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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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Edited by S. M. Qaim Forschungszentrum Jülich GmbH Institut für Nuklearchemie Jülich, Federal Republic of Germany

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Edited by: S.M. Qaim Forschungszentrum Jülich GmbH Institut für Nuklearchemie Jülich, Federal Republic of Germany

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.

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FORSCHUNGSZENTRUM KARLSRUHE INSTITUT FÜR KERNPHYSIK

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

J. Görres¹, C. Arlandini, U. Giesen¹, M. Heil, F. Käppeler, H. Leiste², E. Stech¹, and M. Wiescher¹

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

¹ University of Notre Dame, Notre Dame, Indiana 46556, USA

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. Kazakov¹

The neutron capture cross sections of ¹⁷⁰Yb, ¹⁷¹Yb, ¹⁷²Yb, ¹⁷³Yb, ¹⁷⁴Yb, and ¹⁷⁶Yb 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 ⁷Li(p,n)⁷Be 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 ¹⁷²Yb, ¹⁷³Yb, ¹⁷⁴Yb, and ¹⁷⁶Yb. 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

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

3. Neutron Capture Cross Section of ²³²Th*

K. Wisshak, F. Voss, and F. Käppeler

The neutron capture cross section of ²³²Th 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 ⁷Li(p,n)⁷Be 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 4π BaF₂ Detector for (n,γ) Cross Section Measurements at a Spallation Neutron Source*

M. Heil, R. Reifarth, M.M. Fowler¹, R.C. Haight¹, F. Käppeler, R.S. Rundberg¹, E. H. Seabury¹, J.L. Ullmann¹, J.B. Wilhelmy¹, 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 BaF₂ detector represents an accurate and versatile instrument for such studies. The present work deals with the potential of such a 4π BaF₂ 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. Bao¹, H. Beer, F. Käppeler, T. Rauscher², 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 ⁵⁶Fe Cross Section Data

U. Fischer, I. Kodeli¹, Ch. Konno², R. Perel³

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 ironspherical 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	Tota 1
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 ironspherical 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	Tota
								1
		1.00	1.40	10.1	7 46	5 72	1 25	0.72
MCSEN	3.64	1.00	1.43	12.1	7.40	5.75	4.35	0.72
SUSD	4.10	1.04	1.59	12.4	7.45	5.74	4.54	0.72

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- [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. Konobeyev¹, Yu. Korovin¹, U. v. Möllendorff, P.Pereslavtsev¹,

A. Yu. Stankovsky¹

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, ³He, 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.

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- [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 ⁸⁵Rb(p,n)^{85m,g}Sr, ⁸⁵Rb(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 ¹⁰⁷Ag(n, α)^{104m,g}Rh and ¹⁰⁹Ag(n, α)^{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} ≤ 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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2. Neutron Activation Cross Sections

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During the period of this report a few measurements were completed while some others were initiated. Attempt is made to cover the full neutron energy range from reaction threshold up to 20 MeV. A good triangular cooperation has developed. Measurements in the neutron energy range of 7 to 12 MeV are done using a DD gas target at the compact cyclotron CV 28 in Jülich, for energies around 14 MeV use is made of a DT neutron generator at Debrecen, and the energy range of 14 to 20 MeV is covered by a DT source at the van de Graaff machine in Geel. The data obtained are of considerable technological importance.

Investigations were completed on the following reactions: ${}^{51}V(n,\alpha){}^{48}Sc$, ${}^{nat}V(n,x\alpha){}^{47}Sc$, ${}^{94}Mo(n,p){}^{94}Nb$, ${}^{99}Tc(n,p){}^{99}Mo$, ${}^{99}Tc(n,\alpha){}^{96}Nb$, ${}^{107}Ag(n,p){}^{107m}Pd$, ${}^{109}Ag(n,p){}^{109m,g}Pd$ and ${}^{204}Pb(n,p){}^{204}Tl$. The ${}^{94}Mo(n,p){}^{94}Nb$ and ${}^{204}Pb(n,p){}^{204}Tl$ processes were investigated radiochemically. For the latter reaction, low-level β^{-1} counting was necessary. Most of the cross sections were measured for the first time.

