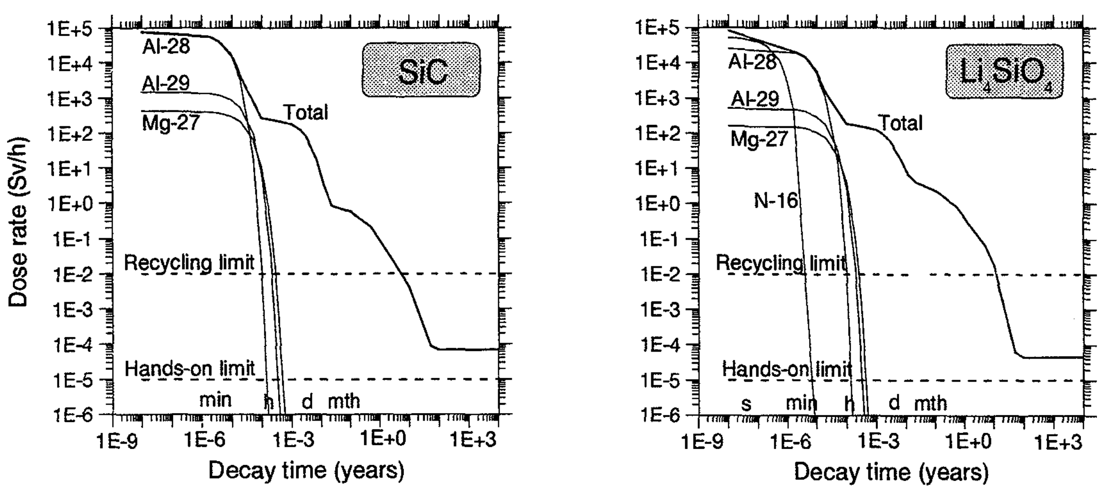

Fig.1 Contact dose rates from the γ-emitting nuclides after irradiation with 14 MeV neutrons of 1.0 MW power for one year as function of the decay time (full line – total, thin line – partial dose rate). Recycling and hands-on limit as recommended by ICRP.

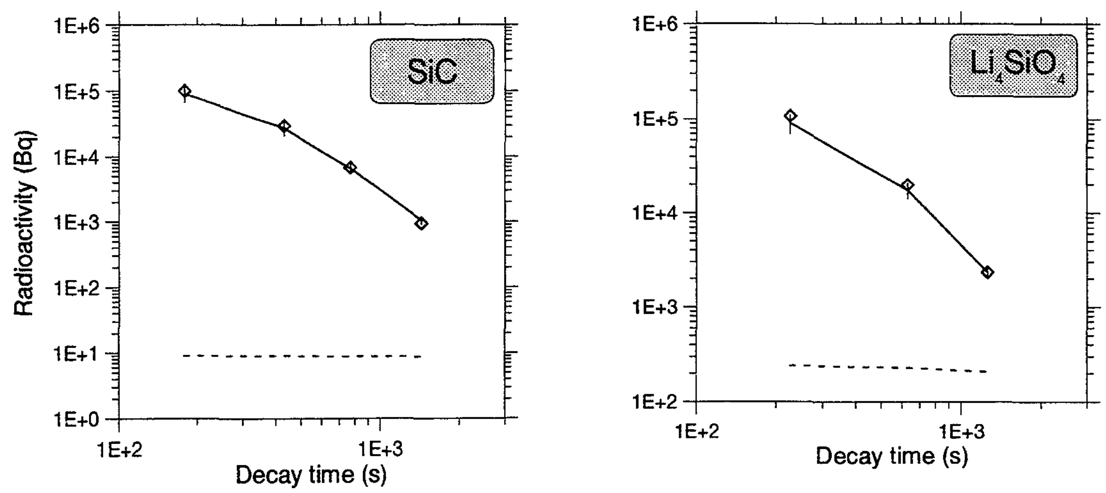

Fig. 2 Measured sum of γ-activities (◇) at short decay times in comparison to the corresponding calculated activities (solid line). Rest: dashed line.

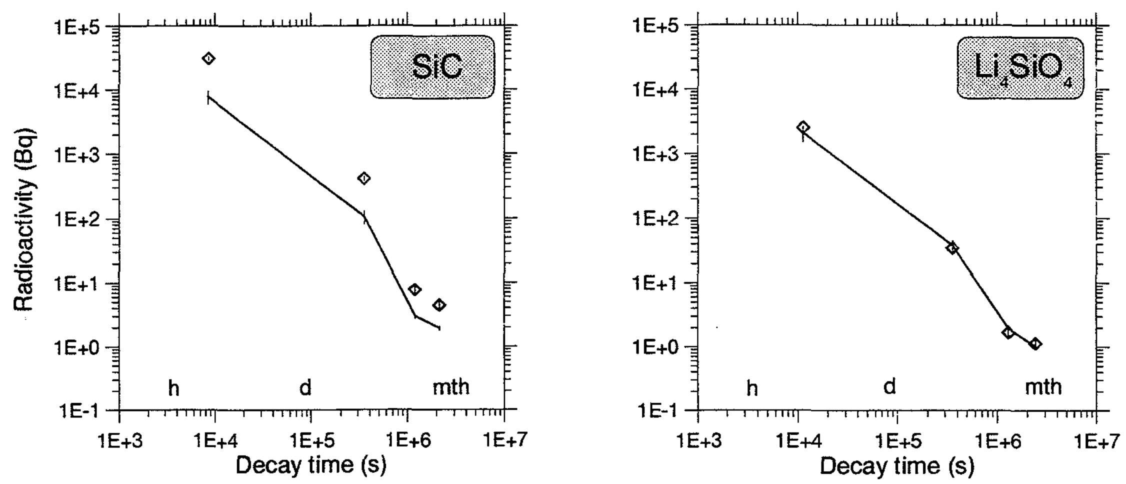

Fig. 3 Measured sum of γ-activities (◇) at long decay times in comparison to the corresponding calculated activities (solid line).

References

[1] L. V. Boccaccini (Ed.): European Helium Cooled Pebble Bed (HPCB) Test Blanket; ITER Design Description Document, Forschungszentrum Karlsruhe, Report FZKA 6127, March 1999.

[2] R. A. Forrest, J.-Ch. Sublet and J. Kopecky, The European Activation System, Proc. Int. Conf. on Nuclear Data for Science and Technology, Trieste, May 19-24, 1997, eds. G. Reffo, A.Ventura, C.Grandi, 1997, p. 1140.

[3] R. A. Forrest, H. Freiesleben, V. D. Kovalchuk, D. V. Markovskij, D. Richter, K. Seidel, V. I. Tereshkin, S. Unholzer, Radioactivities induced in the fusion plant structural material SiC and in the breeder material Li_4SiO_4 by 14 MeV neutrons, Progress Report on Nuclear Data Research in the Federal Republic of Germany, ed. S.M. Qaim, NEA/NSC/DOC(2000)11, INDC(Ger)-046, Jül-3780, July 2000, p. 19-21.

[4] K. Seidel, R. A. Forrest, H. Freiesleben, V. D. Kovalchuk, D. V. Markovskij, D. Richter, V. I. Tereshkin, S. Unholzer, Experimental investigation of radioactivity induced in the fusion plant structural material SiC and in the breeder material Li_4SiO_4

by 14 MeV neutrons, Symposium on Fusion Technology, Madrid (Spain), Sept. 2000, Proc.: Fusion Engineering and Design, in press.

2. Shut-Down Dose Rate Experiment*

Y. Chen[1,2], U. Fischer[1], H. Freiesleben, D. Richter, K. Seidel, S. Unholzer

The dose rates in fusion devices like the International Thermonuclear Experimental Reactor (ITER) have significant influence on the operation scheme of the machine. One of the questions concerns the γ-dose rates inside the cryostat after shut-down, especially for guaranteeing occupational safety during hands-on maintenance.

The γ-radiation originates from radionuclides produced by neutrons in the structural and coolant materials of the reactor during the operation. The calculation of the γ-dose rate for given positions comprises, in principle, a three-step procedure:

a) determination of the spectral neutron flux in the materials with transport code and data as MCNP [1] and FENDL[2],
b) calculation of the radioactivity induced by the neutrons as a function of irradiation and decay time with inventory code as FISPACT [3] and corresponding activation and decay data libraries,
c) γ-transport calculation from the activated materials to the position of interest and conversion of the flux to dose rate.

For validating these procedures, an experiment was performed under a collaboration between ENEA Frascati, FZ Karlsruhe and TU Dresden [4]. Besides checking the codes, it represents an integral test of neutron, photon and decay data relevant to fusion neutronics.

A materials mock-up of the ITER shield blanket and vacuum vessel was irradiated at the Frascati Neutron Generator with DT-neutrons for two days, and after that, γ-dose rates and γ-flux spectra were measured inside the assembly over a period of three weeks.

The dose rates measured with an uncertainty of about 4%, using a tissue-equivalent scintillator, are compared in Fig. 1 with the respective calculated values [5], using data files of the Fusion Evaluated Nuclear Data Library FENDL/MC-2.0 [2] and FENDL/A-2.0 [6]. The ratios of experimental-to-calculated values (C/E) are between 0.84 and 1.08. Some

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underestimation for the shorter decay times and slight overestimation at the end of the experimental campaign was found as a general tendency.

