EANDC(OR) 99 "L"
INDC(SWD) 2/G

PROGRESS REPORT ON NUCLEAR DATA RESEARCH FROM SWEDEN

August 1970

Edited by H Condé

Research Institute of National Defense

S T O C K H O L M

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PREFACE

This progress report gives information about recent neutron cross section measurements and of activities closely related to this type of measurements at several institutions and universities in Sweden. The data given in the report are preliminary and may not be quoted without permission of the authors.

The index of the report has been changed since the progress report of 1969 (EANDC (OR)-83 "L") to hopefully give a better guidance to the different Swedish neutron cross section activities in progress. For the same reason the measurements are also listed according to the CINDA format. The institutions involved in an experiment are given under the heading of each report, while the experimental facilities i.e. the accelerator or experimental research reactor, where the measurements have been performed are given in an index on page 4.

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CINDA INDEX

Following the pattern set by the US WASH-reports, a CINDA-type index has been included in this progress report in order to help the casual reader localize material of particular interest to him. The index has been prepared from the usual CINDA entry cards, which have been passed through an editing programme giving a listing somewhat different from the publication format. Certain information, which is superfluous in the present context, has been suppressed, while other parts of the usual CINDA line have been expanded in order to improve legibility.

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FOR

EANDC(OR)99 "L"

PREPARED BY

L. WALLIN

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1. NEUTRON PHYSICS

1.1 DIFFERENTIAL NEUTRON CROSS SECTION MEASUREMENTS

1.11 Elastic and inelastic neutron scattering cross sections

1.111 Fast neutron elastic scattering at 8 MeV

B Holmqvist and T Wiedling, AB Atomenergi, Studsvik

The aim of the present neutron scattering study was to collect data for reactor physics application as well as to continue a study, being in progress for several years at this laboratory, of the spherical optical model.

Fast neutron elastic scattering angular distributions have been measured for 22 natural elements, ranging from Al to Bi, at 8 MeV neutron energy. Using time-of-flight techniques, differential scattering cross sections were measured in the angular interval 20° to 160° in steps of 10° except in the forward angular region, where 5° steps were used. The angular distributions were corrected for neutron attenuation in the sample, for neutron multiple scattering and for geometrical effects.

The experimental angular distributions are compared with distributions calculated using an optical potential with spherical symmetry. The potential parameters, i.e. the real and imaginary potential depths, the radii and the real diffuseness parameter have been calculated with an automatic parameter search routine. The remaining parameters, namely the imaginary diffuseness parameter and the spin-orbit potential depth were held constant throughout the calculations. The results of these investigations demonstrate that the experimental cross sections can be described satisfactorily in terms of the optical model. The geometrical parameters of the potential obtained by a best fit procedure show no marked variations with mass number. The real potential depth slowly decreases with mass number and neutron excess. This shows the existence of a potential term dependent upon isobaric spin. Its strength is 50 ± 10 MeV. The imaginary potential depth also decreases with mass number for values of the latter larger than about 55. Below this mass number the imaginary potential depth exhibits pronounced fluctuations.

Reports:

1. B Holmqvist, Arkiv Fysik 38, 403 (1968)
2. B Holmqvist and T Wiedling, AE -66 (1969)
3. B Holmqvist and T Wiedling, CN-26/55, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

1.112 Neutron elastic scattering cross sections of vanadium, chromium, iron and nickel

B Holmqvist and T Wiedling, AB Atomenergi, Studsvik

The elements V, Cr, Fe and Ni play an important role as alloying components in construction materials for nuclear power reactors. For this reason the fast neutron elastic scattering cross sections have been requested with a relatively high accuracy for energies from about 1 MeV up to 15 MeV.

Elastic scattering measurements of V, Cr, Fe and Ni have been made in the energy range 1.8 - 8.1 MeV. Between 1.8 and 3.0 MeV these measurements have been performed at intervals of about 0.25 MeV while between 3.0 and 8.1 MeV, the corresponding intervals were generally 0.5 MeV.

As is the case with all elastic scattering data collected in this laboratory, time-of-flight techniques have been employed. The differential scattering cross sections are standardized with respect to well-established n-p scattering cross sections.

The experimental differential and total elastic cross section data have been compared with results deduced from optical model calculations involving a spherical optical potential.

Although it is well known that the total cross sections of V, Cr, Fe and Ni show pronounced resonance structures at neutron energies below about 3 MeV, it has also been considered appropriate to analyse the measurements below 3 MeV in the light of the nuclear optical model. It is clearly advantageous for nuclear-reactor applications to have access to a standardized set of optical model parameters when performing cross section calculations at intermediate energies.

Reports: 1. B Holmqvist, Arkiv Fysik 38, 403 (1968)
2. B Holmqvist and T Wiedling, AE-366 (1969)
3. B Holmqvist, S G Johansson, G Lodin, M Salama and T Wiedling, AE-385 (1970)
4. B Holmqvist, S G Johansson, G Lodin and T Wiedling, Nucl Phys A146, 321 (1970)
5. B Holmqvist and T Wiedling, CN-26/53, 54, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

1.113 Fast neutron inelastic scattering in the energy range 2 to 4.5 MeV

E Almén, M A Etemad*, B Holmqvist and T Wiedling,
AB Atomenergi, Studsvik

A comprehensive investigation of fast neutron inelastic scattering is in progress for a number of elements whose cross sections have been requested for reactor physics calculations.

The inelastic scattering cross sections have been measured for 20 elements but the investigation of only six of them, i.e. Al, V, Mn, Fe, Nb and Bi has been completed up to now. The measurements were made in the energy region 2 to 4.50 MeV in steps of roughly 0.25 MeV. Time-of-flight techniques were used. The inelastic cross sections were determined relative to those established for the n-p reaction.