The cross section data base for the $(n,n'\gamma)$ process in the neutron energy region above 5 MeV is rather weak. An extensive programme of measurements is now under way. Studies on the reaction ⁹⁹Tc $(n,n'\gamma)^{99m}$ Tc have been completed. Measurements on ¹⁰⁷Ag $(n,n'\gamma)^{107m}$ Ag and ¹⁰⁹Ag $(n,n'\gamma)^{109m}$ Ag processes are continuing. Of considerable interest are investigations near the (n,2n) thresholds since the data should provide useful information on the competition between one and two neutron emissions.

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3. Charged Particle Induced Reaction Cross Sections

S. Kastleiner, E. Heß, T. Bastian, K. Kettern, T. Stoll, S. Spellerberg, G. Blessing, B. Scholten, F.M. Nortier^{*}, T.N. van der Walt^{*}, F. Tárkányi[†], Z. Kovács[†], S. Takács[†], S. Sudár^{††}, Y. Skakun^{**}, H. H. Coenen, S. M. Qaim

Our systematic studies on charged particle induced reaction cross sections for medical applications were continued. During the period of the present report following investigations were carried out.

a) Excitation functions of nuclear reactions relevant to the production of positron emitters (${}^{14}O$, ${}^{18}F$, ${}^{76}Br$, ${}^{83}Sr$, ${}^{90}Nb$ and ${}^{124}I$)

The radionuclide ¹⁴O ($T_{1/2} = 70$ s) is formed as an impurity via the ¹⁴N(p,n)-process during the production of ¹¹C using the ¹⁴N(p, α)-reaction. On the other hand, the use of the shorter-lived ¹⁴O in comparison to ¹⁵O ($T_{1/2} = 2.0$ min) in PET studies has also been suggested. Accurate cross section data for the formation of ¹⁴O are therefore of considerable interest. In this connection, the measurements started last year were completed.

The on-going work on cross sections for the formation of ¹⁸F ($T_{1/2} = 110$ min) via the most commonly used ¹⁸O(p,n)¹⁸F reaction was completed. A total of 110 cross section data points were determined. The errors ranged between7 and 18 %. The results are reproduced in Fig. 1. The resonances at 5.1, 6.1 and 7.2 MeV could be resolved and are in agreement with the neutron data. In general, the data fill the gaps in the hitherto known weak data base, especially in the low energy region from threshold up to 4 MeV and at energies above 15 MeV.

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Fig. 1 Excitation function of the ¹⁸O(p,n)¹⁸F 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 ⁷⁶Br (T_{1/2} = 16.0 h) is an important longer-lived β^+ emitter. It is generally produced via the ⁷⁶Se(p,n)⁷⁶Br or ⁷⁵As(³He,2n)⁷⁶Br reaction. We considered it worthwhile to investigate the ⁷⁸Kr(d, α)⁷⁶Br reaction. The standard gas cell technique using 99.95 % enriched ⁷⁸Kr was applied. Though the reaction cross

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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 ⁷⁶Br.

As mentioned in the last Progress Report, the radionuclide ⁸³Sr ($T_{1/2} = 32.2$ h) is a positron emitting analogue of the therapy nuclide ⁸⁹Sr and appears to be well-suited for dosimetry and therapy planning. Measurements on the ⁸⁵Rb(p,xn)^{85m,g, 83,82,81}Sr reactions were now extended up to 100 MeV and completed. The reaction ⁸⁵Rb(p,3n)⁸³Sr over the energy range $E_p = 37 \rightarrow 30$ MeV was found to be very suitable for production of ⁸³Sr. The measured cross sections were tested via an integral experiment. A thick target was irradiated ($E_p = 35 \rightarrow 30$ MeV) at a low current and radiostrontium was radiochemically separated. The practical yield of ⁸³Sr 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 ⁸²Kr(³He,2n)⁸³Sr, were also tested via an integral measurement involving a production gas target. The practical yield of ⁸³Sr 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 ⁸³Sr 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 ⁸³Sr is much higher for the proton induced reaction on highly enriched ⁸⁵Rb and the level of radioactive

