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INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

INTERNATIONAL PARTICIPATION IN EXPERIMENTS USING UNDERGROUND NUCLEAR EXPLOSIONS

edited by
Charles Dunford

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IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

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I. INTRODUCTION

At the Fourth Meeting of the International Nuclear Data Committee held in Bombay in July 1971, Kolstad reported that a plan was being discussed in the USAEC whereby scientists from outside the United States would be invited to participate in experiments using a nuclear explosion as a neutron source. The explosion would be sponsored by the AEC's Division of Peaceful Nuclear Explosions and is provisionally scheduled for sometime in 1975. Types of experiments to be considered for inclusion by the USAEC are neutron physics experiments, heavy element production, geophysical and seismological investigations. This document concerns only proposed neutron physics experiments.

Members of the INDC were asked to submit proposals for neutron physics experiments to the INDC Secretariat so that the proposals could be assembled and submitted to the Fifth Meeting of the INDC to be held in July 1972 in Vienna.

II. BACKGROUND

The Plowshare programme for Peaceful Application of Nuclear Explosions was initiated in 1957. Its original intent was the development of engineering application of nuclear explosions. In addition, the radioactive fallout could be used as a meteorological tracer and the explosion as a point energy source for seismological investigations. This last application has been the most productive to date. As early as 1952 when the heavy elements einsteinium and fermium were discovered in the debris of a thermonuclear explosion, heavy element production has been carried out with nuclear explosives. However no isotope heavier than ^{257}Fm has been produced by this means.

In 1958, the first use of an atmospheric nuclear explosion in carrying out a nuclear physics experiment was made by Cowan and others from Los Alamos Scientific Laboratory. Their experiment used a hydrogenous moderator, time of flight, and a rapidly spinning wheel of ^{235}U. The spinning wheel translated time resolution of the source neutrons to a space resolution. The objective of this experiment was to investigate fission product asymmetry in ^{235}U by a radiochemical analysis of sectors of the wheel. Later in 1963, an above-the-atmosphere nuclear explosion was used for the measurement of ^{233}U fission cross section. In this case the detector system was launched in a second rocket such that the flight path was a few hundred kilometers of empty space.

With the advent of the 1963 Test Ban Treaty came the impetus to utilize underground explosions as a neutron source for nuclear physics measurements. Now there was an automatic shield provided by the surrounding earth which prevented backscattering into the primary neutron beam. Work was started to solve the many technological problems associated with the new experimental technique. These included generation of a line of sight to a safe experimental area at the ground surface, prevention of radioactive debris from reaching the experiments, the generation of the desired neutron spectrum, and the recording of numerous events in the detectors.

Four underground nuclear explosions have been used to date for nuclear physics purposes. The first was the PETREL event in 1965. This event was designed to test the experimental technique developed. Fission cross sections for ^{233}U, ^{235}U, and ^{239}Pu were measured in order to compare with results obtained with conventional techniques. The comparison showed very good agreement. Results for the fission cross section of ^{241}Am, ^{242}Am, and ^{241}Pu were obtained with better resolution than obtained with conventional techniques. Many small p-wave capture resonances were observed in ^{238}U.

The PERSIMMON event of 1967 contained experiments which should be called exploratory. An intensive study of the background was made and new techniques were tested. In particular targets of high radioactivity were used. The measurements included ^{238}Pu, and ^{244}Cm fission cross sections and ^{238}Pu and ^{143}Pm capture. This test shot was followed by POMMARD in 1968 wherein cross sections for many radioactive materials were measured. The targets included one of 18 μgram ^{237}U. The fission cross sections for six uranium isotopes (232,233,234,235,236, and 237) were measured.

The most recent nuclear explosion for nuclear physics experiments was the PHYSICS-8 test in 1969. It contained the most extensive set of experiments of any previous event. One major goal was an investigation of fission systematics. There were targets for six curium isotopes, two californium isotopes, ^{249}Bk, ^{253}Es and several others. Capture cross sections for ^{232}Th, ^{235}U, ^{239}Pu and Cm (244 and 246) were measured. In addition the first attempt was made to measure simultaneously the total, scattering, capture and fission cross sections of ^{239}Pu.

Use of a nuclear explosion as the neutron source has several advantages over conventional neutron sources. These advantages are based chiefly on the intense source strength ($\sim 10^{31}$ neutrons/sec or 10^{24} neutrons). Thus the neutron induced reactions to be studied can easily overpower sample produced backgrounds, e.g. α-pile up. Very small samples ($\sim 10\,\mu$ grams) can be utilized effectively. Because of the short time to complete the experiment, short half life nuclides can be used as targets; even shorter if the target can be produced at the test site. Finally, inherently improbable processes can be measured because of the high neutron flux.

One of the inherent disadvantages in the use of a nuclear explosive neutron source is the necessity of electronic current recording instead of single events due to the high reaction rates. Also detectors must be sensitive only to the reaction being studied. Finally, there is a long delay between experiments so that everything must work properly to the full time.

In summary, the criteria for selection of experiments for inclusion in a nuclear explosion programme should be

1) High sample radioactivity
2) Sample with short half life
3) Small quantity of sample
4) Highly inefficient nuclear process
5) No high precision required (5-10%)
6) No need to repeat with only small improvements

The foregoing discussion has been abstracted from a review article by Diven[1/]. A more detailed discussion, particularly of the physical characteristics of such experiments can be found in that paper preprints of which have been distributed to INDC Members.

III. COSTS

Attached to this document in Annex I is the letter from TASCHEK outlining the various cost factors for an experiment in the proposed nuclear explosion. The following is a brief abstract of that discussion.

The USAEC will pay the cost of the explosion and there will be no assessment for installed apparatus. There may also be help and collaboration with LASL scientists. An experiment of average difficulty is estimated to cost the participant about 2 man-years of effort. This cost includes experiment design, sample preparation and data analyses. Hardware costs are additional and dependent on the experiment; so these costs are best known to the experimenter himself. Several data recording techniques have been worked out by LASL and therefore sufficient recording equipment is probably available for all experiments. Also there would probably be adequate support and service facilities in trailers at the test site for all experiments.

IV. SUMMARY OF RESPONSE TO DATE

1. Japan (Nishimura)

Telegram stating letter with comments to follow. No letter has yet been received.

2. France (Joly)

No interest at present.

3. Mol (Van Assche)

Measurement of fission product yield asymetry for U^{235} using the spinning wheel technique.

This experiment would be a further development of their previous experiment which measured the epithermal to thermal yield ratio for about 30 fission products.[2/] The object would be to measure the yield of 30 fission products in individual U^{235} fission resonances. Their previous experiment suggests that ^{99}Mo yield may not be independent of energy and so many products should be analyzed to determine the ratio of asymetric to symetric fission. The full proposal is included in Annex II.

As a result of this experiment one would hope to use the shape of fission product yield curves to assign spin quantum numbers to the individual resonances. A test of the constancy of the ^{99}Mo yield would be made and possible corrections to previously measured symetric and asymetric fission ratios could be generated.

4. Mol (Ceulemans)

Neutron cross section measurements on ^{226}Ra and ^{227}Ac.

These two nuclides have a short half life, high activity and limited availability common to the unexplored mass region from A = 210 to A = 229. In the interest of both nuclear structure and heavy element synthesis it would be of considerable interest to measure total and partial cross sections for these two nuclides representative of this unexplored mass region.

The handling and measurement techniques for these nuclides are being developed in a series of measurements currently underway for energies less than 50 eV. They propose using two targets of ^{226}Ra for transmission experiments and possibly one other for capture. Hopefully one sample of ^{227}Ac could be used for both transmission and capture. This proposal is given in Annex III.