The experimental cross sections have been corrected for the effects of the neutron source anisotropy, attenuation of the neutron flux in the scatterer as well as for finite geometrical effects, using Monte Carlo techniques.

The experimental excitation functions are compared with those calculated with the Hauser-Feshbach formalism. The effects of level-width fluctuation have also been taken into account. Optical model parameters previously found in a systematic fast neutron elastic scattering investigation on the elements studied here have been used to obtain transmission coefficents for application in the Hauser-Feshbach calculations.

Report: E Almén, M A Etemad, B Holmqvist and T Wiedling, CN-26/56, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

*On leave from Tehran University Nuclear Center, Tehran, Iran

1.12 Gamma-ray production cross sections

1.121 Gamma-rays from inelastic scattering in nitrogen

H Condé, B Lundberg and L G Strömberg, Research Institute of National Defense, Stockholm

G Nyström, Department of Nuclear Physics, University of Lund, Lund

Differential gamma-ray production cross sections at 55^{o} of N has been measured at three different incident neutron energies between 4.5 and 7 MeV. The gamma-ray spectrometer was a 17 ccm Ge(Li)-detector. A time-of-flight technique was employed to supress the background caused by neutron interactions in the Ge(Li)-detector. The efficiency of the gamma-ray spectrometer was measured with calibrated gamma-ray sources and (p,γ)-reactions. The primary neutron flux was measured with a proton-recoil telescope. Gamma-ray lines of energies from 0.7 to 5.8 MeV were observed with pronounced lines at 0.730, 1.637, 2.315 and 5.104 MeV.

Measurements of the angular distribution of gamma-rays from $^{14}N(n,n'\gamma)^{14}N$ have been made.

The experimental arrangement was modified in order to reduce the running time: The detector volume was increased from 17 to 25.5 cm^3, the sample weight increased from 20 to 40 g and the neutron producing beam current was increased from 1.5 to 4.5 μA.

With these modifications better than 5% statistics in the prominent gamma-ray peaks at 0.73, 1.64, 2.3 and 5.104 MeV was obtained in 3 hours running time. With the arrangement it was possible to measure at angles between 37 and 142^{o}. The angular distribution at E_n = 7 MeV has been measur and the data handling is in progress.

1.122 Gamma-rays from inelastic neutron scattering in oxygen

H Condé, B Lundberg and I G Strömberg, Research Institute of National Defense, Stockholm

The cross section and angular distribution of the 6.13 MeV gamma-ray from inelastic neutron scattering in oxygen have been measured at several different incident neutron energies between 6.6 and 8.3 MeV. The measurement was made with a large NaI-crystal as the gamma-ray detector and with a good neutron energy resolution to study the gamma-rays from individual resonances. Data handling is in progress.

1.123 High resolution measurements of gamma-rays produced by 15 MeV neutrons

K Nyberg, B Jönsson and I Bergqvist, Department of Physics, University of Lund, Lund

Gamma-rays produced by 15 MeV neutron interaction in N, O, Mg, Al, Fe, Ni, Cu, Pb and Bi have been measured with a 7 mm Ge(Li) spectrometer. Differential gamma-ray production cross sections at 80° have been determined relative to the cross section for the 4.44 MeV gamma-ray line produced in ^{12}C $(n,n'\gamma)$.

Measurements have also been performed on the gamma-ray production in natural and radiogenic lead using a 31 cc Ge(Li) detector. The analysis yielding separated $(n,n'\gamma)$ and $(n,2n\gamma)$ isotopic cross sections is in progress.

Reports: 1. K Nyberg, B Jönsson and I Bergqvist, Lab.report NP 6902, Department of Physics, University of Lund, Sweden

2. B Jönsson, K Nyberg and I Bergqvist, Arkiv Fysik 39, 295 (1969)

1.13 Neutron capture cross sections

1.131 (n,γ)-cross section measurements

S Beshai, S Malmskog, B Holmqvist and T Wiedling,
AB Atomenergi, Studsvik

For fast reactor calculations it is of interest to know capture cross sections in the keV region accurately. Such cross sections have up to now mainly been accumulated using pulsed linear electron accelerators as neutron sources. The high energy bremsstrahlung will here via the (γ,n)-reaction, create neutrons well up in the MeV region which then have to be moderated to obtain a lower energy neutron spectrum.

An alternative way is to use a charged particle reaction to get a neutron beam of pre-determined energy. It is the intention to use this later method for (n,γ)-cross section measurements with a Van de Graaff accelerator as a neutron source. The produced gamma-rays are to be detected in a modified, more efficient Moxon-Rae detector where the detecting medium will be a liquid scintillator stored in a 0.14 m^3 cylindrical tank divided into 4 identical counter sections. By imposing different coincidence conditions each counter will have an efficiency proportional to the gamma-ray energy, making the detector system independent of the details of the level structure of the final nucleus. The experimental equipment is now being built up and the present status is as follows.

The main scintillation tank has been constructed. Its interior consisting of several concentric cylinders made from 0.5 mm Al sheet has been built and all surfaces have been painted with a reflective coating. The liquid scintillator (200 liter of NE 218) will be filled into the cylinder after proper vacuum tests. Eight XP 1040 photomultipliers together with appropriate light guides will be used, while the corresponding eight driving stages have been made. A preliminary block scheme of the full electric system has been set up and prototypes for a pre-amplifier, a summing circuit and a time-to-pulse-height converter are being built and tested. When the scintillation tank has been finally mounted it will be positioned into a boron-paraffin and lead shielding.