Spectra of the decay γ-flux were measured at eight decay times. An example is presented in Fig. 2. The integral fluxes for E > 0.4 MeV are given in Table 1. The C/E values obtained confirm – as in the case of the dose rates – the good quality of the FENDL data.

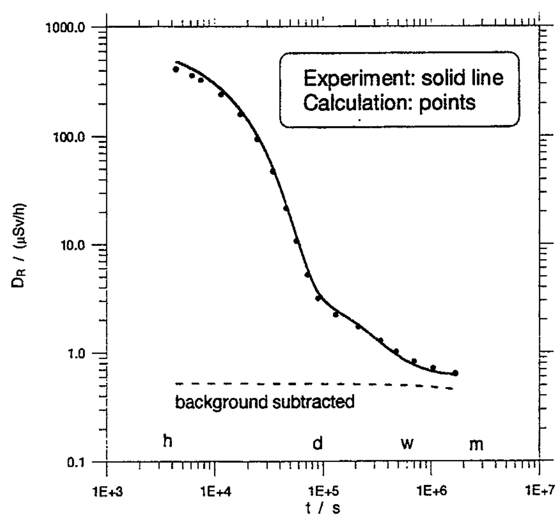

Fig. 1 Experimental and calculated dose rate as a function of the decay time. The background dose rate, subtracted from the measured values, is shown as dashed line.

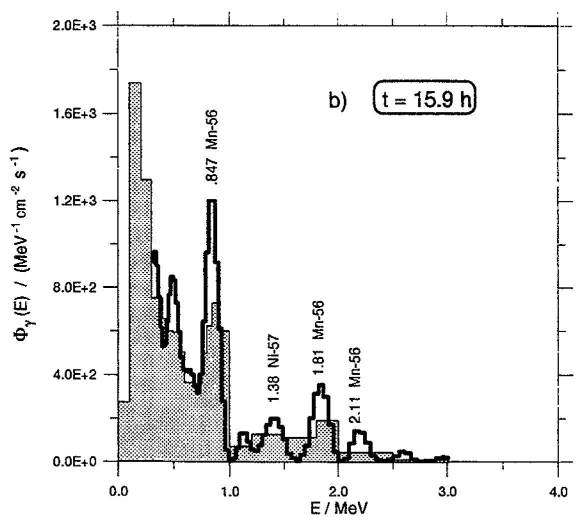

Fig. 2 Flux spectrum of the γ-rays at t = 15.9 h after the end of the irradiation; thick line – measurement, thin line – calculation.

Table 1. Measured flux of the γ-rays with E > 0.4 MeV at several decay times, the corresponding calculated value and the ratio of calculated-to-experimental result (C/E).

Decay time	ϕ_{exp} / ($cm^{-2}\cdot s^{-1}$)	ϕ_{calc} / ($cm^{-2}\cdot s^{-1}$)	C / E
2.08 h	$(1.30 \pm 0.06)\cdot 10^4$	$(1.40 \pm 0.01)\cdot 10^4$	1.08 ± 0.05
15.9 h	523 ± 22	474 ± 5	0.91 ± 0.04
25.2 h	178 ± 9	142 ± 2	0.80 ± 0.04
4.00 d	67.6 ± 3.9	55.7 ± 0.6	0.82 ± 0.05
8.20 d	38.2 ± 2.2	36.6 ± 0.4	0.96 ± 0.06
12.2 d	33.7 ± 2.3	32.4 ± 0.4	0.96 ± 0.07
19.3 d	27.3 ± 1.8	29.6 ± 0.4	1.08 ± 0.07

References

[1] J. F. Briesmeister (ed.), MCNP – A General Monte Carlo N-Particle Transport Code, Version 4C, Los Alamos National Laboratory, Report LA-13709-M, April 2000.
[2] H. Wienke and M. Herman, FENDL/MG-2.0 and FENDL/MC-2.0 - The processed cross section libraries for neutron photon transport calculations, International Atomic Energy Agency, Report IAEA-NDS-176, October 1998.
[3] R. A. Forrest and J.-Ch. Sublet, FISPACT-99: User manual, EURATOM/UKAEA Fusion Association Culham, Report UKAEA FUS 407, December 1998.
[4] H. Freiesleben, D. Richter, K. Seidel, S. Unholzer, Y. Chen, U. Fischer, M. Angelone, P. Batistoni, M. Pillon, Experimental Validation of Shut-Down Dose Rates, Report TU Dresden, TUD-IKTP/0101, March 2001.
[5] Y. Chen, U. Fischer and H. Tsige-Tamirat, Rigorous MCNP Based Shutdown Dose Rate Calculations: Computational Scheme, Verification Calculations and Applications to ITER, Forschungszentrum Karlsruhe, Report IRS-Nr. 2/01 – Fusion Nr. 166, January 2001.
[6] A. B. Pashchenko, H. Wienke, J. Kopecky, J.-Ch. Sublet and R. A. Forrest, FENDL/A-2.0 Neutron Activation Cross Section Data Library for Fusion Applications, International Atomic Energy Agency, Report IAEA-NDS-173, October 1998.

3. X-Ray Spectroscopy on Highly Charged Ions at the Dresden EBIT

F.Grossmann[1], U.Kentsch, S.Landgraf, V.P.Ovsyannikov[1], F.Ullmann[1], G.Zschornack

For the production of highly charged ions and their investigation by X-ray spectroscopy, EBIT devices are a powerful tool and available at different laboratories. The Dresden EBIT, a room-temperature EBIT [1-4] allows to work without any cryogenic techniques in a long-term stable operation regime. Its small dimensions favour spectroscopic investigations with great solid angles that allow to reach sufficient count statistics at relatively small measurement times. A 3D-representation and a more detailed explanation of the operation principle of the Dresden EBIT can be found in Refs. [1,5].

The main activities in 2000 with respect to X-ray spectroscopy on highly charged ions were as follows:

Energy dispersive X-ray spectroscopy on iridium ions. Ir^{q+} ($41 < q < 64$) ions with open-shell configurations were produced in the electron beam of the room-temperature Dresden EBIT at electron excitation energies of 2 keV to 13 keV. Thereby X-ray emission from direct excitation processes and radiative capture in krypton-like to aluminium-like iridium

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ions were measured with an energy dispersive Si(Li) detector. The detected X-ray lines were analysed and compared with results from MCDF atomic structure calculations. This allowed to determine the dominantly produced ion charge states at different electron energies. The analysis shows that at the selected working gas pressure of $5*10^{-9}$ mbar for higher charged ions the maximum ion charge state is not preferentially determined by the chosen electron beam energy needed for ionisation of certain atomic sub-states, but by the balance between ionisation and recombination processes (charge exchange, radiative recombination).

Wavelength dispersive X-ray spectroscopy on neon-like xenon ions. X-ray spectra from direct excitation processes in neon-like xenon at an excitation energy of 12.5 keV were measured with a crystal diffraction spectrometer equipped with a $SiO_2(10\bar{1}0)$ crystal. Intra-shell transitions (n=3) and direct transition energies in Xe^{44+} for n=3→2 (E1, E2, M1, M2 transitions) were determined. Furthermore, the most intense transitions in Xe^{43+} and Xe^{45+} between n=3→2 were observed too. The transition energies were determined with an uncertainty lower than 1 eV.

Production of bare nuclei. In the Dresden EBIT, bare nuclei, hydrogen-like ions and ions of lower charge states can be produced. We have shown that bare nuclei such as Ar^{18+}, Mn^{25+}, Fe^{26+} and Ni^{28+} can be produced. Based on the analysis of X-ray spectra from radiative recombination and direct excitation processes, charge state distributions of ions stored in the electron beam were determined. Fig. 1 shows densities of iron ions at electron energies of 14.4 keV and a pressure of $7 \cdot 10^{-10}$ mbar.

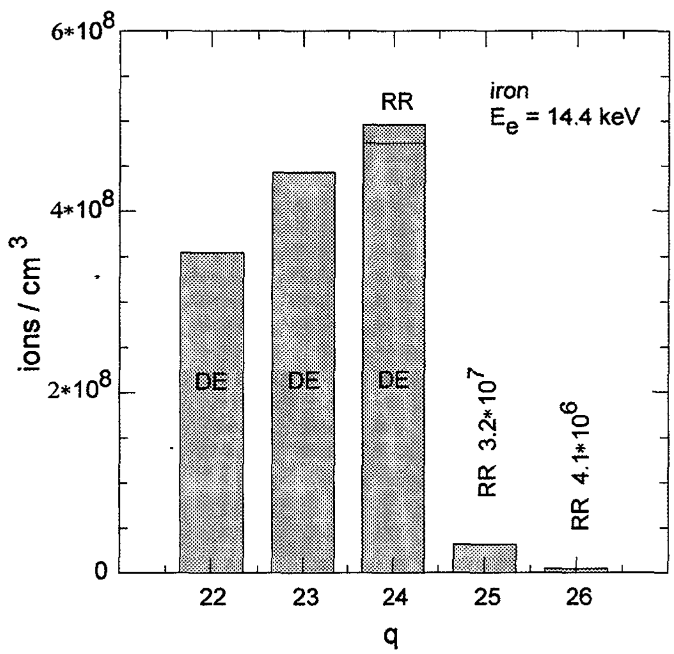

Fig. 1
Ion density distribution of iron ions at the Dresden EBIT determined from radiative recombination (RR) and direct excitation (DE) processes.