Table 1: Comparison of production routes of ⁸³Sr under optimum conditions^a

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

^a Values normalised to 1 hour irradiation, $1\mu A$ 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 ⁹⁰Nb ($T_{1/2} = 14.6$ 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 ¹²⁴I ($T_{1/2} = 4.18$ d) is both of diagnostic and therapeutic use. In recent years its importance has been enhancing. After having investigated the ¹²⁴Te(p,n)¹²⁴I and ¹²⁵Te(p,2n)¹²⁴I processes, studies were started last year on the ¹²⁴Te(d,2n)¹²⁴I 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 ¹²⁴Te(d,n)¹²⁵I reaction has been investigated for the first time. For the ¹²⁴Te(d,2n)¹²⁴I 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 ¹²⁴I and associated impurities (¹²³I and ¹²⁵I) in the three nuclear routes, viz. ¹²⁴Te(p,n), ¹²⁴Te(d,2n) and ¹²⁵Te(p,2n), deduced from the detailed excitation functions measured in our laboratory, showed that the ¹²⁴Te(p,n)-route provides ¹²⁴I of the highest purity. This route can be utilized even at a low energy cyclotron. The ¹²⁵Te(p,2n)-reaction gives about four times higher yield than the other two processes. From the viewpoint of ¹²⁵I impurity, the ¹²⁴Te(d,2n)¹²⁴I 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 ⁶⁷Cu ($T_{1/2} = 61.9$ 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 ⁶⁸Zn(p,2p)⁶⁷Cureaction. 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 ⁶⁷Ga and ⁶⁷Cu. Since ⁶⁷Ga is formed in much higher yields, measurements on ⁶⁷Cu 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 ⁸⁶Y (T_{1/2} = 14.7 h) in therapy planning and quantitative dosimetry with regard to the β^- emitting therapy nuclide ⁹⁰Y (T_{1/2} = 64.1 h) is well established. However, for studying slow biokinetics, the radionuclide ⁸⁸Y (T_{1/2} = 106.6 d) appears to be more suitable. Cross sections were therefore measured for the ^{nat}Sr(p,xn)⁸⁸Y process up to 25 MeV. The suitable energy range for the production of ⁸⁸Y was deduced to be $E_p = 14 \rightarrow 9$ MeV.

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

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The β^+ /EC ratio in the decay of ¹²⁴I (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 ¹²⁴I source, which was produced by irradiation of 99.9 % enriched ¹²⁴Te 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 ¹²⁴I 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 ¹²⁴I.

Publications (During the Period of the Progress Report)

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 Cross sections for the formation of long-lived radionuclides ¹⁰Be, ²⁶Al and ³⁶Cl in 14.6 MeV neutron-induced reactions determined via accelerator mass spectrometry (AMS)
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INSTITUT FÜR KERN- UND TEILCHENPHYSIK TECHNISCHE UNIVERSITÄT DRESDEN