1.132 Neutron capture cross sections in F, Mg, Al, Si, P and S from 20 to 80 keV

I Bergqvist and G Nyström, Department of Physics, University of Lund, Lund

B Lundberg, Research Institute of National Defense, Stockholm

Neutron radiative capture cross sections have been measured in the energy region 20 to 80 keV using time-of-flight techniques with a 12.7 cm x 10.2 cm NaI(Tl) scintillator. The samples studied were natural samples of F, Mg, Al, Si, P and S. Radiative widths were determined for the resonances at 27 keV (1.4 ± 0.3 eV) and 50 keV (1.5 ± 0.3 eV) in ^{19}F, 84 keV (4.0 ± 0.9 eV) in ^{24}Mg and 35 keV (1.9 ± 0.3 eV) in ^{27}Al. Resonances were also observed at 45 keV in Mg, 38 keV and 68 keV in Si, 27 keV in P and at 30 keV and 42 keV in S.

Report: G Nyström, B Lundberg and I Bergqvist, Neutron capture cross sections in F, Mg, Al, Si, P and S from 20 to 80 keV, FOA report in print

1.14 (n,x)-cross sections

1.141 Studies of (n,p)-reactions

G Lodin and T Wiedling, AB Atomenergi, Studsvik

Neutron induced reactions giving charged particle reaction products like protons and alpha particles are of quite large importance in nuclear reactors with their long time integrated intense neutron flux, resulting in serious material destruction. These problems seem to be caused by the gas bubbles from the hydrogen and helium produced. However, at the present time there are rather few measurements of the (n,p)- and (n,α)-cross sections of reactor structural materials and at the neutron energies of interest, i.e. from the reaction thresholds up to some MeV. One reason is that the high monoenergetic neutron flux necessary to be able to perform accurate measurements is lacking in most laboratories.

Konijn and Lauber [1] used a surface barrier silicon detector to detect the protons from the Ni(n,p)-reaction, but in a rather inconvenient geometry. The technique applied consists of a modification of this technique in the respect that the detector has been placed in a shielded position in relation to the neutron source and that time-of-flight technique has been used in order to be able to ascribe the proton groups to the appropriate neutron energy. Measurements have been made on the $^{58}Ni(n,p)^{58}Co$ reaction at 3.65 MeV neutron energy. The proton spectrum showed a pronounced structure, the peaks of which may be identified with proton transitions in the $^{58}Ni(n,p)^{58}Co$ reaction. The usefulness of the time-of-flight technique was clearly demonstrated.

Report: G Lodin, Partial Differential Cross Sections of the $^{58}Ni(n,p)^{58}Co$ Reaction at 3.06 and 3.65 MeV Neutron Energies (in manuscript)

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[1] J Konijn and A Lauber, Nucl. Phys. 48 (1963) 191

1.2 INTEGRAL NEUTRON CROSS SECTION MEASUREMENTS

1.21 Fission product capture cross sections

1.211 Integral measurement of fission product capture cross sections in some fast reactor spectra

T L Andersson, AB Atomenergi, Studsvik

The reactivity worth per atom for a number of fission product isotopes relative to that of ^{235}U was measured in three various fast reactor spectra. The following isotopes were studied: ^{95}Mo, ^{97}Mo, ^{99}Tc, ^{101}Ru, ^{104}Ru, ^{103}Rh, ^{133}Cs, ^{147}Pm and ^{149}Sm. A fission product mock-up sample was also included in the measurements.

The reactivity worths were measured by the pile oscillator technique. The fundamental mode amplitude of the perturbation signal was obtained through Fourier analysis.

The experimental results are compared with calculated values obtained from perturbation calculations using published cross sections for the sample materials. From a comparison between the measured and the calculated reactivity worths it is concluded that only the ^{95}Mo and ^{104}Ru worths are well predicted in all the three systems. For the other samples the calculated values are generally too high.

Report: "Integral measurement of fission product reactivity worths, in some fast reactor spectra". CN-26/51
Presented at the Second International Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970

1.22 Neutron absorption cross sections of gross fission products

1.221 Redetermination of the thermal-neutron absorption cross sections of gross fission products of U-233, U-235 and Pu-239

A Okazaki, Atomic Energy of Canada Ltd, Chalk River, Canada
E K Sokolowski, AB Atomenergi, Studsvik

The thermal cross sections of the long-lived gross fission products from U-233, U-235 and Pu-239 fission have been determined by pile oscillator measurements on highly irradiated samples. The samples, consisting initially of a single fissile nuclide in a matrix of high-purity aluminum, had been irradiated to a depletion of 70-90%, which gave a fission product contribution to the total absorption cross section of about 10%. Measurements with these samples had previously been performed at AECL but have now been repeated under more favourable experimental conditions. The fission product cross sections have been determined with an accuracy of 5%. A comparison with a recent version of the calculational model FISSPROD shows that the calculated cross sections are consistently about 7% higher than the measured ones.

Report: "Redetermination of the thermal-neutron absorption cross sections of gross fission products of U-233, U-235 and Pu-239". CN-26/58
Presented at the Second International Conference on Nuclear Data for Reactors, Helsinki, 15-19 June 1970

1.3 GENERAL NEUTRON PHYSICS

1.31 Thermal neutron capture gamma-ray and electron spectroscopy

1.311 Measurements of conversion electrons and gamma-rays from (n_{th},γ)-reactions in the mass-region 150-190

A Bäcklin, B Fogelberg and E Falkström-Lund, Nuclear spectroscopy group, The Swedish Research Councils' Laboratory, Studsvik