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References

[1] V.P.Ovsyannikov, G.Zschornack; Review of Scientific Instruments, **70** (1999) 2646
[2] V.P.Ovsyannikov, G.Zschornack, F.Grossmann, S.Landgraf, F.Ullmann, T.Werner; Review of Scientific Instruments, **71** (2000) 690
[3] V.P.Ovsyannikov, G.Zschornack, F.Grossmann, O.K.Kulthachev, S.Landgraf, F.Ullmann, T.Werner; Nuclear Instruments \& Methods in Physics Research, **B161** (2000) 1123
[4] T.Werner, G.Zschornack, F.Grossmann, V.P.Ovsyannikov, F.Ullmann; Review of Scientific Instruments, **71** (2000) 2038
[5] http://www.physik.tu-dresden.de/apg

ABTEILUNG NUKLEARCHEMIE, UNIVERSITÄT ZU KÖLN, AND ZENTRUM FÜR STRAHLENSCHUTZ UND RADIOÖKOLOGIE, UNIVERSITÄT HANNOVER

Nuclear Data for Modeling the Formation of Residual Nuclides at Medium Energies

R. Michel[1], W. Glasser[1], M. Uosif[1], J. Kuhnhenn[2], U. Herpers[2]

Cross sections for the formation of nuclides in nuclear reactions induced by medium-energy protons and neutrons are of increasing importance for a wide variety of applications. These applications range from astro- and cosmophysics over space and environmental sciences, medicine (radionuclide production, dosimetry in mixed nucleon fields, radiation therapy), accelerator technology (activation of detectors, radiation protection, on-line mass separation), space and aviation technology to accelerator based nuclear waste transmutation and energy amplification.

We here report on the progress of a long-term project to establish a consistent data base of such cross sections. This project deals mainly with two applications, namely investigations of cosmogenic nuclides in extraterrestrial matter and nuclide production in accelerator driven technologies. On the basis of our previous work which was cited extensively in our last year's report, model calculations on the production of cosmogenic nuclides in extraterrestrial matter became possible. They describe the observed nuclide abundances within 7 % and isotopic ratios within 1 - 2 % [1, 2]. First extensions of the model calculation to the production of cosmogenic nuclides in the earth's atmosphere and in terrestrial surface rocks are promising [3]. For recent results of cross sections for the production of cosmogenic nuclides see [5 - 7].

For accelerator driven technologies, however, the situation is still not satisfactory [8] and much work remains to be done. This is mainly due to the much larger target-element and product-nuclide coverage needed for accelerator-driven systems.

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Our ongoing work should contribute to an improvement of this situation. Activities in year 2000 included evaluations of former irradiation experiments at LNS/Saclay, TSL/Uppsala and PSI/Villigen as well as the performance of new experiments at UCL/Louvain La Neuve, PSI/Villigen and TSL/Uppsala.

With respect to **proton-induced reactions**, we finished the evaluations for the medium-mass target elements Rb, Mo, Rh, Ag, In, Te and La. Examples of the excitation functions obtained are given in Fig. 1. Investigations of heavy-mass target elements which are of particular interest for accelerator-driven technologies were continued. Recent proton-irradiation experiments at PSI/Villigen with energies up to 72 MeV performed in collaboration with PSI and IPP/ETH Hönggerberg, Zürich, allowed to complete the cross section data-set for Bi. In the latest experiments we determined more than 160 cross sections for 17 reactions. Complete excitation functions now exist for the production of radionuclides from Ta, W, Pb and Bi [9-14]. As an example we show in Fig. 2 the experimental excitation function for the production of ^{205}Bi from Bi.

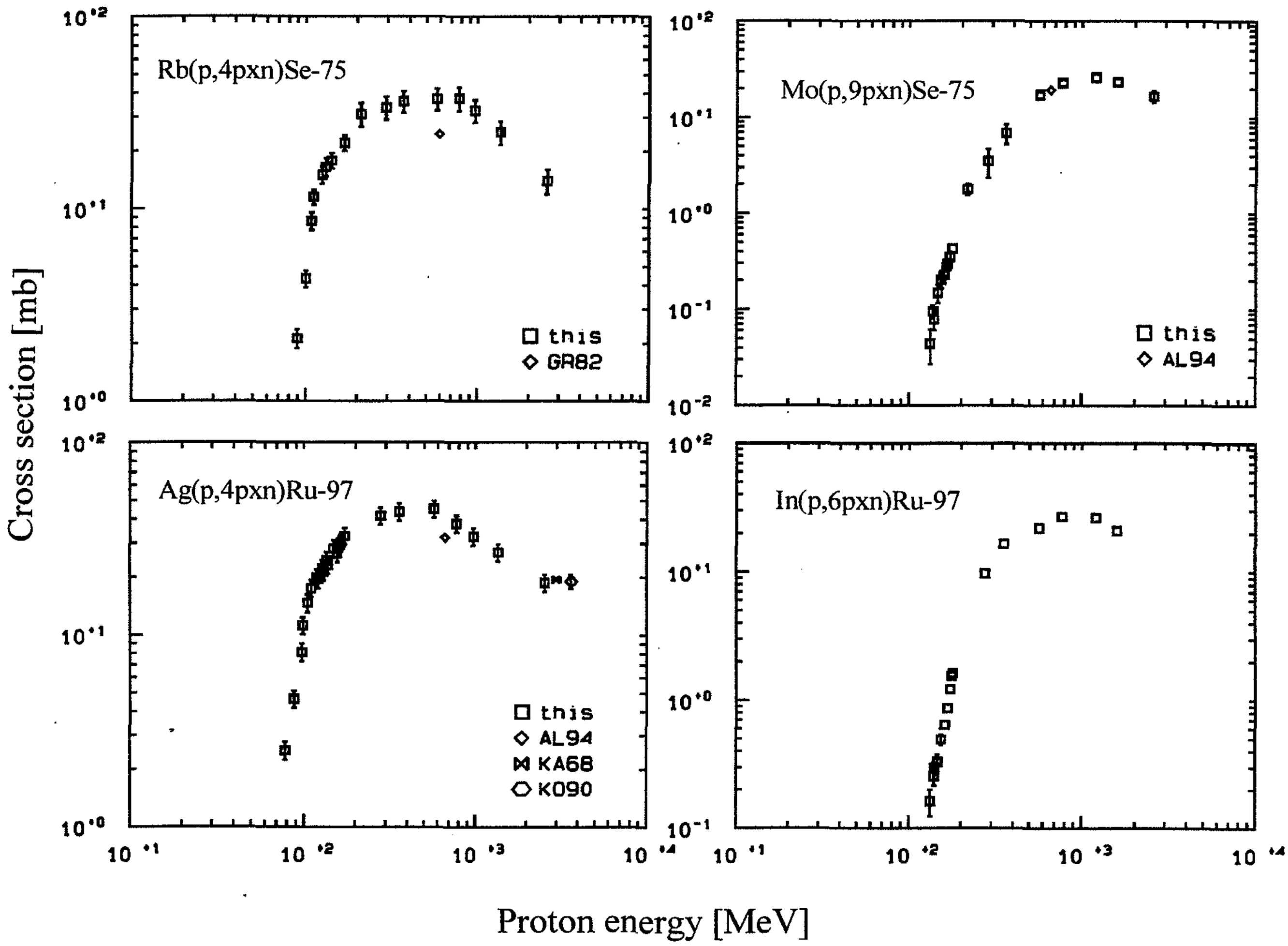

Fig. 1 Examples of excitation functions of proton-induced reactions on Rb, Mo, Ag and In which were derived from former experiments at TSL, LNS and PSI. The work of other authors is coded as AL94 [15],GR82 [16], KA68 [17] and KO90 [18].