5. Mol and Geel (Deruytter et al)

Measurement of the ratio of ternary binary fission.$^{(T/B)}$

The aim of the experiment would be to expand the energy range and nuclide range of measured (T/B) ratios. This includes investigation of energy variation and resonance correlation of that dependence. Target would be ^{235}U, ^{233}U, ^{239}Pu, and ^{241}Pu. The details of this proposal are given in Annex IV.

6. Geel-Mol (Theobald et al)

Resonance parameters for fission product nuclei.

Several nuclides, important in calculations are either radioactive or have short half lives. Among them are ^{93}Zr, ^{99}Tc, ^{101}Ru, ^{107}Pd, ^{135}Cs, ^{147}Nd, ^{147}Pm, ^{151}Sm. A few of these could be measured in a bomb shot experiment. Some of the experimental techniques mentioned in the proposal require further testing on the CBNM linac. This proposal is contained in Annex V.

7. Geel-Mol (Theobald et al)

Fission barrier parameter systematics.

Fission cross section data for isotopes with $88 \leq Z \leq 91$ are very scanty. In order to investigate the systematics of fission for this region targets of ^{231}Pu, ^{228}Th, ^{232}Th, ^{227}Ac and ^{226}Ra are suggested. It is this region in which shell effects are expected to be minimized. There is also interest in measuring (n,γ) and (n,n) for these nuclides. Annex VI contains this proposal in full as well as a supporting document on data analysis methods.

8. Yugoslavia (Slaus)

Measurement of the neutron-neutron cross section using nuclear explosions.

Critical evaluation of neutron-neutron experiments demonstrates that there is currently an uncertainty of 20% in the neutron scattering length and 50% in the effective range. Underground nuclear explosion experiments are expected to improve this situation considerably. The proposal will be found in Annex VII.

References

1/ B.C. Diven, "Nuclear Explosions as a Nuclear Physics Tool", Ann.Rev.Nuc.Sc. 20 (1970), pp. 79-109.

2/ P. Popa, M. De Coster and P.H.M. Van Assche, NSE 39 (1970), pp. 50-55.

Annex I

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : Members of INDC

DATE: August 31, 1971

FROM : R. F. Taschek

SUBJECT: COSTS OF DOING NEUTRON PHYSICS EXPERIMENTS ON AN UNDERGROUND NUCLEAR DETONATION. ACTION 7

SYMBOL : ADR

The possibility of doing neutron physics experiments on "open" underground nuclear detonations raises the question of costs to experimenters who might be interested in participating in such a program.

Although no precise answer can be given to this still very general question, enough experience has been developed in previous physics shots so that a reasonably good guide has been developed by Ben Diven who has been in charge of part of this program. In what follows most of the costs have been converted to scientific man years which need to be applied since the monetary costs in the various countries cannot really be normalized. It is assumed for want of other information that there will be no assessed costs for the nuclear explosive and installed apparatus; namely this will be done much like an outside "user" participating in an approved experiment at a large accelerator. Similarly there may be guidance, service help, and collaboration with LASL scientists. The comments below are mostly Diven's:

The cost of doing an experiment with a nuclear explosive is high. Most experiments that are worth doing are very difficult ones and use exotic samples that may require some degree of remote handling and care in radiation safety practices. Measurements extend over many decades in neutron energy and proper analysis of the data may require extensive computation. It is felt that for the kind of experiments done so far a minimum effort for any experimental group would be about two man years.

The effort required to do a cross-section experiment on a nuclear explosion will be estimated in two ways. One is based on LASL experience on Shot 8 and the other on U.K. experience on Pommard.

Certain detailed information on Physics 8 is available. The equivalent of 12 scientific staff participants in two groups at the LASL worked two years in preparation for the shot and in the data analysis which followed. This 24 man-year effort produced 24 experiments, of which most have been published or are in preparation for publication. The experiments were:

Fission

^{243}Am

^{249}Bk

$^{249,252}Cf$

$^{243,244,245,246,247,248}Cm$

^{253}Es

^{237}Np

$^{239,242,244}Pu$

$^{234,236,238}U$

Capture

^{197}Au

^{238}U

$^{244,246}Cm$

^{239}Pu

Other: Neutron polarization by transmission through LMN polarized proton crystal at 1°K.

Next, consider the U.K. experiments on Pommard. They performed four very complex experiments. Two of their measurements were capture-to-fission ratios (^{239}Pu and ^{241}Pu) and one was the (n,p) cross section of ^{7}Be which provided a difficult sample problem. They used five physicist man years and three electronics technician man years. It would probably have been wiser for them to have done somewhat easier experiments for their early try and to have relied on LASL equipment design rather than develop all of their own in which case their manpower requirements would have been considerably reduced.

From the above, a good estimate would indicate that two staff member years per experiment may be a reasonable effort for an average cross-section measurement with a nuclear explosion. If the sample is very difficult to prepare and handle, the cost would be correspondingly higher.

The possibility of requests for trivial experiments exists. People with certain special interests may wish to "put a mouse in the beam." Possibly some useful, but near-zero-effort experiments would be suggested. One example might be calibration of threshold detectors in a well-known flux. One should probably expect some such experiments and, if kept within reason, they should be permitted.

In the discussion above there is no specific reference to hardware costs, primarily because these will vary from experiment to experiment and will be best known by the experimenter himself. It seems likely that the method of data recording, whether by fast photography of oscilloscope traces or recording on magnetic disks, have already been worked out by LASL and there is probably enough such apparatus available for as many experiments as can be done at any one time. Likewise there may be enough support and service facilities housed in trailers available for nearly all possible programs. If specific experiments are proposed the LASL staff can help in establishing what is needed.

Action 8 -- A selected list of reports giving results of previous neutron experiments underground nuclear detonations is being sent to you.

R. F. Taschek

R. F. Taschek
Assistant Director for Research

Annex II

P. VAN ASSCHE
Neutron Physics Department
S.C.K./C.E.N.
Mol

Mol, November 17, 1971

Proposal for Fission Physics Experiment using an Underground Nuclear Explosion as Neutron Source.

1. Description of the proposed experiment.

The symmetry of neutron induced fission in ^{235}U has been measured radio-chemically by the ratio of ^{115}Cd to ^{99}Mo with the "wheel" experiment of Cowan et al.[1] However, this information is very fragmentary, in the sense that it only gives a very rough indication on mass-yield changes. We propose to extend this study by measuring the relative fission yield of at least 22 mass-chains for as many individual neutron resonances as possible .

The relative fission yields can be determined in a non-destructive way by measuring the gamma activity of about 30 fission products. With this method we already determined fission yields in ^{235}U for epithermal reactor neutrons, relative to the thermal neutron yields; a first experiment [2] covered the mass regions 85 to 105 and 129 to 146 and reached precisions on the relative fission yield down to 2 %. With improved equipment and a better analysis on a similar experiment [3] the mass regions 83 to 105 and 131 to 149 were covered and precisions of 1.5 % were obtained on the relative fission yields.

From these experiments it has been concluded that changes as high as 20 % occur in the fission yield curve of the neutron induced fission of ^{235}U, by going from thermal to epithermal reactor neutrons.

The proposed experiment consists in applying this method of non-destructive gamma ray spectroscopy of fission products to the individual resonances in neutron induced ^{235}U fission, as found along the periphery of a fast rotating wheel covered with a ^{235}U deposit.

The relative fission yields of the individual resonances are probably related to the spin J and spin projection K of the individual resonances, and could therefore be helpful for the identification of these fission channels (J,K).