The studies of even-even nuclei in the mass-region 150-190 by means of electron- and gamma-spectroscopy have continued at the R2 reactor, Studsvik. The following reaction are under investigation:

a $^{155}Gd(n_{th},\gamma)^{156}Gd$ and $^{157}Gd(n_{th},\gamma)^{158}Gd$

Electron spectra up to 2 MeV and gamma-ray spectra up to 8.5 MeV have been registered. About 500 transitions have been identified below 2 MeV. Efforts are continuing to construct the level schemes with the aid of gamma-gamma coincidence information. The project is a collaboration with groups at Risö, Denmark and Idaho Falls, USA.

b $^{177}Hf(n_{th},\gamma)^{178}Hf$

Electron spectra, gamma-ray spectra and gamma-gamma coincidences have been registered up to about 1.5 MeV using a $\pi\sqrt{2}$ electron spectrometer and Ge(Li) and Na(I) detectors. A large number of new levels have been identified, among these 5 members of the gamma vibrational band.

c $^{167}Er(n_{th},\gamma)^{168}Er$

The gamma-ray spectrum has been investigated up to 1.5 MeV using a Ge(Li) spectrometer in combination with a crystal monochromator. A large number of new transitions have been observed.

d $^{235}U(n_{th},\gamma)^{236}U$

Conversion electrons and gamma-rays have been observed in the region 0.5-1.5 MeV from the reaction $^{235}U(n_{th},\gamma)^{236}U$. Methods have been developed to make possible to sort out the capture transitions from the strong background activity from the fission products.

e $^{239}Pu(n,\gamma)^{240}Pu$

The conversion electron spectrum from the reaction $^{239}Pu(n,\gamma)^{240}Pu$ is being studied in the energy-region 30-1200 keV using the method of Report 5 in the reference list for discriminating between prompt electrons and electrons emitted by fission products.

f Level structure of ^{164}Dy and ^{165}Dy

J P Roalsvig, C Larsson and M S Alwash, Chalmers University of Technology, Gothenburg

Extensive studies of the reactions $^{163}Dy(n,\gamma)^{164}Dy$ and $^{164}Dy(n,\gamma)^{165}Dy$ using enriched dysprosium isotopes have been started.

Reports: 1. A Bäcklin, R Boleu and B Fogelberg, Gamma-rays in the 1 MeV region from the reaction $^{161}Dy(n,\gamma)^{162}Dy$, Arkiv Fysik 39 (1969) 221

2. H A Baader, H R Koch, D Breitig, O W B Schult, R C Greenwood, C W Reich, B Fogelberg and A Bäcklin, Investigation of the ^{155}Gd level scheme by thermal neutron capture, Report at the Neutron Capture Gamma-Ray Spectroscopy Conference, Studsvik 1969, Published by IAEA, Vienna 1969

3. A Bäcklin, B Fogelberg, G Hedin, M Saraceno, R C Greenwood, C W Reich, H R Koch, H A Baader, D Breitig and O W B Schult, Energy levels in ^{156}Gd, ibid. p. 147

4. B Fogelberg and A Bäcklin, A K=2^+ band in ^{178}Hf, ibid. p. 155

5. A Bäcklin, B Fogelberg and E Falkström-Lund, Conversion electrons and gamma-ray from neutron capture in ^{235}U, ibid. p. 141.

6. E Falkström-Lund and A Bäcklin, Study of the reaction $^{167}Er(n,\gamma)^{168}Er$, ibid. p. 351

7. A Bäcklin, A method for numerical construction of level schemes, Invited paper at the Conference on Radioactivity in Nuclear Spectroscopy, August 11-15, 1969, Vanderbilt University, Nashville.

1.312 Thermal neutron capture spectroscopy in the medium weight mass region

P H Blichert-Toft, S Boreving, L Broman, C Larsson and K C Tripathi, Chalmers University of Technology and the University of Gothenburg

The facility used for this purpose is set up at the Swedish R2 reactor. The gamma-rays from the source inside the reactor in a high neutron flux are collimated in a Sollen slit collimator and diffracted in a crystal. After passing a similar collimator the diffracted beam hit a Ge(Li)-detector by which the gamma-ray spectrum is registered. By this arrangement the Compton background and double-escape peaks due to lines beyond the diffraction region are to a very high degree reduced. This measuring method is especially suited for studying the energy region up to 2 à 3 MeV. For higher energies direct spectra were taken with the Ge(Li)-detector.

a Level structure of ^{29}Si, ^{30}Si and ^{31}Si

The structure of these nuclei is of special interest as they are situated within a region that has been subject for theoretical calculations and where therefore a comparison between theory and experiment is possible. The structure has been studied by means of the reactions $^{28}Si(n,\gamma)^{29}Si$, $^{29}Si(n,\gamma)^{30}Si$ and $^{30}Si(n,\gamma)^{31}Si$. Up till now highly purified natural silicon has been used. The investigations will be prosecuted by neutron capture studies on separated silicon isotopes. The energies of the capturing states have been determined to 8475.2 ± 0.5, 10612.3 ± 1.0 and 5591 ± 5 keV in ^{29}Si, ^{30}Si and ^{31}Si respectively. Energies and intensities have been measured for about 50 lines, most of them belonging to ^{29}Si. On the basis of these measurements level schemes have been constructed for the three isotopes.

b Level structure of ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{50}Ti and ^{51}Ti

The level structure particularly of the odd titanium isotopes are of interest from the point of view of Coulomb energy systematics. Detailed and precise measurements of the gamma-rays following thermal neutron capture in natural titanium have been performed and will be followed up by measurements on separated titanium isotopes. The neutron separation energies for ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{50}Ti and ^{51}Ti

were determined to 8873 ± 3, 11629 ± 2, 8143.3 ± 1.2, 10943 ± 2 and 6378.7 ± 1.0 keV respectively which all tally well with values derived from mass data. Energies and intensities for about 150 lines have been measured, most of which have been fitted in decay schemes. A detailed discussion of the level structure and a comparison with existing theories have been performed.

c Level structure of ^{36}Cl and ^{38}Cl

The structure has been studied by means of the reactions $^{35}Cl(n,\gamma)^{36}Cl$ and $^{37}Cl(n,\gamma)^{38}Cl$ using natural chlorine. These works will be completed with measurements on separated chlorine isotopes.