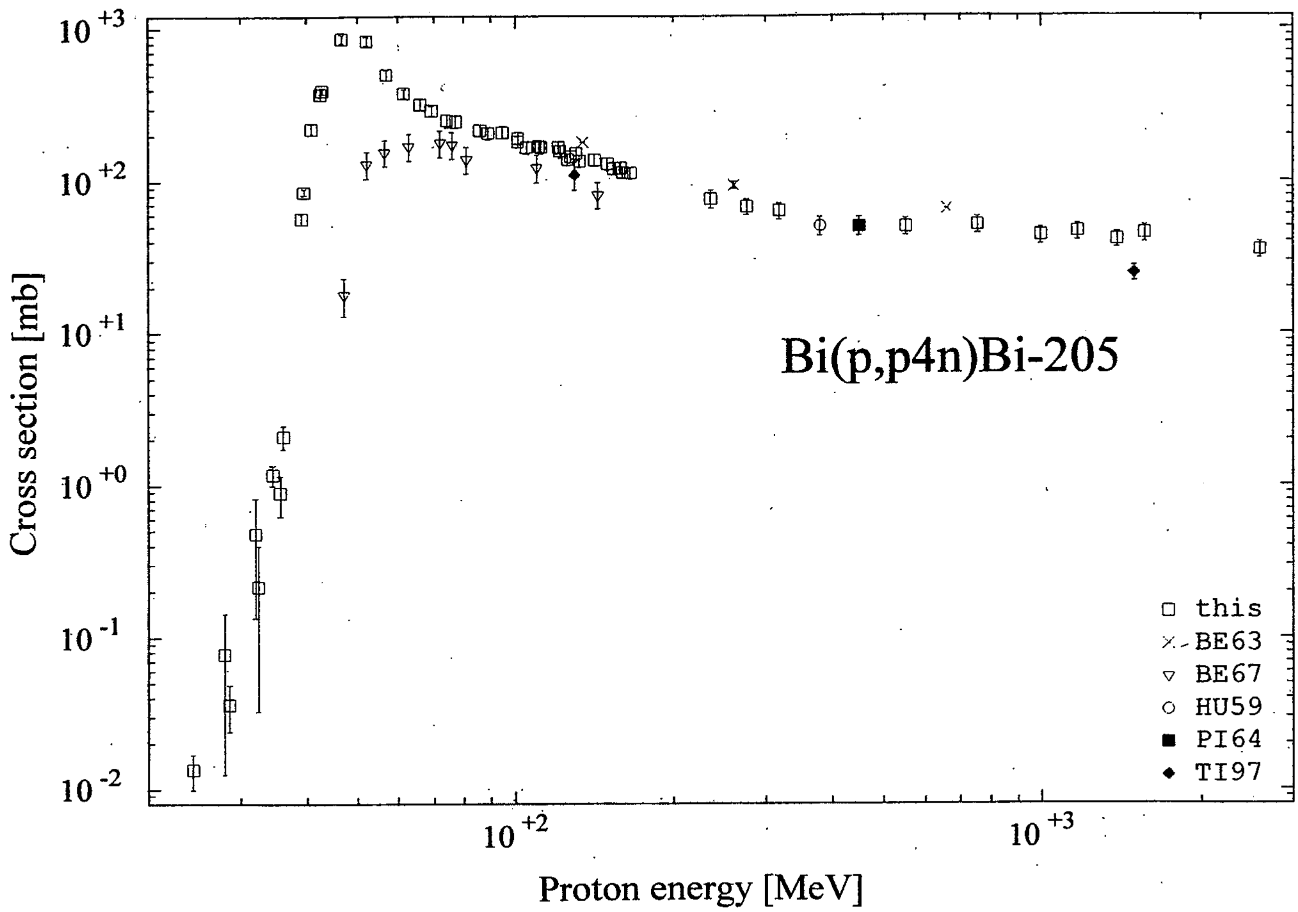

Fig. 2 Experimental excitation function of the $^{209}Bi(p,p4n)^{205}Bi$ reaction. The work of other authors is coded as BE63 [19], BE67 [20], HU59 [21], PI64 [22] and TI97 [23].

Together with the new cross sections, our entire consistent data base now covers the target elements C, N, O, Mg, Al, Si, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Rb, Sr, Y, Zr, Nb, Mo, Rh, Ag, In, Te, Ba, La, Ta, W, Au, Pb and Bi. It contains data for about 1 300 nuclear reactions covering more than 24 000 cross sections.

With respect to **neutron-induced reactions**, we continued our irradiation experiments with quasi-monoenergetic neutrons obtained by the $^7Li(p,n)$-reaction at TSL/Uppsala and UCL/Louvain La Neuve in collaboration with IPN/Louvain La Neuve, KRI/St. Petersburg, PTB/Braunschweig and TSL/Uppsala. The UCL cyclotron facility provides such neutron beams in the energy range from about 25 to 70 MeV, and well-characterized neutron reference fields have been previously established [24]. The neutron beam-line at TSL [25], equipped with a special irradiation chamber [26], allows for irradiations with peak neutron energies up to 175 MeV. A first series of ten irradiation experiments with proton energies of 36.4, 48.5 and 62.9 MeV at UCL and of 69.1, 76.4, 98.5, 136.7, 148.4, 162.7 and 178.8 MeV at TSL was finished in 2000 covering the target elements

C, N, O, Mg, Al, Si, Fe, Co, Ni, Cu, Ag, Te and Pb. Residual radionuclides with half-lives between 20 min and 5 years were measured by off-line γ-spectrometry. Cross sections cannot be directly calculated from the experimental data since the neutrons used are just "quasi-monoenergetic" with only about 30 to 50% of the neutrons in the high-energy peak with a width of a few MeV. Therefore, neutron cross sections are determined by unfolding techniques from the experimental response integrals determined in a series of irradiation experiments with different neutron energies. These evaluation are going on.

The work reported here contributed to the meanwhile finished EC Concerted Action *Physical Aspects of Lead as a Neutron Producing Target for Transmutation Devices* [27]. A new series of proton- and neutron-irradiation experiments was started at PSI and TSL in 2000 to contribute to the 5^{th} Framework EC Project HINDAS: *High and Intermediate Energy Nuclear Data for Accelerator Driven Systems* [28].

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References

[1] I. Leya, H.-J. Lange, M. Lüpke, U. Neupert, R. Daunke, O. Fanenbruck, R. Michel, R. Rösel, B. Meltzow, T. Schiekel, F. Sudbrock, U. Herpers, D. Filges, H. Busemann, G. Bonani, B. Dittrich-Hannen, M. Suter, P.W. Kubik, H.-A. Synal, Meteoritics & Planetary Science 35 (2000) 287.

[2] I. Leya, H.-J. Lange, S. Neumann, R. Wieler, R. Michel, Meteoritics & Planetary Science 35 (2000) 259.

[3] D. Kollár, I. Leya, J. Masarik, R. Michel, Meteoritics and Planetary Science 35 (2000) A90.

[4] J. Kuhnhenn, U. Herpers, W. Glasser, R. Michel, P. W. Kubik, M. Suter, in: Progress Report on Nuclear Data Research in the Federal Republic of Germany for the Period April 1, 1999 to March 31, 2000, (S. M. Qaim, Editor) NEA/NSC/ DOC(2000)11, INDC(Ger)-046, Jül-3780, July 2000, 26.

[5] S. Merchel, Th. Faestermann, U. Herpers, K. Knie, G. Korschinek, I. Leya, R. Michel, G. Rugel, Ch. Wallner, Nucl. Instr. Meth. Phys. Res. B 172 (2000) 144.

[6] C. Schnabel, I. Leya, R. Michel, J. Csikai, Z. Dezso, J.M. Lopez-Gutierrez, H.-A. Synal, Radiochimica Acta 88 (2000) 439.

[7] C. Schnabel, J.M. Lopez-Gutierrez, H.-A. Synal, I. Leya, M. Gloris, R. Michel, J. Kuhnhenn, U. Herpers, Meteoritics & Planetary Science 35 (2000) A143.

[8] R. Michel, Proc. of "Model and Codes for Spallation Neutron Sources", Special Session within the SARE-5/SATIF-5 Meeting, July 17-18, 2000, Paris, in press.

[9] M. Gloris, R. Michel, F. Sudbrock, U. Herpers, P. Malmborg, B. Holmqvist, Proton-induced production of residual nuclei in lead at intermediate energies, in: Special Issue on Accelerator Driven Systems, (H. S. Plendl, Editor), Nucl. Instr. Meth. A (2001) in press.

[10] M. Gloris, S. Neumann, I. Leya, R. Michel, Ch. Schnabel, F. Sudbrock, U. Herpers, O. Jonsson, P. Malmborg, B. Holmqvist, H. Condé, P.W. Kubik, M. Suter, E. Gilabert, B. Lavielle, in: Progress Report on Nuclear Data Research in the Federal Republic of Germany for the Period April, 1st, 1997 to March, 31th, 1998, (S. M. Qaim, Editor) NEA/ NSC/DOC(98) 7, INDC(Ger)-044, Jül-3550 (1998) 27.

[11] J. Protoschill, M. Gloris, S. Neumann, R. Michel, J. Kuhnhenn, U. Herpers, 0. Jonsson, P. Malmborg, P.W. Kubik, I. Leya, E. Gilabert, B. Lavielle, in: Progress Report on Nuclear Data Research in the Federal Republic of Germany for the Period April 1, 1998 to March 31, 1998, (S. M. Qaim, Editor) NEA/NSC/ DOC(99)10, INDC(Ger)-045, Jül-3660, 1999, 26.

[12] M. Miah, J. Kuhnhenn, U. Herpers, R. Michel, P.W. Kubik, Production of residual nuclides by proton-induced reactions on target W at an energy of 72 MeV, Int. Conf. on Nucl. Data for Science and Technology, Tsukuba, Japan, (2001), submitted

[13] J. Kuhnhenn, U. Herpers, W. Glasser, R. Michel, P.W. Kubik, M. Suter, Thin target cross sections for proton-induced formation of radionuclides in lead for $E_p \leq 71$ MeV, Radiochimica Acta (2001) in press

[14] J. Kuhnhenn, Protonen-induzierte Erzeugung radioaktiver Restkerne in Blei und Wismut bei Energien bis 71 MeV ,Ph.D. Dissertation, Universität zu Köln (2001) submitted.

[15] Y.V. Alexandrov, V.P. Eismont, R.B. Ivanov, M.A. Mikhailova, V.P. Prikhodtseva, V. Saulsky, S.K. Vasiljev, Proc. 2nd Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications, Kalmar, 3-7 June (1996) 576.

[16] A. Gruetter, Int. J. Appl. Radiat. Isot. 33 (1982) 725.

[17] S. Katcoff, H. R. Fickel, A. Wyttenbach, Phys. Rev. 166 (1968), 1147.

[18] P. Kozma, B. Tumendemberel, Czech. J. Phys. 40 (1990) 29.