2. Experimental conditions

In the previous experiments [2,3] a total number of about 7×10^{10} fission occurred in the ^{235}U target. The gamma activity was measured for different time intervals going from 45 min. up to a few days after the end of the neutron irradiation. With a different experimental geometry and a higher efficiency of the Ge(Li)-detectors, a density of 10^9 to 10^{10} fission of ^{235}U per resonance, (the number of fissions obtained in ref. 1) should be sufficient to perform the same experiment.

The previously obtained relative fission yields were deduced from the ratios of gamma intensities of fission products from thermal and epithermal fission, measured consecutively with exactly the same timing and with the same detector and counting equipment.

These conditions can probably not be realised in a nuclear explosion experiment, due to the number of resonances to be examined.

In this case, several similar Ge(Li) detectors should be used. Each of these has to be yield-calibrated with gamma spectra of fission products from a ^{235}U sample, irradiated for a short time period in a thermal neutron flux. It is estimated that at least 5 distinct timing conditions can be realized, each of them being still typical enough to recognize a sufficient number of fission products by their characteristic gamma energies and half-lives. Therefore, the number of detector equipments could be about 1/5 the number of resonances or rotating-wheel sectors to be scanned.

By doing so, the gamma spectra taken under different timing conditions are all exactly related to known spectra from thermal fission.

It is proposed that, for at least come resonances, gamma spectra should be registered as soon as possible after zero time ; for the observation of fission products with half-lives longer than e.g. 10h, the samples could be transported to other laboratories.

Depending on the time limitations for radiochemical analyses, this experiment could be performed on targets, which afterwards may be turned over to radiochemists for further measurements and controls.

3. Critique of the method

a) "bomb" neutron source

The two other methods available for studying in some detail the fission mass-distribution in individual neutron resonances are listed below, together with their limitation :

(1) Irradiation of the fissile target with monoenergetic neutrons from a crystal spectrometer followed by gamma spectrometry or chemical analysis of the fission products : very low intensity, dropping fast with neutron energy.

(2) Pulsed neutron source (fast chopper or Linac), and semiconductor detectors around the fissile target : low overall intensities, unavoidable poor mass-resolution due to the fact that the mass-distribution is deduced from the energy-distribution, and additional uncertainty due to the variation of the number of secondary neutrons from the various fission products.

As compared to these methods, the gamma spectrometry of a rotating wheel coupled to a nuclear explosion seems to be much superior, provided that, for the subsequent analysis, a sufficient number (probably between 5 to 10) of well-intercalibrated Ge(Li) spectrometers be available.

b) Comparison with the wheel-experiment followed by radiochemical separation of ^{115}Cd and ^{99}Mo.

From our data [2,3] it may be concluded that the fission yields in the mass number region 95-105 and 131-135 do change significantly when going from fission with thermal to fission with epithermal reactor neutrons. The assumed constancy of the ^{99}Mo yield (ref. 1) is therefore at least questionable.

On the contrary, measuring the relative fission yields of many mass numbers with high or medium-high fission yield could be useful in two aspects :

1) a different shape of the yield curve may be obtained for different (J,K) values, making it a valuable tool for characterising the fission channels associated with individual neutron resonances.

2) the constancy of the ^{99}Mo yield may be checked by comparing this yield to the ones of other mass numbers ; the ^{99}Mo yield may be corrected subsequently in order to obtain exact symmetric to asymmetric fission ratios for the individual resonances, as deduced from the ^{115}Cd/^{99}Mo ratios of the radiochemical analysis in ref. 1.

P. VAN ASSCHE

References

1. G.A. Cowan, B.P. Bayhurst, R.J. Prestwood, J.S. Gilmore and G.W. Knobeloch, Phys. Rev. C2 (1970) 615 and previous publications on the same subject.
2. P. Popa, M. De Coster and P.H.M. Van Assche, Nucl. Sc. and Eng. 39 (1970) 50
3. P.H.M. Van Assche, M. De Coster and Cl. Brandt, Proceedings of the International Conference of Radioactivity in Nuclear Spectroscopy, Nashville (Tenn.) 1969
4. G.A. Cowan, A. Turkevich and C.I. Browne, Phys. Rev. 122 (1961) 1286.

Annex III

Neutron Physics
H.C./jm

Mol, December 31, 1971

PROPOSAL FOR A COLLABORATION BETWEEN LASL AND S.C.K./C.E.N. FOR MEASUREMENTS OF TOTAL AND PARTIAL NEUTRON CROSS SECTIONS OF ^{226}Ra AND ^{227}Ac USING AN UNDERGROUND NUCLEAR EXPLOSION AS A NEUTRON SOURCE.

1. Introduction

Due to their short half life and the associated problems of high activity and limited availability, both ^{226}Ra and ^{227}Ac have poorly known neutron cross sections. As such, these nuclei are no exceptions in the mass region between A = 210 and A = 229, which as a whole, is unexplored.

It seems of considerable interest, both from the point of view of nuclear structure and of heavy element synthesis to explore this region further. However, conventional neutron spectroscopy techniques can hardly be used for total or capture cross section experiments and at present only explosion sources can give the required high intensity for meaningful measurements over a broad energy range.

2. Status of experiments

At present, experiments are underway at the high flux reactor BR2 in order to determine the total cross section of ^{226}Ra. The measurement is done at a crystal spectrometer in the energy range between 0.025 eV and 2 eV. The sample contains about 1 g of $RaCO_3$ and has a thickness of 14 mm representing about 2,8 g/cm^2 or 6.10^{-3} atoms Ra/barn. A sample area of 0.5 cm x 0.5 cm is exposed to the neutron beam. The sample is encapsulated in a thin-walled aluminium holder, which is mounted inside a He-tight stainless steel cylinder. All the operations for purifying the sample, filling the sample holders and the final encapsulation have been performed at S.C.K./C.E.N.

The same sample will probably be used at a short flight path ($\approx$ 10 m) at the Linac of C.B.N.M., Euratom, at Geel. The energy range covered will probably extend beyond 50 eV so as to provide sufficient overlap with explosion source experiments.

Reasonable amounts of ^{227}Ac, of the order of grams are also available at our laboratory. The actinium is produced by neutron irradiation of ^{226}Ra. Facilities exist to separate the Ac from the other reaction products and to purify it to a high degree (99.9 % can be obtained). The material is available in the form of its chemical compound Ac_2O_3. Samples for neutron cross section measurements will be assembled in the course of 1972.

3. Proposed experiments

We propose transmission experiments on two different sample thicknesses of ^{226}Ra, with approximately 1.0×10^{-2} atoms Ra/barn and another about twenty times thinner viz. 5×10^{-4} atoms Ra/barn. As an alternative, if only one sample can be used a thickness of 2×10^{-3} atoms Ra/barn would be the best compromise. This sample would have a beam-exposed area of 1 cm^2, a physical thickness of 0.5 cm and would contain about 1 g of Ra.

The same sample, or a similar one could be used for measuring the capture cross section with a Moxon-Rae type detector.

Measurements on ^{227}Ac ($T_{1/2}$ = 21,8 yr) would have to be limited to one sample, in view of the limited availability. Again a sample with an area of about 1 cm^2, containing about 1 g of material and 2×10^{-3} atoms Ac/barn is proposed. Such a sample, where ^{227}Ac is in equilibrium with its daughter products, produces an activity of approximately 2200 Ci. Fortunately 62 % of this activity is due to α-decay and 38 % to β-decay. Roughly 10 % of all transitions are accompanied by γ-radiation of energy between 100 keV and 1 MeV and another 10 % by gammas of energy below 100 keV. The gamma dose rate represents about 14 rem/h.g at a distance of 1 m. The heat produced by the source is 14.3 Watt/g, and the source is normally at a temperature of several hundred °C.