List of publications, 1969

1. P H Blichert-Toft and K C Tripathi, Neutron capture gamma-ray studies of silicon isotopes, Proceedings of the International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Studsvik, p. 173, 1969

2. K C Tripathi, P H Blichert-Toft and S Boreving, Thermal neutron capture gamma-ray studies of natural titanium, Proceedings of the International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Studsvik, p. 183, 1969.

1.313 Thermal neutron capture gamma-rays at the R1 reactor, Stockholm

S E Arnell, R Hardell, A Hasselgren, H Linusson, L Jonsson, E Selin, Ö Skeppstedt and E Wallander, Chalmers University of Technology, Gothenburg

The studies of gamma-ray spectra following thermal neutron capture have been continued at the 1 MW R1 reactor using internal reactor targets. The Ge(Li) detector has been operated in pair and anti-Compton spectrometer modes.

Reports: In Proc. of the Intern. Symp. on Neutron Capture Gamma-Ray Spectroscopy, Studsvik 1969, 199-255:

1. L Jonsson and R Hardell; Energies and intensities of gamma-rays from slow neutron capture in nitrogen
2. R Hardell, Gamma-rays from thermal neutron capture in ^{24}Mg
3. Ö Skeppstedt, Thermal neutron capture gamma-rays from ^{39}K and ^{41}K
4. S E Arnell, R Hardell, Ö Skeppstedt and E Wallander, Gamma-rays from thermal neutron capture in $^{40,42,43,44,48}Ca$
5. E Selin and R Hardell, Energy levels of ^{26}Mg studied with the (n,γ)-reaction, Nucl. Phys. A139 (1969) 375
6. E Selin and E Wallander, Thermal neutron capture gamma-rays from the $^{26}Mg(n,\gamma)^{27}Mg$-reaction, Nucl. Phys. (in press)
7. R Hardell and C Beer, Thermal neutron capture in natural argon, Physica Scripta (in press).

1.32 Fast neutron capture studies

1.321 Studies of fast neutron capture

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B Lundberg, Research Institute of National Defense, Stockholm

L Nilsson*, AB Atomenergi, Studsvik

To explain the magnitude of MeV nucleon capture cross sections in medium-weight and heavy nuclei, one is forced to take into account the influence of semi-direct capture processes through the giant dipole resonance. The interaction between the incident nucleon and the target nucleus may excite the latter to its giant dipole resonance while the incident nucleon is captured into a low-lying single-particle orbit. The decay of the giant dipole excitation gives a high-energy gamma-ray transition from the capturing state to a low-lying single-particle state. In a few cases it is possible to study gamma-ray decay to distinct single-particle states. In such cases the comparison with theoretical predictions becomes sufficiently simple to permit definite conclusions concerning the importance of semi-direct capture processes.

Gamma-ray spectra from neutron capture in the energy range 1 to 8.5 MeV were recorded for Si, P, S, Ni, ^{206}Pb and Bi using time-of-flight techniques. The gamma-ray detector is a NaI(Tl) scintillator, 20.8 cm long and 22.6 cm in diameter.

The results for Ni and Bi have been published previously. The cross sections for transitions to low-lying levels in ^{59}Ni and ^{61}Ni are reasonably well accounted for by the semi-direct capture theories, whereas for Bi the agreement is not equally convincing. The latter observation is supported by a similar study of the ^{206}Pb(n,γ)-reaction. The semi-direct capture theories account for only 10 to 20% of the cross sections at the peak of the giant dipole resonance for transitions to low-lying single-particle states in ^{207}Pb. The semi-direct capture theories predict an enhancement of the direct capture cross sections by a factor of 10 to 15 in the region of the giant dipole resonance. whereas the observed enhancement is about 50. On the

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other hand, the shapes of the gamma-ray spectra from neutron capture in ^{206}Pb in the MeV region are in agreement with those expected from the semi-direct capture theories.

For the nuclei in the 2s1d shell the analysis is not yet completed.

Report: I Bergqvist, B Lundberg and L Nilsson, Cross sections for high-energy gamma transitions from MeV neutron capture in ^{206}Pb, AB Atomenergi report AE-388 and to be published in Nuclear Physics

1.322 Gamma-rays from neutron capture in Mg, Si, P and S

I Bergqvist, Department of Physics, University of Lund, Lund

B Lundberg, Research Institute of National Defense, Stockholm

The gamma-ray spectra from neutron resonance capture in Mg, Si, P and S (natural samples) in the energy range 10-75 keV have been recorded. The gamma-ray spectrometer was a NaI(Tl) crystal, 20.8 cm long and 22.6 cm in diameter. Time-of-flight techniques were used. The gamma-ray spectra were found to be dominated by a few intense gamma-ray lines through low-lying levels in agreement with previous observations. Branching ratios were calculated for the dominating primary lines.

Report: I Bergqvist and B Lundberg, Gamma-rays from neutron capture in Mg, Si, P and S, FOA report in print

1.323 Studies of (d,pγ)-reactions

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L Nilsson*, AB Atomenergi, Studsvik

With the aim to achieve an understanding of the neutron capture mechanism in nuclei with mass numbers around 60, (d,pγ)-reactions have been studied in $^{58,60}Ni$ and $^{63,65}Cu$ at 5.5 MeV deuteron energy. The gamma-rays were detected by a NaI(Tl) scintillator, 12.7 cm in diameter and 10.2 cm long, and the protons by a silicon surface-barrier detector of high resistivity. With the use of two-parameter multichannel analysis it was possible to record simultaneously the gamma-ray spectra from several excitation energy regions populated by neutron transfer, in particular those below the neutron binding energies. The gamma-ray spectra from excitation energy regions not too far below the neutron separation energy show strong-intensity high-energy gamma-rays. The shapes of the spectra are similar to those obtained in (n,γ)-reactions and disagree with those expected from the theory of the compound-nucleus capture process. A report on the experiment has been published previously.