1. Integral Activation Experiment with SiC and Li₄SiO₄*

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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 Li₄SiO₄ [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 ²⁶Al (T_{1/2} = 7.2·10⁵ y) produced by the ²⁷Al(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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The C/E-values for ²⁷Mg, ²⁸Al and ²⁹Al 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 ²⁴Na, ⁴⁶Sc, ⁴⁷Sc, ⁴⁸Sc, ⁵¹Cr, ⁵⁴Mn, ⁵⁶Mn, ⁵⁷Co, ⁵⁸Co ⁸⁹Zr and ^{92m}Nb were measured for SiC, and the activities of ²⁴Na, ⁴⁶Sc, ⁴⁷Sc, ⁴⁸Sc, ⁵¹Cr, ⁵⁴Mn, ⁵⁶Mn, ⁵⁸Co and ^{92m}Nb for Li₄SiO₄. 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 ²⁴Na activity, produced by the ²⁷Al(n, α)²⁴Na reaction. Using the C/E obtained for ²⁴Na, 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 Li₄SiO₄ 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_{1/2} of 2.10⁴ y. Several other values of the impurity content in the SiC and in the Li₄SiO₄ 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 (\diamond) at short decay times in comparison to the corresponding calculated activities (solid line). Rest: dashed line.



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

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2. Shut-Down Dose Rate Experiment*

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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.





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

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

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

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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 openshell 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 SiO₂(1010) crystal. Intrashell transitions (n=3) and direct transition energies in Xe⁴⁴⁺ for n=3 \rightarrow 2 (E1, E2, M1, M2 transitions) were determined. Furthermore, the most intense transitions in Xe⁴³⁺ and Xe⁴⁵⁺ between n=3 \rightarrow 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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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

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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 acceleratordriven 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 ²⁰⁵Bi 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 ²⁰⁹Bi(p,p4n)²⁰⁵Bi 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 quasimonoenergetic 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 5th Framework EC Project HINDAS: *High and Intermediate Energy Nuclear Data for Accelerator* Driven Systems [28].

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INSTITUT FÜR KERNCHEMIE JOHANNES GUTENBERG-UNIVERSITÄT MAINZ

Measurement of Excitation Functions Relevant to the Production of the Positron Emitter ⁹⁰Nb via the ⁹⁰Zr(p,n)-Reaction

S. Busse^{1,2}, F. Rösch¹ and S. M. Qaim²

The radioisotope ⁹⁰Nb 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. ⁹⁰Nb was originally identified via (p,n) and (d,2n) reactions on ⁹⁰Zr. Highpurity ⁹⁰Nb was first obtained via the decay of ⁹⁰Mo [1]. For the production of ⁹⁰Nb today, several nuclear reactions seem to be reasonable: the (p,n)- or (d,2n)-processes on ⁹⁰Zr and the (³He,2n)- or (α ,3n)-reactions on natural yttrium. A medium-sized cyclotron would be able to produce ⁹⁰Nb via the (p,n)-, (d,2n)- or the (³He,2n)-process. In fact even a small-sized (≤ 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 (³He,2n)-process a ³He-energy of ≥ 30 MeV and the (α ,3n)-reaction an α -particle energy of ≥ 45 MeV [5]. Furthermore, the systematics of (³He,2n)- and (p,n)-reactions suggest that the production yield of ⁹⁰Nb 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 ⁹⁰Nb. 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 ⁹⁰Nb, 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 ⁹⁰Nb, the cross sections of ⁹⁰Zr(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 ⁹⁰ZrO₂ as targets. The results are shown in Fig. 1. Thick target yields of ⁹⁰Nb were calculated from the measured excitation functions and verified experimentally.

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Fig. 1 Excitation functions of ⁹⁰Zr(p,xn)-processes leading to the formation of ⁹⁰Nb, ^{89m}Nb and ⁸⁹Nb. The values for ⁹⁰Nb 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 ⁹⁰Nb via the ⁹⁰Zr(p,xn)-process was found to be $E_p=17\rightarrow7$ MeV, with a yield of 600 MBq ⁹⁰Nb/µA·h. The yield and radionuclidic purity of ⁹⁰Nb over the energy range of $E_p = 17.6\rightarrow8.1$ MeV were determined experimentally using ^{nat}Zr. At 4 h after EOB the yield of ⁹⁰Nb was found to be 290 MBq/µA·h and its purity \geq 95%.

The results of cross section measurements indicate that ⁹⁰Nb 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 ⁹⁰Zr at a small-sized cyclotron providing $E_{\rho} \le 16$ MeV. Sufficient quantities of ⁹⁰Nb 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.