This sample should be used primarily for capture measurements. A transmission experiment can probably be combined with the capture experiment. Measurements on ^{227}Ac at energies below 2 eV are scheduled at our laboratory for the end of 1972.

H. CEULEMANS

Annex IV

Proposal for a Collaboration LASL-SCK/CEN-CBNM with a bomb shot experiment on LRA fission of the common fissile isotopes

Introduction and Situation of the Proposal

Since approximately 10 years the interest in ternary fission (two heavy fragments and a light fragment) has steadily increased (Conf. Salzburg 1965, Conf. Vienna 1969). However a concerted effort on several nuclei in a broad neutron energy range is still lacking.

Several measurements were made of the ratio of binary to ternary fission in ^{235}U and the fluctuations of this ratio were compared with changes of other fission characteristics such as the total kinetic energy of the heavy fragments, mass asymmetry, $\bar{\nu}$, anisotropy of fission fragments emission N(0°)/N(90°), in the neutron resonances. Correlation with the spins of the resonances was also examined. Our contributions to this research can be found in ref. (1) and ref. (2). A full account of this work is to be presented for publication in Nucl. Physics (ref. 3).

Very few measurements of the ratio in higher neutron energy regions (above 100 eV) exist. However it would be interesting to check how this ratio varies with the excitation energy of the compound nucleus, since one knows e.g. that symmetric fission increases with E_n, and so does $\bar{\nu}$. Does the relative amount of long range α particle fission follow the same trend with excitation energy?

Proposition of Experiment

1) Aims of the experiment are: 1°) The variation of T/B with neutron energy well -above the barrier (neutron energy > 500 eV up to if possible a few MeV) . 2°) The fluctuations of T/B in the resonance region and eventual correlations with J (E_n < 500 eV)
2) The nuclei we would consider are ^{235}U, ^{233}U, ^{239}Pu and ^{241}Pu, for which isotopes CBNM has developed the skill to prepare the high quality targets required.

3) Experimental set-up:

The targets would be back-to-back targets, with on one side (binary fission side) a thin layer of approximately 500 $\mu g/cm^2$ of the fissile isotope, on the other side (ternary α-side) a thicker layer of approximately 10 mg/cm^2 of material. So four back-to-back targets would have to be prepared (CBNM contribution).

On each side of these foils there should be one Si surface barrier detector or more, depending on the beam diameter, resp. target and detector dimensions. The binary fission experiment should be feasible as we propose the same techniques as were used in previous bomb shot fission physics experiments and with the same thickness of foils (cf. Annual Rev. of Nucl. Sciences by Diven, 1970). On the ternary side there should be a 30 micron Al screen in front of the detectors to absorb the heavy fission fragments and the natural α-particles of the targets. Here the fissile layers may be considerably thicker (of the order of 10 mg/cm^2) because the α-particle ranges are considerably larger than the range of the heavy fission fragments.

In this way the 20 times thicker layers partly counterbalance the smaller cross sections for ternary fission ($\sigma_{n,f}/\sigma_{n,f\alpha} \simeq 500$ at thermal energy). With selected 'very low dark current' detectors (if necessary cooled) a measurement by the 'normal current type' experiment seems to be possible.

Another problem of course is the γ-energy released in binary fission, penetrating through the Al-screen and partly being stopped in the solid state detector. An approximate calculation assuming that in binary fission about 8 MeV γ-ray energy is released (8 photons of about 1 MeV) yields an energy deposition in a 50 μm thick depletion layer of a junction detector of about $6 \times 10^{-4} \times 8$ MeV or about 5×10^{-3} MeV. (this value should be considered as an upper limit). In view of the ratio of the binary to ternary fission cross sections a signal from all γ-ray energy of the binary events would amount to about 1 MeV per ternary fission α-particle depositing about 10 MeV energy (or a signal to noise ratio of about 10).

Of course a pulse registration in the solid state detector would allow an even better selection of the ternary events. (e.g. count-rate meter with discrimination level).

Furthermore we would like to mount in the same beam a ^{10}B foil and a ^{6}LiF foil of about 200 $\mu g/cm^2$ calibrated at CBNM and also viewed by a solid state detector to be able to calculate fission cross sections relative to the usual standard cross-sections. A rough scheme of the proposed experiment is given in fig. 1. Further details of the proposed experiments have to be discussed and can partly be checked at CBNM and SCK-CEN during 1972.

(1) A. J. Deruytter and M. Nève de Mévergnies, Proceedings of the Symposium on Physics and Chemistry of Fission, Salzburg Vol. II, 429-437 (1965).

(2) A. J. Deruytter and C. Wagemans, EANDC (E) 133 AL (1969).

(3) C. Wagemans and A. J. Deruytter to be sent to Nuclear Physics (1972)

A. J. Deruytter C. Wagemans M. Nève de Mévergnies A. Aten

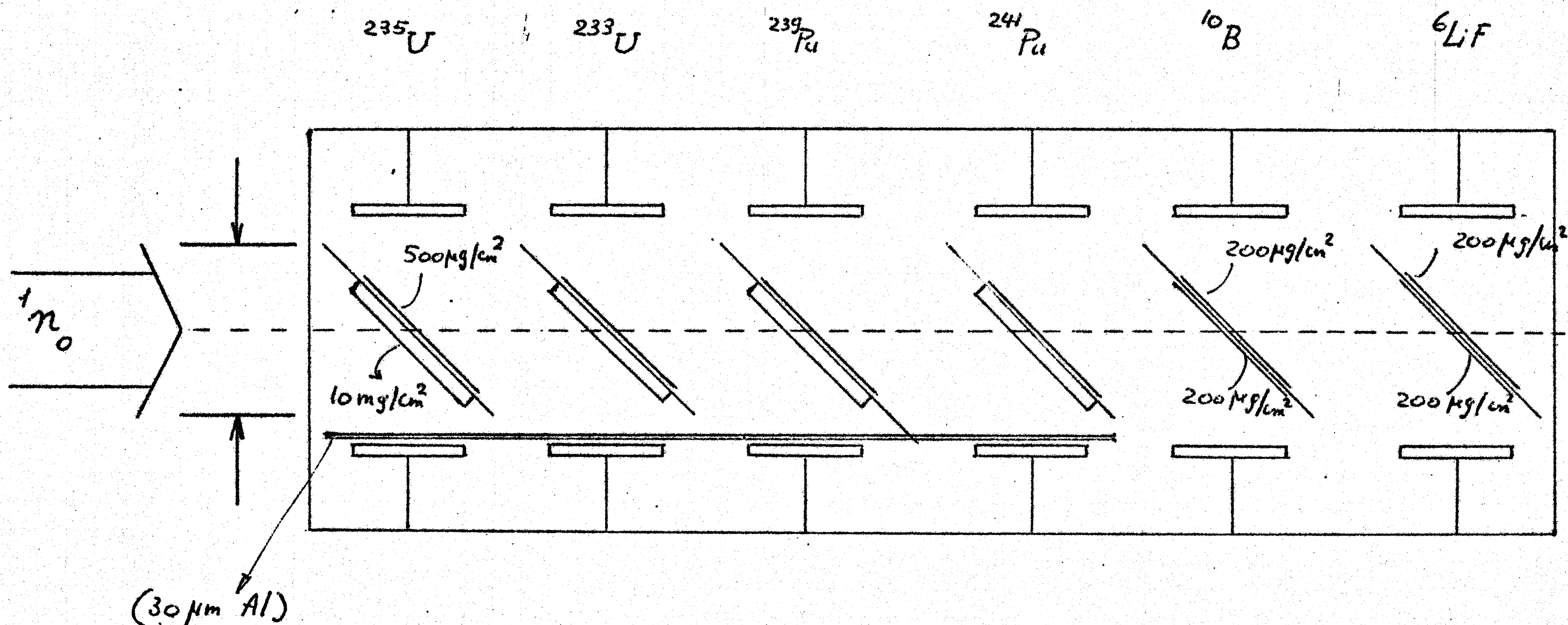

Fig 1 Scheme of proposed experiment

CBNM - CEN/SCK

23.12.1971

Resonance Parameters of Fission Product Nuclei.