[19] B.N. Beljaev, A.B. Kaliamin, A.N. Murin, Izv. AN SSR ser. Fiz (1963) 923 (ref. taken from Lanoldt-Börnstein)

[20] Y. le Beyec, M. Lefort, Nucl. Phys. A99 (1967), 131

[21] E.T. Hunter, J.M. Miller, Phys. Rev. 115 (1959) 1053

[22] W.R. Pierson, N. Sugarman, Phys. Rev. B133 (1964) 384 (ref. taken from Lanoldt-Börnstein)

[23] Y.E. Titarenko, O.V. Shvedov, M.M. Igumnov, S.G. Mashnik, E.I. Karpikhin, V.D. Kazaritsky, V.F. Batyaev, A.B. Koldobsky, V.M. Zhivun, A.N. Sosnin, R.E. Prael, M.B. Chadwick, T.A. Gabriel, M. Blann, Nucl. Instr. Meth. A414 (1998) 73.

[24] H. Schuhmacher, H.J. Brede, V. Dangendorf, J.P. Meulders, W.D. Newhauser, R. Nolte, Nucl. Instr. Meth. A421 (1999) 284.

[25] H. Condé, S. Hultqvist, N. Olsson, T. Rönnqvist, R. Zorro, J. Blomgren, G. Tibell, A. Håkansson, O. Jonsson, A. Lindholm, L. Nilsson, P.U. Renberg, A. Brockstedt, P. Ekström, M. Österlund, F.P. Brady, Z. Szeflinski, Nucl. Instr. Meth. A292 (1990) 121.

[26] S. Neumann, R. Michel, F. Sudbrock, U. Herpers, P. Malmborg, O. Jonsson, B. Holmqvist, H. Condé, P.W. Kubik, M. Suter, Proc. Int. Conf. Nuclear Data for Science and Technology, IPS Proc. Vol 59 (1997) 379.

[27] J.-P. Meulders, I. Slype, W. Glasser, R. Michel, S. Neumann, U. Herpers, J. Kuhnhenn, O. Jonsson, P. Malmborg, V. Dangendorf, R. Nolte, H.Schuhmacher, A.V. Prokofiev, A.N. Smirnov, P.W. Kubik, M. Suter, A. Atac, B. Bergenwall, J. Blomgren, S. Dangtip, K. Elmgren, C. Johansso, O. Jonsson, L. Nilsson, P.-U. Renberg, T. Enqvist, W. Wlazlo, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, S. Czajkowski, R. Legrain, S. Leray, B. Mustapha, M. Pravikoff, F. Rejmund, K.-H. Schmidt, J. Taieb, L. Tassan-Got, C. Volant, F. Borne, F. Brochard, S. Crespin, D. Drake, J.C. Duchazeau-beneix, D. Durand, J.M. Durand, J. Fréhaut, F. Hanappe, L. Kowalski, C. Lebrun, X. Ledoux, F.R. Lecolley, J.F. Lecolley, F.

Lefebvres, R. Legrain, M. Louvel, E. Martinez, S.I. Meigo, S. Ménard, G. Milleret, Y. Patin, E. Petibon, F. Plouin , P. Pras, L. Stuttgef, Y. Terrien, J. Thun, C. Varignon, D.M. Whittal, D. Filges, F. Goldenbaum, R.-D. Neef, K. Nünighoff, N. Paul, H. Schaal, G. Sterzenbach, C.-M. Herbach, D. Hilscher, U. Jahnke, J. Galin, A. Letourneau, B. Lott, A. Peghaire, L. Pienkowski, W.U. Schröder, J. Töke, Physical Aspects of Lead as a Neutron Producing Target for Accelerator Transmutation Devices, Final Report of an EU Concerted Action, July 2000, in press.

[28] J.-P. Meulders, H. Beijers, J. Benlliure, O. Bersillon, J. Cugnon, Ph. Eudes, D. Filges, A. Koning, J.F. Lecolley, S. Leray, R. Michel, N. Olsson, K.-H. Schmidt, H. Schuhmacher, I. Slypen, H. Synal, R. Weinreich, High and Intermediate Energy Nuclear Data for Accelerator-Driven Systems – the HINDAS Project in: Proc. "Sixth Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation", Madrid, 11-13 December 2000, in press.

INSTITUT FÜR KERNCHEMIE
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Measurement of Excitation Functions Relevant to the Production of the Positron Emitter ^{90}Nb via the ^{90}Zr(p,n)-Reaction

S. Busse[1,2], F. Rösch[1] and S. M. Qaim[2]

The radioisotope ^{90}Nb decays with a positron branching of 53% and a relatively low β^+-energy of E_{mean} = 0.66 MeV and E_{max} = 1.5 MeV. Its half-life of 14.6 h makes it especially promising for quantitative investigations of biological processes with slow distribution kinetics using positron emission tomography. ^{90}Nb was originally identified via (p,n) and (d,2n) reactions on ^{90}Zr. High-purity ^{90}Nb was first obtained via the decay of ^{90}Mo [1]. For the production of ^{90}Nb today, several nuclear reactions seem to be reasonable: the (p,n)- or (d,2n)-processes on ^{90}Zr and the (^{3}He,2n)- or (α,3n)-reactions on natural yttrium. A medium-sized cyclotron would be able to produce ^{90}Nb via the (p,n)-, (d,2n)- or the (^{3}He,2n)-process. In fact even a small-sized ($\leq$ 16 MeV proton energy) cyclotron should lead to sufficient quantities of the radioisotope via the (p,n)-reaction. A few studies have shown that the (d,2n)-reaction requires a deuteron energy of about 16 MeV [2-4], the (^{3}He,2n)-process a ^{3}He-energy of $\geq$ 30 MeV and the (α,3n)-reaction an α-particle energy of $\geq$ 45 MeV [5]. Furthermore, the systematics of (^{3}He,2n)- and (p,n)-reactions suggest that the production yield of ^{90}Nb should be higher in the latter process.

With the common availability of dedicated cyclotrons for producing short-lived β^+-emitters, the (p,n) reaction represents an advantageous route for production of ^{90}Nb. Some cross section data on the ^{nat}Zr(p,xn)-reactions using thick target irradiations with high initial proton energy have already been reported in the literature [6]. However, those experiments were not designed to determine cross sections in the low energy region relevant to the production of ^{90}Nb, i.e. at E_p < 20 MeV. The data display large uncertainties because large foil-stacks with high incident proton energies (for example, E_p = 70$\rightarrow$10 MeV) were used.

To optimise the production of ^{90}Nb, the cross sections of ^{90}Zr(p,xn)-processes were studied over the most relevant proton energy range of 7.5 to 19 MeV via the stacked-foil technique using both ^{nat}Zr and 99.22% enriched $^{90}ZrO_2$ as targets. The results are shown in Fig. 1. Thick target yields of ^{90}Nb were calculated from the measured excitation functions and verified experimentally.

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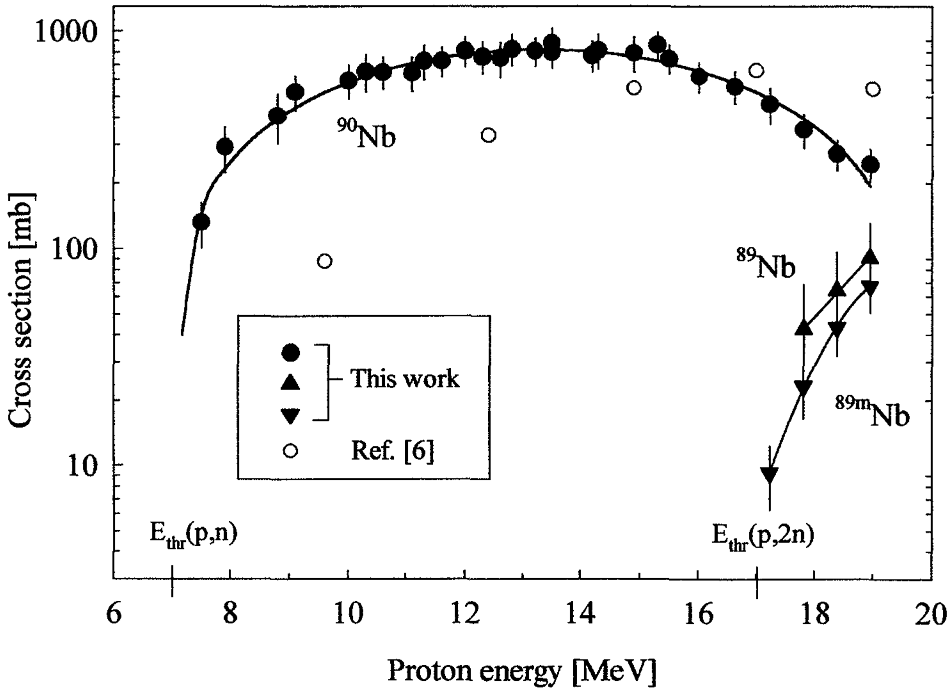

Fig. 1 Excitation functions of $^{90}Zr(p,xn)$-processes leading to the formation of ^{90}Nb, ^{89m}Nb and ^{89}Nb. The values for ^{90}Nb describe the cumulative formation cross section. Error bars are also shown. The solid curve is an eye-guide through our data. A few available points from the literature [6] are also shown.

The optimum energy range for the production of ^{90}Nb via the $^{90}Zr(p,xn)$-process was found to be E_p=17→7 MeV, with a yield of 600 MBq ^{90}Nb/μA·h. The yield and radionuclidic purity of ^{90}Nb over the energy range of E_p = 17.6→8.1 MeV were determined experimentally using ^{nat}Zr. At 4 h after EOB the yield of ^{90}Nb was found to be 290 MBq/μA·h and its purity ≥ 95%.