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PHYSIKALISCH-TECHNISCHE BUNDESANSTALT BRAUNSCHWEIG

1. Measurement of the ²⁹Si(n,p)²⁹Al 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 $D(d,n)^3$ He 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 ²³⁸U fission chamber and is based on the ²³⁸U(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 ²⁹Al. 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 ²⁹Si (4.7%) and ³⁰Si (3.1%) could be obtained, although their abundances in the natural sample were rather small (main isotope ²⁸Si: 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 ²⁸Si₇: 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 Xichao¹

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 <Q> = -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 ¹⁷⁷Lu and ¹⁸⁸Re

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

The activity values for ¹⁷⁷Lu and ¹⁸⁸Re standard sources were measured using the $4\pi\beta$ - γ -coincidence method and by liquid scintillation counting. ¹⁸⁸Re is obtained carrier-free from a generator with the long-lived ¹⁸⁸W parent ($T_{1/2} = 69.4$ (5) d). ¹⁷⁷Lu and ¹⁸⁸W 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 ¹⁷⁷Lu

Energy	Radiation	p	p	$\alpha_T^{b)}$	$p_{ m \gamma+ce}$
in keV		this work	evaluation ^{a)}		this work
7.0	$Hf-L_{\ell}$	0.000734(24)	0.00053(6)		
7.9	$Hf-L_{\alpha;\eta}$	0.01505(27)	0.0130(10)		
9.0	Hf-L _{β1;3;4;6}	0.01333(24)	(0.0143(11)		
9.4	$Hf-L_{\beta 2,15}$	0.00273(6)	$\left\{ (\text{sum of } L_{\beta}) \right\}$		
10.5	$Hf-L_{\gamma 1; 6}$	0.00231(6)	∫ 0.00228(20)		
11.0	$Hf-L_{\gamma_{2;3}}$	0.000223(14)	l (sum of L_{γ})		
54.6	Hf-K _{α2}	0.01551(25)	0.0163(8)		
55.8	Hf-K _{a1}	0.0272(5)	0.0285(14)		
63.2	Hf-K _{β1}	0.00883(12)	0.0093(5)		
65.2	Hf-K _{β2}	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].

Energy	Radiation	p	р	p	$\alpha_{\rm T}^{\rm b)}$	$p_{\gamma+\infty}$
in keV		this work	Miyahara [6]	evaluation ^{a)}		this work
8.9	Os-L _{an}	0.0133(6)		0.0121(8)		
10.4	Os-L _β	0.0155(13)	-	0.0139(9)		
12.1	Os-L _y	0.00260(17)	-	0.00242(19)		
61.5	Os-K _{a2}	0.01397(17)	-	0.0134(5)		
63.0	Os-K _{a1}	0.0240(3)	-	0.0231(9)		
71.3	Os-K _{β1'}	0.00780(11)	-	0.0080(3)		
73.4	Os-K _{β2'}	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/		0.000347(4)	0.000364(10)	0.000310(10)		
1151.0	·.	0.0001024(24)	0.000107(0)			
11/4.0		0.0001924(24)	0.000197(8)	0.000185(8)	<u> </u>	
1191.9		0.0001498(13)	-	0.000131(5)		
1209.8		0.0000349(9)	-	0.0000293(22)		
1302.4/		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. Results of X- and gamma-ray emission probabilities p per disintegration of ¹⁸⁸Re

Table 2. continued

Energy	Radiation	р	р	р	$\alpha_{\rm T}^{\rm b)}$	$p_{ m \gamma+ce}$
in keV		this work	Miyahara [6]	evaluation ^{a)}		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 ¹⁸⁸Re, 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 ¹⁷⁷Lu and ¹⁸⁸Re 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].

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 <i>et al</i> . [20]
	17.021(25)	0.7092(10)	Unterweger et al. [21]
	17.0035(22)	0.70848(9)	this work

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

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APPENDIX

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