The (d,pγ)-studies are being extended to chromium and iron isotopes and also to the A=90 mass region. Selfsupporting targets of natural iron (91.66% ^{56}Fe), natural chromium (83,76% ^{52}Cr) and yttrium (100% ^{89}Y) have been delivered and enriched ^{54}Fe targets are being prepared. Preliminary experiments on natural iron and yttrium have been performed. In a recent two-parameter (d,pγ)-experiment at 5.0 MeV deuteron energy on natural iron, gamma-ray spectra were recorded by a large NaI(Tl) scintillator, 22.6 cm in diameter and 20.8 cm long. The analysis of these data is in progress.

This experiment will be moved to the Tandem Accelerator Laboratory in Uppsala, where it will become possible to investigate a larger mass region. Furthermore, it is planned to use a Ge(Li) detector as a gamma-ray spectrometer.

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1.4 THEORETICAL STUDIES

1.41 Compound nucleus calculations of low-energy neutron reaction cross sections using level densities from exact counting of shell model states

J R Eriksson, AB Atomenergi, Studsvik

The proton and alpha-particle production in neutron chain reactors appears to be a most important long-term property leading to brittleness in supporting materials. Since the (n,p) and (n,α) cross sections are difficult to measure it is of interest to treat these processes theoretically.

The prediction of the energy dependent (n,p) and (n,α) cross sections from the compound nucleus model is usually based on the assumption that the level density of the residual nucleus is of the Fermi-gas form $\rho_{FG}(E,I)$, where E is the nuclear excitation energy and I is the spin. With this assumption the integral mean of the (n,p) (or(n,α)) production cross section $\langle\sigma_{n,p}\rangle_{\Phi}$ over a thermal reactor neutron flux distribution $\Phi(E)$ shows that the most important part of the level density is the residual excitation below 5 MeV.

The level density $\rho(E,I)$ is calculated at low excitation energies E by the method of exact counting of the spherical model states. The single-particle shell model levels are subject to a modified BCS calculation after which the quasi-particle states obtained are used as input in a level counting program giving the level density $\rho(E,I)$. The resulting $\rho(E,I)$ shows pronounced effects arising from the specific neutron and proton single-particle level schemes up to energies above 10 MeV. Despite this low-energy picture and the overall scatter of the values of $\rho(E,I)$ an adequate $\rho_{FG}(E,I)$ can always be obtained at higher energies. It turns out that except for a few cases the Fermi-gas ground state lies above the ground state of the model nucleus indicating that $\rho_{FG}(E,I)$ tends to underestimate the low energy level density.

Reports: J R Eriksson, CN-26/52, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

2. FISSION PHYSICS

2.11 Average number of fission neutrons ($\bar{\nu}$)

2.111 Prompt $\bar{\nu}$ in fast neutron fission of ^{236}U

M Holmberg and H Condé, Research Institute of National Defense, Stockholm

The average number of prompt neutrons per fission, $\bar{\nu}$, for the neutron induced fission of ^{236}U has been measured in the energy region 0.8-6.5 MeV. The experimental values are well fitted by a linear energy dependence.

A least square fit gave the result

$$\bar{\nu}\ (E_n) = 2.40 + 0.14\ E_n.$$

Within 5% the $\bar{\nu}$-values for ^{233}U, ^{235}U, ^{236}U and ^{238}U are in the energy region 1-6 MeV fitted to the same straight line, which indicates that the atomic number Z is the critical parameter, since the $\bar{\nu}$-values for other elements, e.g. Pu and Th, are quite different.

Report: M Holmberg and H Condé, Prompt $\bar{\nu}$ in spontaneous and neutron induced fission of ^{236}U and the half-life for spontaneous fission, FOA report to be published

2.112 $\bar{\nu}$ of ^{235}U and ^{239}Pu in a fast reactor spectrum

H Condé and L Widén, Research Institute of National Defense, Stockholm

The average number of prompt neutrons per ^{235}U and ^{239}Pu fission are being measured at the fast zero power reactor (FRO) at Studsvik, Sweden. Special attention is paid to the fission resonance region where earlier measurements with good energy resolution have given different $\bar{\nu}$-values for different groups of resonances. As fission neutron detector is used a large liquid scintillator. The reactor neutron energy spectrum is measured in separate time-of-flight and proton-recoil detector experiments.

A preliminary measurement was made with a critical reactor and the $\bar{\nu}$-values were corrected for fissions induced by neutrons above about 70 keV by use of a theoretical 34 group reactor spectrum.

The obtained $\bar{\nu}$-values in the energy region 0-70 keV were 6.7 and 0.3 per cent below the corresponding thermal values for ^{239}Pu and ^{235}U, respectively.

A time-of-flight measurement of the energy spectrum is in progress as well as $\bar{\nu}$-measurement where the fissions induced by neutrons above about 100 keV energy will be eliminated by a time-of-flight arrangement.