It is proposed to use neutrons from an underground nuclear explosion for the determination of resonance parameters of fission products from measurements of elastic scattering and radiative capture cross sections as well as for the determination of resonance spins.

Measurements of elastic scattering cross sections would be done with ^{3}He gas scintillators, measurements of radiative capture cross sections either with a conventional Moxon-Rae-detector or, provided that test measurements at the Geel linac have positive results, with a Cerenkov detector which combined with the DC current measuring technic commonly used in bomb shot experiments, is assumed to have essentially Moxon-Rae properties, i.e. to deliver an output signal essentially proportional to the binding energy E_b of the captured neutron.

Resonance spin determination would be done by a method utilizing the spin dependence of the multiplicity of the capture γ-ray cascade, provided again that test measurements to be done at the linac demonstrate the usefulnes of the method envisaged. A method utilizing the capture γ-ray multiplicity has been succesfully applied in linac measurements by Coceva et. al. who used the relative number of coincidences as a measure of the γ-ray multiplicity. As in the DC current measuring technique necessary in bomb shot experiments, no coincidence measurements are possible, another quantity depending on the γ-ray multiplicity has to be measured. Such a quantity would be the ratio of output signals (DC currents) of the above-mentioned Cerenkov detector (output signal approximately $\sim E_b$) and of a thin (e.g. 0.5 mm) plastic scintillator (output signal proportional to the number N of γ-quanta in the cascade).

Tests to be done at the CBNM linac would have to show that 1) a Cerenkov detector with a pulse height weighting proportional to the pulse height (this corresponds to DC measuring) has to,a reasonable approximation Moxon-Rae properties, and 2) the method envisaged for the spin determination proves to be sufficiently sensitive.

The following isotopes are candidates for such measurements: ^{93}Zr, ^{99}Tc, ^{101}Ru, ^{107}Pd, ^{135}Cs, ^{147}Nd, ^{147}Pm, ^{151}Sm. All of them are important in fast reactor burnup calculations and resonance parameters of these nuclei are requested in RENDA (EANDC 85 "U"). All the isotopes are either radioactive or available only in small quantities so that they are not measurable in accelerator experiments. Of course, in a single bomb shot experiment only a few (2 to 4) of these isotopes would be measured.

J. THEOBALD
H. WEIGMANN
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Annex VI

CBNM - CEN/SCK

Fission Barrier Parameter Systematics

In the paper enclosed one possible approach to deduce fission barrier parameters for a double humped barrier from near barrier fission cross sections is described. The experimental data used for the heavy actinides are partially taken from measurements with bomb shot neutrons. Isotopes as heavy as Curium have been already investigated using this type of neutron source.

Data on isotopes with $88 \leq Z \leq 91$ are rather scanty. ^{230}Th has been investigated by E.Lynn, L.Earwaker and G.D. James and ^{231}Pa by S.M. Dubrovina and V.A.Shigin, both isotopes very close to the threshold.

There is a lack of systematic fission cross section measurements on ^{231}Pa, ^{228}Th, ^{229}Th, ^{230}Th, ^{227}Ac and ^{226}Ra in the energy range covered by bomb shots neutrons.

It is proposed to measure fission cross sections for these nuclides, with the possible exception of ^{229}Th, as it may be that this nuclide will not be available for the purpose. We dispose at the moment of the required amounts of ^{231}Pa, ^{227}Ac and ^{226}Ra and we shall procure the ^{230}Th and ^{228}Th sufficiently early. We have at the moment experience in handling Pa, Ac and Ra. For the last two experience also exists at CEN in using targets by measurements obtained in connection with the use at the BR2 reaction.

These data are of particular importance for the systematics of barrier parameters of the uranium isotopes. The potential landscapes representing the nuclear potential energies as a function of deformation and the neutron number calculated by Strutinsky shows just in the region of isotopes with $88 \leq Z \leq 91$ the tendency of reduced shell effects for nuclear deformation below the scission line.

Till now this prediction has never been studied.

It is proposed therefore that the cross section of the isotopes mentioned above for the neutron induced nuclear

reactions	(n,f) in particular
and, if possible	(n,γ)
and	(n,n)

are measured with bomb shot neutrons. A linear electron accelerator target is not suited as neutron source for this purpose.

For the latter two reactions detectors mentioned in the preceding note "Resonance Parameters of Fission Product Nuclei" can be suggested. The (n,f) reaction for resonances, which fullfil the condition

$$\Gamma_f > 10^{-3} \; \Gamma_\gamma$$

can be recorded through the fragment induced current in surface barrier detectors feeding logarithmic amplifiers, a technique developed at the Laboratories in Los Alamos.

The use of spinning wheels or similar fast mechanical devices covered with fragment track registrating layers can also be envisaged.

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EVALUATION OF FISSION BARRIER PARAMETERS FROM NEAR BARRIER FISSION AND ISOMERIC HALF LIFE DATA

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DOUBLE HUMPED FISSION BARRIER
evaluation of parameters E_2, E_A, E_B, $\hbar\omega_A$, $\hbar\omega_B$

ABSTRACT

A combined analysis of data from narrow intermediate structure in near-barrier fission cross sections and from shape isomere half-lifes has been tried in a very phenomenological model.
Among the results one observes a marked even-odd effect on $\hbar\omega_B$-values, whilst barrier heights do not show a significant effect of this type. It seems that one of the most important open questions is whether or not narrow intermediate structure exists close to the neutron binding energy in the Cm isotopes.

INTRODUCTION

Strutinsky's theory of nuclear deformation [1] which led to the prediction of a second minimum of the potential energy surface for large values of deformation, has been used to explain three different types of phenomena: the existence of shape isomeres decaying by spontaneous fission, the occurence of broad maxima in the cross section near threshold for neutron induced fission and (d, pf) reactions, and the observation of narrow intermediate structure in the cross section for sub-barrier neutron induced fission. In principle, all of these phenomena may in turn be used to obtain quantitative information on the potential energy surface as a function of deformation. In fact, systematic studies of shape isomere half-lifes [2] and excitation functions [3] as well as (d, pf) reaction data [4] have been done with this aim.

In contrast, analysis of narrow intermediate structure has been limited to individual cases [5] due to the restricted experimental information available. On the other hand, a combination of information from narrow intermediate structure in near barrier fission cross sections with data from shape isomere half-lifes may be useful for a more complete determination of the parameters of the double-humped fission barrier in particular the barrier heights E_A and E_B (Fig. 1). In the present paper an attempt of a very phenomenological analysis along these lines is reported.

EXPERIMENTAL INFORMATION USED

The experimental data selected for the analysis are listed in table 1. E_A-values have been taken from thresholds for neutron induced or (d, p) fission [4, 6, 7]. Besides of these, up to a certain level of the analysis practically only data (the class II level spacing D_{II}, the spreading width $\Gamma^{\downarrow}$ and the escape width $\Gamma^{\uparrow} = \Gamma_f$ (II) of class II levels) from narrow intermediate structure in fission cross sections have been used. This has been done in order to enable a direct comparison with other fits to other types of experimental data, and to circumvent an indefinite mixture of data with systematic differences. The detailed procedure of the analysis is described below.