The results of cross section measurements indicate that ^{90}Nb can be produced with batch activities of the order of 10 GBq and in high isotopic purity by means of the (p,n)-process on highly enriched ^{90}Zr at a small-sized cyclotron providing E_p ≤ 16 MeV. Sufficient quantities of ^{90}Nb can also be produced using ^{nat}Zr as target material, the radionuclidic purity, however, would then be about 96%, the main contaminant being 10.2 d ^{92m}Nb.

References

[1] F.D.S. Butement, S.M. Qaim, J. Inorg. Nucl. Chem. **26** (1964) 1481
[2] R.C. Mercader, M.C. Caracoche, A.B. Mocoroa, Z. Physik **255** (1972) 103
[3] C. Wasilevsky, F. Dos Santos, O. Herreros Usher, S.J. Nassiff, Radiochem. Radioanal. Lett. **32** (1978) 127
[4] A.V. Gonchar, S.N. Kondratev, Yu. N. Lobach, S.V. Nevskii, V.D. Skylyarenko, V.V. To karevskii, Atomnaja Energija **75** (1993)205
[5] F.Smend, W. Weirauch, W.-D. Schmidt-Ott, A. Flammersfeld, Z. Physik **207** (1967) 28
[6] S.N. Kondratev, V.A. Kuzmenko, Yu. N. Lobach, V.S. Prokopenko, V.D. Skylyarenko, V.V. Tokarevskii, Atomnaja Energija **71** (1991) 325

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT BRAUNSCHWEIG

1. Measurement of the $^{29}Si(n,p)^{29}Al$ Cross Section between 6.9 and 14.0 MeV

W. Mannhart, D. Schmidt

The cross section of the reaction $^{29}Si(n,p)^{29}Al$ has been measured at 19 neutron energies between 6.9 and 14.0 MeV. The measurement represents the first experiment performed at neutron energies lower than 13 MeV.

Disk-shaped samples, 10 mm in diameter, were fabricated from a 1 mm thick plate of polycrystalline silicon by laser cutting, and were irradiated in the $D(d,n)^3He$ neutron field generated with a deuterium gas target. Neutron energy determination is based on TOF measurements and defines the energy within ± 20 keV. The energy resolution (FWHM/2) varies between 77 and 52 keV with increasing neutron energy. The neutron fluence was monitored with a ^{238}U fission chamber and is based on the $^{238}U(n,f)$ cross section taken from the ENDF/B-VI evaluation. Corrections for background and deuterium breakup neutrons were applied, the latter being of the order of 35% at maximum neutron energy. The induced radioactivity was measured with a calibrated HPGe detector by analysis of the 1273.3 keV γ-ray, with a transition probability of 0.906(6), of the 6.56(6) min decay of ^{29}Al. The value used for the isotopic abundance was 0.0467(1). Each data point is based on the average of three independent irradiation cycles. The final overall uncertainties of our data are of the order of 4.5%.

The result of the present work is shown in Fig. 1 and compared with the ENDF/B-VI evaluation. The experimental database for the $^{29}Si(n,p)^{29}Al$ reaction, as given in the EXFOR file [1], comprises 17 experiments, all of which were performed at neutron energies around 14 MeV. Only one of the experiments covers a broader energy range, extending up to 18 MeV neutron energy. In the figure our data are compared with a few selected experiments which confirm the validity of our measurement results at high neutron energies. The difference between our data and the ENDF/B-VI evaluation is substantial, amounting to a factor of 2. It is obvious that the ENDF/B-VI evaluation is based on a theoretical model calculation which has finally been normalized at 14 MeV with the data of a single experiment (Ranakumar 68). The result of Fig. 1 clearly shows the risk and the deficiencies of such an evaluation method which is often applied today.

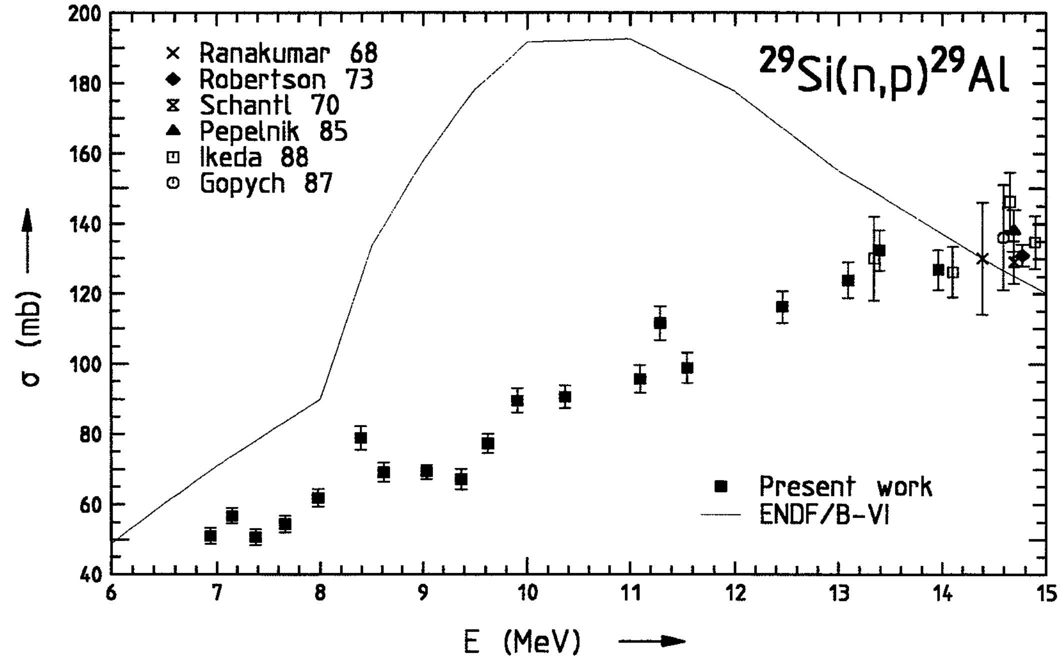

Fig. 1 Excitation function of $^{29}Si(n,p)^{29}Al$ reaction. The present data are compared with selected previous experiments and the ENDF/B-VI evaluation.

The present data show some pronounced structures which are of a physical nature. Because of the low level density of this light nucleus, the contributions of the individual excited levels to the excitation function are not masked as it happens with heavier nuclei.

2. Precise Measurement of Neutron Scattering Cross Sections on Silicon at Energies between 8 and 14 MeV

D. Schmidt, W. Mannhart

Precise and systematic measurements of neutron scattering cross sections need to be carried out to validate theoretical model calculations, as are often used in neutron data evaluations, and for other applications. Procedures for measurement and data processing have been developed at PTB to obtain fast neutron scattering cross sections with high precision. Here, an important instrument is a realistic Monte Carlo simulation of the whole measurement, including all relevant details of neutron production, scattering and detection. Recently, such measurements have been carried out on natural silicon, a widely used semiconductor material.

The measurements were carried out at ten neutron energies between 7.89 MeV and 13.85 MeV. The measuring set-up and the procedure to obtain the differential cross sections was the same as for the previous measurement with iron [2]. When the disturbing fraction of non-monoenergetic neutrons from the DD source ("breakup neutrons") was simulated and subtracted, the determination of partial cross sections could be extended up to excitation energies above 7 MeV, see Fig. 2. Also, cross sections for the isotopes ^{29}Si (4.7%) and ^{30}Si (3.1%) could be obtained, although their abundances in the natural sample were rather small (main isotope ^{28}Si: 92.2%).

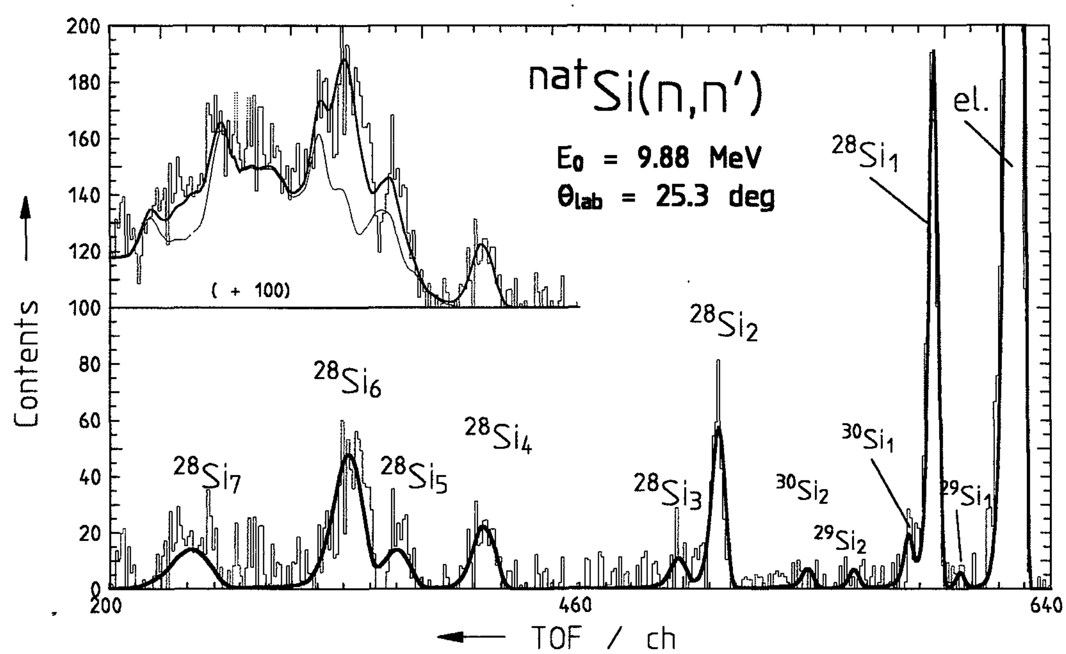

Fig. 2 TOF spectra of elemental silicon with lines related to levels of the three isotopes denoted; thin histogram: measurement, thick polygon: calculation (in both cases breakup neutrons subtracted); insert: thin histogram = measurement, thin polygon = simulated breakup neutrons only, thick polygon = full simulation; channel width about 1 ns; Q-value $^{28}Si_7$: 7.415 MeV.