Report: H Condé and L Widén, $\bar{\nu}$ of ^{235}U and ^{239}Pu in a fast reactor spectrum, CN-26/ 59, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

2.12 Fission neutron spectrum measurements

2.121 Neutron energy spectra from neutron induced fission of ^{238}U at 1.35 and 2.02 MeV

E Almén, B Holmqvist and T Wiedling, AB Atomenergi, Studsvik

The shapes of fission neutron spectra are of interest for power reactor calculations. Recently it has been suggested that the neutron induced fission spectrum of ^{235}U should be harder than was earlier assumed. For this reason measurements of the neutron spectra of some fissile isotopes are in progress at our laboratory.

The measurements were performed at incident neutron energies of 1.35 and 2.02 MeV using time-of-flight techniques. The time-of-flight spectra were analysed only above the position of the neutron elastic scattering peaks. Corrections for neutron attenuation in the uranium sample were calculated using a Monte Carlo program.

The corrected fission neutron spectra were fitted to Maxwellian temperature distributions. A temperature of 1.29 ± 0.03 MeV was obtained at 1.35 MeV incident neutron energy compared with 1.29 ± 0.02 MeV at 2.02 MeV. These values are consistent with previous results of ^{238}U. There are thus no indications that the ^{238}U fission spectra do not follow the generally observed temperature trend, at least within the energy region considered in this investigation.

Reports: E Almén, B Holmqvist and T Wiedling, CN-26/57, Contribution to the International Conference on Nuclear Data for Reactors, Helsinki, Finland, 15-19 June, 1970

2.2 GENERAL FISSION PHYSICS

2.21 Fission threshold studies

2.211 Studies of the fission threshold structure for ^{232}Th, ^{231}Pa and ^{227}Ac

M Holmberg and L-E Persson, Research Institute of National Defense, Stockholm

Measurements of the fission cross section and of the angular distributions of the fission fragments have been started for ^{232}Th and measurements are in progress for ^{227}Ac and ^{231}Pa. The "Makrofol" technique is used in the measurements of the angular distributions.

2.22 Fission gamma-ray studies

2.221 Prompt gamma radiation from fission fragments

H Albinsson, Chalmers University of Technology, Gothenburg

The prompt gamma radiation, emitted from fission fragments in slow neutron induced fission of ^{235}U, was studied as a function of fragment mass and time after fission. A gamma detector, a NaI scintillator, was placed about 70 cm from the fission foil in order to get time discrimination between the fission gammas and the prompt neutrons released in the fission process. The gamma radiation emitted in different time intervals after the fission events was studied by changing the position of a collimator along the path of the fission fragments. In this way it was possible to get estimates of the life times of the gamma-emitting states.

Time-of-flight spectra were accumulated with different collimator settings and the intensity variation of the gamma peaks was a measure of the intensity as a function of the time intervals after fission which were studied. Three main decay components have been found so far, having tentative half-lives of 7, 20 and 50 ps.

In some of the measurements the time-of-flight spectra were accumulated as a function of gamma-ray energy. The energy region was mostly from 100 to 2000 keV. In the prompt gamma radiation there are very few photons with energies about or less than 100 keV and above 2 MeV.

Gamma-ray energy spectra as a function of fragment mass have been recorded for which the collimator settings were chosen to select as much as possible of the three respective decays mentioned above. With the collimator set so that most of the fission gamma radiation consisted of the 7 ps component, the gamma-ray spectra looked very similar for all masses, with a broad bump around 1200 keV. With the collimator placed to let through photons with a half-life of mostly 20 ps, there were some differences in the gamma spectra, but not much. Most of them had a bump around 700 keV. When the 50 ps component was enhanced, however, clear differences appeared between the gamma spectra. Spectra from fragments with mass numbers around 110 and above 150 had distinct peaks with energies around 250 keV, and spectra from fragments with mass numbers around 82 and 132 had bumps around 250 and 1200 keV.

The connection between half-life and gamma-ray energy is a good indication that we are dealing with collective quadrupole radiation in the prompt gamma decays.

Two reactor periods, each of almost three weeks, have been devoted to the study of gamma-ray energy spectra as functions of the sum of the fragment kinetic energies. This type of measurement must be considered as preliminary as the variation with fragment mass is not included. The first measurement was done without the lead collimator, so all prompt gamma radiation within about 2 ns was recorded. The yield of the number of photons with energies less than about 2 MeV as a function of the total kinetic energy is a smooth function, decreasing slowly with total kinetic energy. The general trend of the yield curve does not change when more limited gamma energy regions are studied. The second measurement was done with the collimator placed so it just "shadowed" the foil and the very first gamma radiation, but let through the main part of the prompt gamma radiation. The yield of the number of photons with energies less than about 2 MeV as a function of the total kinetic energy was very similar to the first case.

Reports: 1. H Albinsson and L Lindow, Prompt Gamma Radiation from Fragments in the Thermal Fission of ^{235}U, AE-398 (1970)

2. H Albinsson, Prompt Gamma Radiation in Slow-neutron induced Fission of ^{235}U in Coincidence with the total Fragment Kinetic Energy, AE-FN-10 (1970)

3. SPECIAL TOPICS

3.1 STUDIES OF (d,n)-REACTIONS

3.11 The $^{16}O(d,n)^{17}F$-reaction

G Lodin*and L Nilsson**, AB Atomenergi, Studsvik

The $^{16}O(d,n)^{17}F$ transitions to the ground state and to the first excited state have been studied in the deuteron energy range 2.5 - 5.5 MeV. Time-of-flight techniques and gas target have been used. Differential cross sections in the angular range 0 - 160^{o} at deuteron energies from 3.0 to 5.5 MeV in steps of 0.5 MeV have been recorded as well as yield curves at 0^{o} and 30^{o} from 2.5 to 5.5 MeV in steps of 100 keV. The total uncertainty in the absolute cross section determination is estimated to 11%. DWBA calculations using seven different deuteron optical potentials have been performed. It is found that the spectroscopic factors depend strongly on the deuteron optical potential parameter set. Also the ratio between the spectroscopic factors for the transitions to the ground state and to the first excited state is sensitive to this parameter set. The most straightforward choice of deuteron optical potential gives the ratio 1.4 between these spectroscopic factors. This result disagrees with those obtained in stripping and pick-up experiments at higher energies and is also unexpected from theoretical predictions.