The fact that fission thresholds are associated with E_A instead of E_B implies that $E_A \geq E_B$. Direct experimental evidence for this is available in at least three cases:

a. ^{241}Am+n

This system has been studied by Dahlsuren et al. [25], who measured the ratio of delayed (14 msec) to prompt fission after capture of thermal and epithermal neutrons in ^{241}Am. This measurement directly yields the ratio Γ_γ (II)/Γ_f(II) and the numerical value which is obtained is $\approx 10^{-4}$. Using for the class II capture width Γ_γ(II) $\approx$ 10 meV one obtains Γ_f (II) $\approx$ 100 eV which means that at the neutron binding energy one is near or above the top of the outer barrier; as, on the other hand, one is below the fission threshold, the inner barrier must be higher.

b. $^{240}Pu+n$

Evidence comes from the Petrel-data [26], which, although they are of less quality with respect to resolution than the data of ref. [17], nevertheless let recognize the group of fissioning resonances around 790 eV and, moreover, have the for the present discussion important advantage of a very low background. The essential thing that came up more recently is that $T_{1/2}$ (^{241}Pu) = 27 μsec [14]. If we were dealing with the case $E_A < E_B$ (or more correctly $P_A > P_B$ where P represents barrier-penetrabilities), then the fission width $\Gamma_f(II) = \Gamma\uparrow$ of the class II level at 790 eV would have to be associated with the sum over the fission widths of the fine-structure resonances, $\Gamma_f(II) = \sum_\mu \Gamma_{\mu f} = 0.1$ eV. Then, $\Gamma_\gamma(II)/\Gamma_f(II) \approx 0.1$,

and the Petrel data should show a tail on the group of fissioning resonances corresponding to a half-life of 27 μsec and containing about 10% as many counts as does the group.

The cross section integral over the 790 eV group in the Petrel data is $\int \sigma dE = 147$ beV, thus the tail should contain an apparent cross section integral of 14.7 beV. We examine the energy range 732 eV to 686 eV, corresponding to a time range of (0.68 to 1.28)x$T_{1/2}$ (the zero of the time scale being set to 790 eV). This range should contain 21% of the tail or an apparent cross section integral of 3.15 beV. The tabulated experimental points scatter very much and have large errors, but if one sums the upper limits of the error bars of all 17 experimental points in the energy range considered one obtained 0.6 beV, a factor of 5 below expectation for the case $P_A > P_B$. Thus we conclude that again we are dealing with the opposite situation.

c. $^{237}Np+n$

In this case [27] one looks for changes in the gross shape of the neutron capture γ-ray spectra in going from a usual class I resonance to the 39.9 eV resonance which is the central resonance of the lowest energy group of fissioning resonances. The absence of any such change leads to the conclusion that the 39.9 eV resonance has no predominant class II component which directly yields $\Gamma\downarrow \ll \Gamma\uparrow$ for the narrow intermediate structure in this case and thereby again $E_A > E_B$.

For the U-isotopes the situation is not clear. Nevertheless it has been assumed for the present analysis that $E_A > E_B$ still for U. There is some experimental indication that $E_A > E_B$ for ^{237}U [11] and ^{236}U [28]. Moreover, the fit which is finally obtained does not conflict with this assumption. Corresponding to the above discussion, the narrow intermediate structure in sub-barrier fission cross sections is generally to be interpreted in the way as discussed in ref. [29] for the case $\Gamma\downarrow \ll \Gamma\uparrow$. Shortly, $\Gamma\downarrow$ is given by the sum of the fission widths of the fine structure resonances belonging to one class II doorway, whilst $\Gamma\uparrow$ is given by the full width at half maximum of the Lorentzian describing the distribution of these fission widths. In this way most of the values for $\Gamma\downarrow$ and $\Gamma\uparrow$ given in table 1 have been obtained. Only for ^{235}U the opposite situation has been assumed. It seems that both barriers are about equally high in this nucleus (see ref. [11]) and that $\Gamma\downarrow \gg \Gamma\uparrow$ because the outer barrier is generally considerably thicker.

From $\Gamma\uparrow$ the "experimental" E_B-values given in table 1 have been obtained according to

$$\Gamma\uparrow = \frac{D_{II}}{2\pi} \quad \frac{N}{1+\exp(2\pi\,(E_B - E)/\hbar\omega_B)} \qquad (1)$$

(effective number of fission channels N = 1, 3 for odd, odd-odd compound nuclei, resp.).

Here, for the barrier thickness $\hbar\omega_B$ = 0.55 MeV has been used. This may be wrong by 30%, but as $E_B - E \leq 0.7$ MeV in all cases where one observes narrow intermediate structure, the error on E_B introduced by this uncertainty is certainly smaller than 0.2 MeV. Unfortunately, no value for E_B of ^{242}Am is obtainable, although $\Gamma\uparrow$ is known from the work of Dahlsuren et al.[25], because information on D_{II} is lacking. It may well be that the value $\Gamma\uparrow$ = 100 eV represents the limit $\Gamma\uparrow = D_{II}N/2\pi$ for penetration through the outer barrier equal to one, i.e. E_B may be considerably smaller than the neutron binding energy. It should be mentioned here, that data on narrow intermediate structure in ^{244}Cm+n [7] have not been used to obtain a value for E_B of ^{245}Cm. This point is further discussed below.
Up to this point, practically only data from narrow intermediate structure in fission cross sections have been used. Below, these data, in particular E_B-values, will be combined with the isomere half-life data listed in table 1 in order to obtain "experimental" values for $\hbar\omega_B$. Before, however, an extrapolation of the few available experimental E_B-values is necessary. This is done with a general fit of the parameters of the double-humped fission barrier described in the following paragraph.

FIT OF BARRIER PARAMETERS

In order to enable a simple comparison, we adopt several features of ref. [2]. Thus the total energy W is written as the sum of a liquid drop energy $W_{L.D.}$ plus a shell correction S:

$$W = W_{L.D.} + S \quad \text{with} \quad S \sim 1 - c_1\,(N - 146)^2$$

$$W_{L.D.}(\alpha) = 17.8\ \text{MeV}\left(1 - 1.79\left(\frac{N-Z}{A}\right)^2\right)A^{2/3}\left(\frac{2}{5}(1-\chi)\alpha^2 - \frac{4}{105}(1+2\chi)\alpha^3\right)$$

$$\chi = 2.01\cdot 10^{-2}\ \frac{Z^2}{A}\ \frac{1}{1 - 1.79((N-Z)/A)^2} \qquad (2)$$

$$\alpha = \frac{c/a - 1}{1 + c/2a}$$ (c and a are the long and short main axis of the ellipsoid).

We do not use, however, a general form for the α-dependence of the shell correction but simply think of barriers as inverted parabolas with free $\hbar\omega$. The heights of the two barriers as well as the depth of the second minimum are individually fitted to the experimental data. Thus we use:

$$
\begin{aligned}
E_2 &= W_{L.D.}(\alpha_2) - c_2(1 - c_1(N-146)^2) - E_{g.s.} \\
E_A &= W_{L.D.}(\alpha_A) + a\,(1 - c_1(N-146)^2) - E_{g.s.} \\
E_B &= W_{L.D.}(\alpha_B) + b\,(1 - c_1(N-146)^2) - E_{g.s.}
\end{aligned}
\qquad (3)
$$

As is done in ref. 2), we correct for the shell effects on the ground state masses by applying on a relative scale, the semi-empirical correction of Myers and Swiatecki

$$E_{g.s.} = W_{L.D.}(\alpha_{g.s.}) + \delta M \qquad \delta M = M_{exp} - M_{L.D.} \qquad (4)$$

The goodness of the fit does practically not depend on the absolute scale of δM-values. Of course, the parameters a, b, c_1 and c_2 obtained from the fit, do.