Fig. 3 shows the elastic angle-integrated cross sections of the present work, together with data from literature and the ENDF/B-VI evaluation. The differences from the ENDF/B-VI evaluation are of the order of 5%.

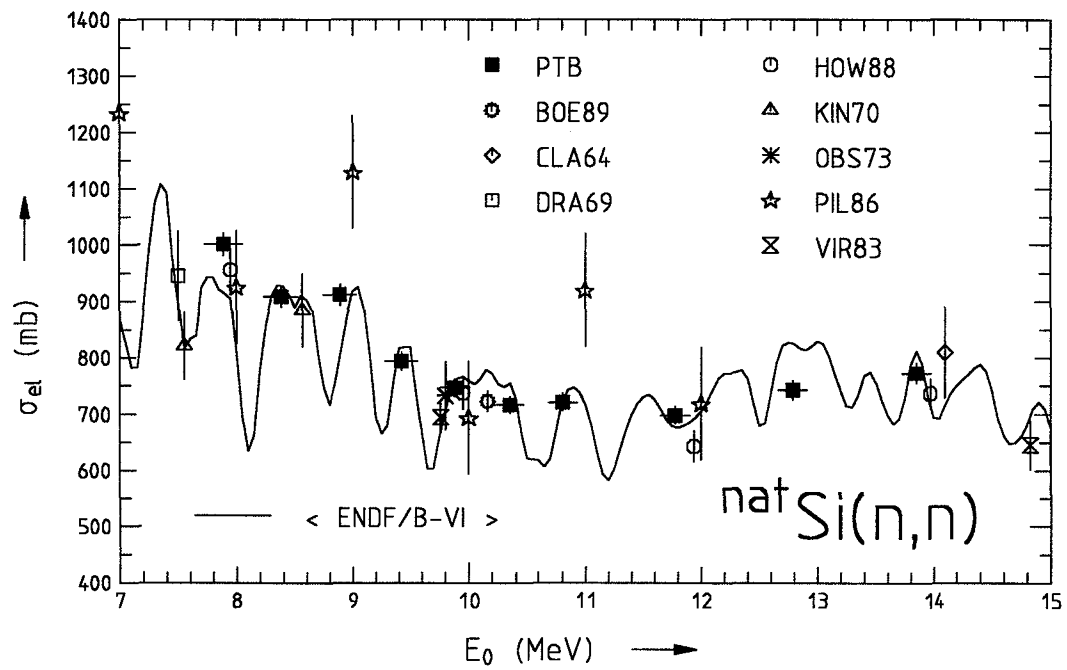

Fig. 3 Angle-integrated cross sections for the elastic scattering of neutrons from natural silicon; results obtained by other authors (EXFOR database [1]) are also given. The curve represents the ENDF/B-VI evaluation averaged over 150 keV (energy resolution of the experiment in the present work).

3. Differential Cross Sections of Neutron Scattering on Elemental Titanium in the Energy Range from 8 to 15 MeV

D. Schmidt, W. Mannhart, Ruan Xichao [1]

The PTB's program on systematic fast neutron scattering cross section measurement was continued with titanium. As usual, the existing experimental data for the incident neutron energy region between 10 and 14 MeV are sparse. An extensive measurement at incident neutron energies below 10 MeV was done at ANL [3], but no angle-integrated cross sections were reported.

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The measurements using a sample of natural titanium were carried out at eleven neutron energies between 7.93 and 14.72 MeV. The measuring set-up and the procedure to obtain the differential cross sections were the same as for the previous measurement with iron [2].

Differential cross sections for elastic and inelastic scattering were determined. Elemental titanium consists of five stable isotopes ^{46,47,48,49,50}Ti, the main isotope being ^{48}Ti (73.8%). As scattering fractions of the levels of all isotopes overlap in the experiment, also at low excitation energies, partial inelastic cross sections could be obtained only for level groups belonging to different isotopes with averaged Q-values $\langle Q \rangle$ = -0.98 MeV, -1.58 MeV and -2.38 MeV.

Fig. 4 shows the elastic angle-integrated cross sections of the present work, together with data from literature and the ENDF/B-VI evaluation. Above neutron energies of 9 MeV, the evaluation lies higher than our data by about 10%.

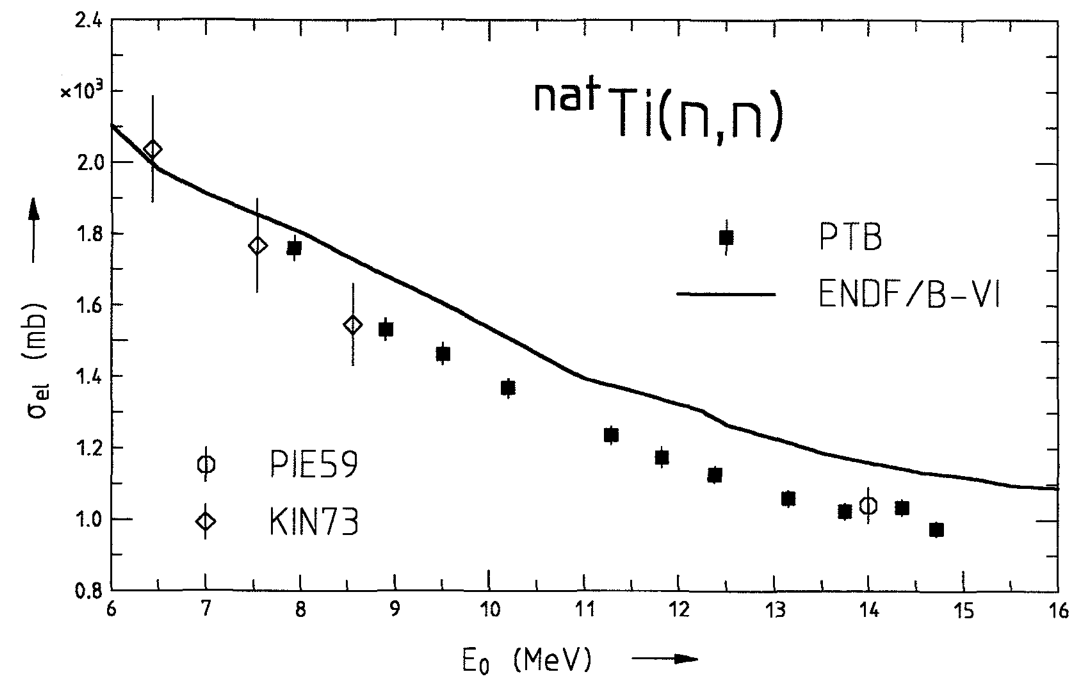

Fig. 4 Angle-integrated cross sections for the elastic scattering of neutrons from natural titanium; results obtained by other authors [4,5] are also given; the curve represents the ENDF/B-VI evaluation.

4. Standardisation and Decay Data of ^{177}Lu and ^{188}Re

U. Schötzig, H. Schrader, E. Schönfeld, E. Günther, R. Klein

The activity values for ^{177}Lu and ^{188}Re standard sources were measured using the $4\pi\beta$-γ-coincidence method and by liquid scintillation counting. ^{188}Re is obtained carrier-free from a generator with the long-lived ^{188}W parent ($T_{1/2}$ = 69.4 (5) d). ^{177}Lu and ^{188}W were produced by neutron bombardment of purified target materials in reactors. The X- and gamma-ray emission probabilities per disintegration were determined by photon spectrometry with calibrated Ge and Si(Li) detectors using the pertinent activity values. Results are presented in Table 1 and Table 2,

Table 1. Results of X- and gamma-ray emission probabilities p per disintegration of ^{177}Lu

Energy in keV	Radiation	p this work	p evaluation [a)]	α_T [b)]	$p_{\gamma+ce}$ this work
7.0	Hf-L_ℓ	0.000734(24)	0.00053(6)		
7.9	Hf-$L_{\alpha;\eta}$	0.01505(27)	0.0130(10)		
9.0	Hf-$L_{\beta1;3;4;6}$	0.01333(24)	0.0143(11) (sum of L_β)		
9.4	Hf-$L_{\beta2,15}$	0.00273(6)			
10.5	Hf-$L_{\gamma1;6}$	0.00231(6)	0.00228(20) (sum of L_γ)		
11.0	Hf-$L_{\gamma2;3}$	0.000223(14)			
54.6	Hf-$K_{\alpha2}$	0.01551(25)	0.0163(8)		
55.8	Hf-$K_{\alpha1}$	0.0272(5)	0.0285(14)		
63.2	Hf-$K_{\beta1}$	0.00883(12)	0.0093(5)		
65.2	Hf-$K_{\beta2}$	0.00238(4)	0.00242(12)		
71.64		0.001734(18)	0.00154(8)	0.90(4)	0.00329(8)
112.95		0.0617(4)	0.064(3)	2.27(7)	0.202(5)
136.72		0.000464(8)	0.00048(2)	1.16(4)	0.001002(26)
208.37		0.1036(7)	0.110(6)	0.066(8)	0.1104(12)
249.67		0.001987(12)	0.00212(11)	0.141(5)	0.002267(17)
321.32		0.002074(13)	0.00219(11)	0.0349(20)	0.002146(14)

a) For X-rays the evaluated data of Browne and Firestone [8] were used; for gamma rays, the data were taken from the evaluation by Firestone [9].

b) The total internal conversion coefficients were taken from Browne [10].