Report: G Lodin and L Nilsson, The $^{16}O(d,n)^{17}F$-reaction at deuteron energies from 2.5 to 5.5 MeV, Zeitschrift für Physik, 233 (1970) 181

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3.12 The $^{50}Cr(d,n)^{51}Mn$ and $^{54}Fe(d,n)^{55}Co$ reactions

L Nilsson*, AB Atomenergi, Studsvik

B Erlandsson, Department of Physics, University of Lund, Lund

The $^{50}Cr(d,n)^{51}Mn$ and $^{54}Fe(d,n)^{55}Co$ reactions have been studied at an incident deuteron energy of 5.5 MeV. Angular distributions of neutron groups to a number of low-lying levels in the residual nuclei have been recorded. Time-of-flight techniques have been used to record neutron spectra. A liquid scintillator with pulse-shape discrimination property has been used as neutron detector. DWBA calculations have been performed and relative spectroscopic strengths determined for transitions with various l_p values. The ratios between spectroscopic strengths for $l_p = 3$ and $l_p = 1$ transitions were found to be considerably larger than corresponding ratios obtained from the $(^3He,d)$ reactions. Twostep stripping processes competing with the direct stripping process are suggested as explanation of the discrepancy between the (d,n) and the $(^3He,d)$ results.

Report: L Nilsson and B Erlandsson, A study of the $^{50}Cr(d,n)^{51}Mn$ and $^{54}Fe(d,n)^{55}Co$ reactions, Zeitschrift für Physik 232 (1970) 303

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3.13 (d,nγ)-reactions in 2s1d shell nuclei

L Nilsson*, AB Atomenergi, Studsvik

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A method has been developed for recording coincidences between neutrons and gamma-rays produced in (d,nγ) reactions. Neutron energies were measured by time-of-flight techniques and a large NaI(Tl) crystal was used to determine gamma-ray energies and intensities. The neutron detector was placed in the forward direction to emphasize the excitation of $l_p = 0$ levels in the residual nuclei. The method was applied to the $^{27}Al(d,n\gamma)^{28}Si$ and $^{31}P(d,n\gamma)^{32}S$ reactions at the deuteron energy 4.0 MeV. The gamma-ray decay of a number of levels below 12 MeV in ^{28}Si and below 9 MeV in ^{32}S was studied. The isobaric analogue levels are prominently populated by the (d,n)-reaction. The method is in particular suitable for studies of the decay of these levels.

The limited energy resolution of the NaI(Tl) detector does not permit unambiguous assignments of gamma-ray transitions in several cases. In these cases it is desired to use a Ge(Li) detector as a gamma-ray spectrometer. In a recent $^{27}Al(d,n\gamma)$ experiment a 30 cc Ge(Li) detector was used and the distance between the target and the neutron detector was reduced from 3 m to about 1 m. The analysis of the data is in progress.

Report: L Nilsson, A Nilsson and I Bergqvist, The decay of bound isobaric analogue states in ^{28}Si and ^{32}S using (d,nγ) reactions, AB Atomenergi report AE-386 and to be published in Physics Scripta

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4. ACCELERATOR PHYSICS

4.1 VAN DE GRAAFF ACCELERATOR, AB ATOMENERGI, STUDSVIK

P Tykesson, AB Atomenergi, Studsvik

During the period October 1, 1968 - September 30, 1969 the van de Graaff accelerator has been used with protons, deuterons and helium ions, both with DC beams and pulsed beams. The accelerator was run in alternately two and three shifts for 5 days per week and the calculated total time available for experiments was 3336 hours 3224 hours of which were used by the scientists and 112 hours were required for unforeseen maintenance.

The distribution of the available machine time for experiments with the accelerator performed by physicists from various institutions is shown in Table I and of different experimental branches in Table II.

Table I

AB Atomenergi	77.7%
Research Institute of National Defense (FOA)	11.9%
Chalmers University of Technology	8.9%
University of Aarhus, Denmark	1.5%

Table II

Nuclear physics	17.2%
Neutron physics	67.8%
Solid state physics	13.9%
Irradiations	1.1%

The number of normal breaks for maintenance of the machine have been four during the year, each generally consisting of one week. The accelerator has been equipped with the klystron bunching system for about one and a half year and the system has been working under ordinary working conditions for about 3000 hours. It has proved the expected performance with regard to ion beam intensity and time compression. At the beginning there were some problems caused by metallic contamination of the insulators of the bunching tube, but after shielding the bunching system has proved very good reliable.

Report: P Tykesson and T Wiedling, A Klystron Bunching System for a 6 MV van de Graaff Accelerator, Nucl. Instr. and Meth. 77 (1970) 277

4.2 TANDEM ACCELERATOR LABORATORY, UNIVERSITY OF UPPSALA, UPPSALA

A Johansson, University of Uppsala, Uppsala

A 12 MeV EN-tandem van de Graaff accelerator is being installed at a national laboratory in Uppsala. The machine is planned to be used for experimental research from September 1970. In the target area nine beamtubes will be available for different experiments. The laboratory will have a small computer (PDP 15/30) to be used for on line experiments.

In the end of 1970 a klystron bunching system of the Ortec design will be installed. It will be possible to produce contineous as well pulsed beams of protons, deutrons, ^{3}He- and ^{4}He-ions with a pulswidth down to about 1 nanosecond.