With the choice $\delta M(^{239}U) = 0$, the best fit is obtained for the following set of parameters:

$c_1 = 0.003$ $\qquad$ $c_2 = 1.7$ MeV $\qquad$ $a = 3.4$ MeV $\qquad$ $b = 1.5$ MeV.

In table 2, barrier parameters calculated with these parameters from equations (2 - 4) are listed and compared to the "experimental" parameters of table 1 if these are known.

The calculated E_B-values of table 2 are now used together with the isomere half-life data of table 1 to determine $\hbar\omega_B$ according to

$$T_{1/2}(f) = 10^{-20.3} \text{ sec } \frac{1}{1 + \exp(2\pi\,(E_B - E_2)/\hbar\omega_B)} \qquad (5)$$

$\hbar\omega_B$-values obtained that way should be correct within $\pm$ 20%. Finally, for the four cases where $\Gamma^{\downarrow}$ is known experimentally, an estimate for $\hbar\omega_A$ is obtained from the equation

$$\Gamma^{\downarrow} = \frac{D_{II}}{2\pi} \; \frac{N}{1 + \exp(2\pi\,(E_A - E)/\hbar\omega_A)} \qquad (6)$$

again using the calculated E_A-values of table 2. As for three out of the four cases E_A-E is only about 0.6 MeV with an uncertainty of maybe 0.3 MeV, the $\hbar\omega_A$-values cannot be expected to be certain to more than 50%. The values obtained for $\hbar\omega_B$ and $\hbar\omega_A$ are also contained in table 2.

DISCUSSION

A comparison of the calculated and "experimental" barrier parameters (E_2, E_A, and E_B) of table 2 shows that the fit is not bad: Only in 3 cases out of 30 does the difference between calculated and experimental values exceed 0.3 MeV, which is an estimate of the uncertainty of the experimental data.

The $\hbar\omega_B$-values obtained show a marked even-odd effect. If we average over nuclei with the same isotopic character we obtain:

$$\langle \hbar\omega_B \rangle = \begin{cases} 0.68 & \text{e-e nuclei} \\ 0.50 \quad \text{for} & \text{odd nuclei} \\ 0.40 & \text{o-o nuclei} \end{cases} \qquad (7)$$

It is a satisfying feature of the fit that inside each of these groups the $\hbar\omega_B$-values are remarkably constant. Moreover, they are in remarkly good agreement with corresponding data obtained by Back et al. [4] and by S. Bjørnholm [30].
The addition of a term $d \cdot \varepsilon$ (ε = -1, 0, 1 for e-e, odd and o-o nuclei, resp.) to the shell correction S and thereby to the barrier heights, as has been used in ref. [2], does not improve the fit. Quantitatively, according to the present analysis, $d < 0.05$ MeV, which means that its effect on E_A and E_B is certainly smaller than 0.2 MeV and 0.1 MeV, respectively.

The even-odd effect on isomere half-lifes is, according to our combined analysis of intermediate structure and half-life data, due to the above-mentioned even-odd effect on $\hbar\omega_B$ rather than to E_B.

There is a slight tendency of the calculated E_B-values to drop off too quickly with increasing Z. This tendency would be strongly pronounced if one would include into the experimental data also the results of Moore and Keyworth [7] on sub-barrier neutron induced fission of ^{244}Cm. It should be emphazised that this is not a question of quantitative analysis of the ^{244}Cm data. If the ^{244}Cm(n, f) cross section shows narrow intermediate structure, of which Moore and Keyworth state that the "evidence is strong but not conclusive", then E_B of ^{245}Cm would have to be of the order of the neutron binding energy, i.e. about 5.7 MeV, whilst the calculated value from our fit is 4.3 MeV. Of course, the decrease of calculated E_B-values with increasing Z is due to the liquid drop energy $W_{L.D.}$, and a reasonable fit of E_B-values including the ^{245}Cm data could only be obtained by introducing a Z-dependent shell correction for E_B. This, on the other hand, would destroy the above-mentioned constancy of

$\hbar\omega_B$-values of definite e-o-character. Thus, from the point of view of the present analysis, it seems to be very important to verify the narrow intermediate structure in ^{245}Cm or in neighbouring nuclei.

Finally, table 2 contains a list of calculated shape isomere half-lifes against fission ($T_{1/2}(f)$) and against γ-decay into the first minimum ($T_{1/2}(\gamma)$). The fission half-lifes have been calculated according to equ. (5), using the calculated values for E_2 and E_B (table 2) and the above average values for $\hbar\omega_B$ (equation 7). The γ-decay half-lifes are calculated according to

$$T_{1/2}(\gamma) = 10^{-14}\sec \frac{1}{1 + \exp(2\pi\,(E_A - E_2)/\hbar\omega_A)} \qquad (8)$$

Again, we use the calculated E_A and E_2 values and for $\hbar\omega_A$ averages of the values given in table 2 (obtained from $\Gamma\downarrow$): $<\hbar\omega_A> = 1.05$ and 0.72 for odd and o-o nuclei, respectively; as no $\hbar\omega_A$ for e-e nucleus is available in table 2, we simply use a value 20% larger than for odd nuclei, i.e. $<\hbar\omega_A> = 1.26$ for e-e nuclei.
It is interesting to note that, according to the half-lifes calculated that way, the Np- and the odd U-shape isomeres should decay predominantly by γ-decay into the first minimum. This might explain the fact that these isomeres have not been detected up to now. The same conclusion was reached by Metag et al. [2], but in contrary to their work in the present analysis this effect is not due to barrier heights but instead to the $\hbar\omega$-values obtained.

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Table 1: Experimental data used for the analysis

Nucleus	D_{II}[eV]	$\Gamma^{\downarrow}$[eV]	$\Gamma^{\uparrow}$[eV]	E_2[MeV]	E_A^{*}[MeV]	E_B[MeV]	$T_{1/2}$[sec]	Refer.
^{234}U					6.2			
^{235}U	7.10^3	50	0.3	2.7	5.9	6.0		8
^{236}U	260			2.6	6.1		$1.3\cdot 10^{-7}$	9, 10
^{237}U		≈ 8	≈ 8		6.3	5.7		11
^{238}U							$2\cdot 10^{-7}$	12
^{239}U					6.25			
^{238}Np	54	0.01	3.3	2.2	6.05	5.6		13
^{235}Pu							$3\cdot 10^{-8}$	3
^{237}Pu							$9\cdot 10^{-7}$	14
^{239}Pu	1.10^3			2.1	6.27		$8\cdot 10^{-6}$	15, 14
^{240}Pu	460			2.35	6.05		$3.8\cdot 10^{-9}$	16, 4, 3
^{241}Pu	700	0.1	40	2.0	6.05	5.45	$2.7\cdot 10^{-5}$	17, 14
^{242}Pu				2.2	6.1		$5\cdot 10^{-8}$	4, 10
^{243}Pu	600		20	1.8	5.8	5.2	$6\cdot 10^{-8}$	18, 10
^{245}Pu	$1.5\cdot 10^3$			2.3	5.5			18
^{237}Am							$5\cdot 10^{-9}$	14
^{238}Am							$6.6\cdot 10^{-5}$	19
^{239}Am							$1.6\cdot 10^{-7}$	10
^{240}Am							$9\cdot 10^{-4}$	20
^{241}Am							$1.5\cdot 10^{-6}$	10
^{242}Am			100		6.35		$1.4\cdot 10^{-2}$	25, 21
^{243}Am							$6.5\cdot 10^{-6}$	14
^{244}Am					6.15		$1.1\cdot 10^{-3}$	22
^{241}Cm							$1.5\cdot 10^{-8}$	3
^{243}Cm							$3.8\cdot 10^{-8}$	14
^{245}Cm					6.3		$2.3\cdot 10^{-8}$	3
^{247}Cm					6.1			
^{244}Bk							$1\cdot 10^{-7}$	23
^{245}Bk							$2\cdot 10^{-9}$	24