Table 2. Results of X- and gamma-ray emission probabilities p per disintegration of ^{188}Re

Energy in keV	Radiation	p this work	p Miyahara [6]	p evaluation [a)]	α_T [b)]	$p_{\gamma+ce}$ this work
8.9	Os-$L_{\alpha\eta\ell}$	0.0133(6)	-	0.0121(8)		
10.4	Os-L_β	0.0155(13)	-	0.0139(9)		
12.1	Os-L_γ	0.00260(17)	-	0.00242(19)		
61.5	Os-$K_{\alpha2}$	0.01397(17)	-	0.0134(5)		
63.0	Os-$K_{\alpha1}$	0.0240(3)	-	0.0231(9)		
71.3	Os-$K_{\beta1'}$	0.00780(11)	-	0.0080(3)		
73.4	Os-$K_{\beta2'}$	0.00206(5)	-	0.00202(8)		
155.0		0.1579(15)	0.15425(72)	0.1495(64)	0.821	0.288(5)
312.0		0.000057(6)	-	0.000046(10)	0.082	0.000062(7)
322.9		0.0001726(23)	0.000163(10)	0.000166(6)	0.074	0.0001854(24)
453.3		0.000830(9)	0.00082(2)	0.00073(6)	0.029	0.000854(10)
478.0		0.01089(10)	0.01073(10)	0.0101(2)	0.026	0.01117(11)
486.1		0.000857(10)	0.000853(15)	0.00077(3)	0.04(3)	0.000891(11)
514.9		0.000058(10)	-	0.000052(4)	0.023(2)	0.000059(11)
633.0		0.01366(13)	0.01382(16)	0.0125(5)	0.0132	0.01384(14)
635.0		0.001641(19)	0.001571(71)	0.00146(6)	0.0136(12)	0.001663(26)
672.5		0.001209(13)	0.00122(2)	0.00109(4)	0.0042	0.001214(14)
824.5		0.000169(5)	0.000211(11)	0.000174(7)	0.014(6)	0.000171(6)
829.5		0.00436(4)	0.00454(6)	0.00403(13)	0.0028	0.00437(4)
845.0		0.0000765(12)	-	0.000069(5)		
931.3		0.00594(6)	0.00600(7)	0.00545(23)	0.0058	0.00594(6)
1017.6		0.0001621(26)	0.000166(8)	0.000144(6)		
1086.4		0.0000258(10)	-	-		
1132.4		0.000912(11)	0.000924(14)	0.00084(3)		
1149.7/ 1151.0		0.000347(4)	0.000364(10)	0.000310(10)		
1174.6		0.0001924(24)	0.000197(8)	0.000185(8)		
1191.9		0.0001498(15)	-	0.000131(5)		
1209.8		0.0000349(9)	-	0.0000293(22)		
1302.4/ 1304.9		0.000046(5)	-	0.000080(7)		
1308.0		0.000701(9)	0.000735(14)	0.000643(18)		
1322.9		0.0001424(18)	-	0.000114(26)		
1332.0		0.0000178(12)	-	0.0000172(21)		

Table 2. continued

Energy in keV	Radiation	p this work	p Miyahara [6]	p evaluation [a)]	α_T [b)]	$p_{\gamma+ce}$ this work
1457.5		0.000204(3)	0.000211(11)	0.000185(8)		
1530.5		0.0000060(9)	-	0.0000055(17)		
1574.6		0.0000082(9)	-	0.0000063(11)		
1610.4		0.001042(10)	0.001048(15)	0.000960(28)		
1652.6		0.0000330(7)	-	0.0000343(32)		
1669.9		0.0001117(13)	-	0.000102(5)		
1765.1		0.0000025(4)	-	0.00000111(11)		
1786.0		0.0002095(21)	0.000208(7)	0.000194(7)		
1802.1		0.000398(4)	0.000401(14)	0.000361(13)		
1807.4		0.0000088(8)	-	0.0000081(3)		
1864.7		0.0000535(9)	-	0.0000515(32)		
1936.9		0.0000010(7)	-	0.0000021(5)		
1941.0		0.0000200(5)	-	0.0000192(11)		
1957.1		0.0001584(16)	0.000156(7)	0.000149(6)		
2022.5		0.0000160(4)	-	0.0000162(11)		

a) For X-rays the evaluated data of Browne and Firestone [8] were used; for gamma rays, the data were taken from the evaluation by Firestone [9].

b) The total internal conversion coefficients were taken from Singh [11].

respectively, together with evaluated data and, for ^{188}Re, values recently measured (Miyahara *et al.*, [6]). The standard uncertainties (in terms of the last digit) given in brackets include an uncertainty component for the activity, the detector efficiency and the peak fitting. The half-lives of ^{177}Lu and ^{188}Re were measured using a 4π-ionization chamber filled with argon at a pressure of 2 MPa which was coupled to current measuring electronics. The results and standard uncertainties are compared in Table 3 with those of other authors. For details of the measurements, see Schötzig *et al.* [7].

Table 3. Half-life ($T_{1/2}$) measurements

Radionuclide	$T_{1/2}$ (h)	$T_{1/2}$ (d)	Reference
^{177}Lu	-	6.75(5)	Betts *et al.* [12]
	-	6.74(4)	Schmid *et al.* [13]
	-	6.71(1)	Emery *et al.* [14]
	-	6.645(30)	Lagoutine *et al.* [15]
	-	6.7479(7)	Abzouzi *et al.* [16]
	-	6.646(5)	this work
^{188}Re	16.74(6)	0.6975(25)	Gueben *et al.* [17]
	16.98(2)	0.7075(8)	Michel *et al.* [18]
	16.93(17)	0.705(7)	Zhou *et al.* [19]
	17.006(4)	0.70858(17)	Abzouzi *et al.* [20]
	17.021(25)	0.7092(10)	Unterweger *et al.* [21]
	17.0035(22)	0.70848(9)	this work

References

[1] EXFOR Database, IAEA, Vienna (2001)

[2] D. Schmidt, W. Mannhart, H. Klein, R. Nolte, Report PTB-N-20, Braunschweig, Germany (1994)

[3] A.B. Smith, Report ANL/NDM-141, Argonne, USA (1997)

[4] C. St. Pierre, M.C. Machwe, P. Lorraine, Phys. Rev. **115** (1959) 999

[5] W.E. Kinney, F.G. Perey, Report ORNL-4810, Oak Ridge, USA (1973)

[6] H. Miyahara, G. Wurdiyanto, H. Nagata, A. Yoshida, K. Yanagida, C. Mori, Appl. Radiat. Isot. **52** (2000) 573

[7] U. Schötzig, H. Schrader, E. Schönfeld, E. Günther, R. Klein, Appl. Radiat. Isot. (to be published)

[8] E. Browne, R.B. Firestone, Table of Radioactive Isotopes (1986), Wiley and Sons, New York

[9] R.B. Firestone, Table of Isotopes, 8th ed. (1996), John Wiley and Sons, New York

[10] E. Browne, Nuclear Data Sheets **68** (1993) 747

[11] B. Singh, Nuclear Data Sheets **59** (1990) 133

[12] R.H. Betts, O.F. Dahlinger, D.M. Munro, Can. J. Phys. **36** (1958) 73

[13] L.C. Schmid, W.P. Stinson, Nucl. Sci. Eng. 7 (1960) 477

[14] J.F. Emery, S.A. Reynolds, E.I. Wyatt, G.I. Gleason, Nucl. Sci. Eng. **48** (1972) 319

[15] F. Lagoutine, J. Legrand, Int. J. Appl. Radiat. Isot. **33** (1982) 711

[16] A. Abzouzi, M.S. Anthony, V.B. Ndocko Ndongue, J. Radioanal. Nucl. Chem. **144** (1990) 359

[17] G. Gueben, J. Govaerts, Interuniv. Sci. Nucleaires (Bruxelles), Monographie No. 2 (1958); cited in [11]

[18] R. Michel, U. Herpers, Radiochim. Acta **16** (1971) 115

[19] L. Zhou, S. Wen, J. Zhao, B. Yu, B. Han, Ch. Yang, J. Radioanal. Nucl. Chem. Letters **87** (1984) 247

[20] A. Abzouzi, M.S. Anthony, V.B. Ndocko Ndongue, J. Radioanal. Nucl. Chem. **137** (1989) 381

[21] M.P. Unterweger, D.D. Hoppes, F.J. Schima, Nucl. Instr. and Meth. **A 312** (1992) 349

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