* from ref. 4, 6, 7)

Table 2: Comparison of experimental and calculated parameters

Nucleus	E_2 [MeV]		E_A [MeV]		E_B [MeV]		$\hbar\omega_B$ [MeV]	$\hbar\omega_A$ [MeV]	$T_{1/2}(f)$ [sec]		$T_{1/2}(\gamma)$ [sec]
	exp.	calc.	exp.	calc.	exp.	calc.			exp.	calc.	
^{234}U		2.68	6.2	6.02		5.95				$8.1\cdot10^{-8}$	$1.6\cdot10^{-7}$
^{235}U	2.7	2.55	5.9	5.97	6.0	5.93		1.44		$1.1\cdot10^{-2}$	$6.9\cdot10^{-6}$
^{236}U	2.6	2.44	6.1	5.89		5.90	0.70		$1.3\cdot10^{-7}$	$4.6\cdot10^{-7}$	$2.8\cdot10^{-7}$
^{237}U		2.58	6.3	6.05	5.7	6.10		0.96		$6.9\cdot10^{-2}$	9.4·10-6
^{238}U		2.33		5.78		5.90	0.72		$2\cdot10^{-7}$	$1.2\cdot10^{-6}$	$2.8\cdot10^{-7}$
^{239}U		2.34	6.25	5.74		5.93				$1.5\cdot10^{-1}$	$6.4\cdot10^{-6}$
^{237}Np		2.35		6.13		5.48				$5.1\cdot10^{-4}$	$5.9\cdot10^{-5}$
^{238}Np	2.2	2.55	6.05	6.33	5.6	5.74		0.72		$5.2\cdot10^{1}$	$2.3\cdot10^{0}$
^{239}Np		2.15		5.92		5.39				$2.0\cdot10^{-3}$	$5.6\cdot10^{-5}$
^{240}Np		2.21		5.93		5.48				$1.6\cdot10^{2}$	$1.3\cdot10^{0}$
^{235}Pu		2.14		6.05		4.62	0.53		$3\cdot10^{-8}$	$1.4\cdot10^{-7}$	$1.3\cdot10^{-4}$
^{236}Pu		2.12		6.12		4.72				$1.5\cdot10^{-10}$	$4.2\cdot10^{-6}$
^{237}Pu		2.36		6.42		5.06	0.52		$9\cdot10^{-7}$	$2.6\cdot10^{-6}$	$3.3\cdot10^{-4}$
^{238}Pu		2.25		6.35		5.04				$9.5\cdot10^{-10}$	$7.0\cdot10^{-6}$
^{239}Pu	2.1	2.40	6.27	6.51		5.26	0.51		$8\cdot10^{-6}$	$1.8\cdot10^{-5}$	$4.3\cdot10^{-4}$
^{240}Pu	2.35	2.11	6.05	6.20		5.02	0.67		$3.8\cdot10^{-9}$	$2.7\cdot10^{-9}$	$6.5\cdot10^{-6}$
^{241}Pu	2.0	2.22	6.05	6.26	5.45	5.16	0.51	0.76	$2.7\cdot10^{-5}$	$4.4\cdot10^{-5}$	$2.8\cdot10^{-4}$
^{242}Pu	2.2	2.00	6.1	5.96		4.94	0.62		$5\cdot10^{-8}$	$3.7\cdot10^{-9}$	$3.4\cdot10^{-6}$
^{243}Pu	1.8	2.08	5.8	5.93	5.2	5.01	0.61		$6\cdot10^{-8}$	$4.0\cdot10^{-5}$	$9.0\cdot10^{-5}$

Table 2 (continued)

Nucleus	E_2[MeV] exp	E_2[MeV] calc.	E_A[MeV] exp.	E_A[MeV] calc.	E_B[MeV] exp.	E_B[MeV] calc.	$\hbar\omega_B$ [MeV]	$\hbar\omega_A$ [MeV]	$T_{1/2}(f)$[sec] exp.	$T_{1/2}(f)$[sec] calc.	$T_{1/2}(\gamma)$ [sec]
^{244}Pu		1.92		5.63		4.82				$2.4\cdot 10^{-9}$	$9.9\cdot 10^{-7}$
^{245}Pu	2.3	1.87	5.5	5.41		4.71				$1.3\cdot 10^{-5}$	$1.4\cdot 10^{-5}$
^{237}Am		2.05		6.39		4.30	0.51		$5\cdot 10^{-9}$	$8.6\cdot 10^{-9}$	$1.7\cdot 10^{-3}$
^{238}Am		2.29		6.69		4.65	0.40		$6.6\cdot 10^{-5}$	$9.3\cdot 10^{-5}$	$5.1\cdot 10^{2}$
^{239}Am		2.03		6.47		4.49	0.50		$1.6\cdot 10^{-7}$	$1.0\cdot 10^{-7}$	$3.0\cdot 10^{-3}$
^{240}Am		2.34		6.78		4.86	0.40		$9\cdot 10^{-4}$	$1.1\cdot 10^{-3}$	$7.2\cdot 10^{2}$
^{241}Am		2.15		6.57		4.72	0.48		$1.5\cdot 10^{-6}$	$4.5\cdot 10^{-7}$	$2.7\cdot 10^{-3}$
^{242}Am		2.12	6.35	6.49		4.72	0.38		$1.4\cdot 10^{-2}$	$3.9\cdot 10^{-3}$	$3.7\cdot 10^{2}$
^{243}Am		1.80		6.08		4.40	0.47		$6.5\cdot 10^{-6}$	$7.2\cdot 10^{-7}$	$1.2\cdot 10^{-3}$
^{244}Am		1.89	6.15	6.06		4.48	0.41		$1.1\cdot 10^{-3}$	$3.7\cdot 10^{-3}$	$6.7\cdot 10^{1}$
^{241}Cm		2.11		6.90		4.29	0.47		$1.5\cdot 10^{-8}$	$3.1\cdot 10^{-9}$	$2.4\cdot 10^{-2}$
^{242}Cm		1.83		6.59		4.05				$4.6\cdot 10^{-12}$	$1.8\cdot 10^{-4}$
^{243}Cm		1.85		6.56		4.11	0.48		$3.8\cdot 10^{-8}$	$8.6\cdot 10^{-9}$	$1.5\cdot 10^{-2}$
^{244}Cm		1.74		6.35		4.00				$6.7\cdot 10^{-12}$	$9.0\cdot 10^{-5}$
^{245}Cm		2.08	6.3	6.58		4.33	0.49		$2.3\cdot 10^{-8}$	$8.7\cdot 10^{-9}$	$4.5\cdot 10^{-3}$
^{246}Cm		1.72		6.08		3.95				$4.6\cdot 10^{-12}$	$2.5\cdot 10^{-5}$
^{247}Cm		1.88	6.1	6.07		4.05				$3.2\cdot 10^{-9}$	$6.8\cdot 10^{-4}$
^{244}Bk		1.68		6.72		3.57	0.39		$1\cdot 10^{-7}$	$6.1\cdot 10^{-8}$	$1.4\cdot 10^{5}$
^{245}Bk		1.56		6.52		3.47	0.45		$2\cdot 10^{-9}$	$1.2\cdot 10^{-10}$	$6.7\cdot 10^{-2}$
^{246}Bk		1.80		6.65		3.71				$6.6\cdot 10^{-8}$	$2.4\cdot 10^{4}$

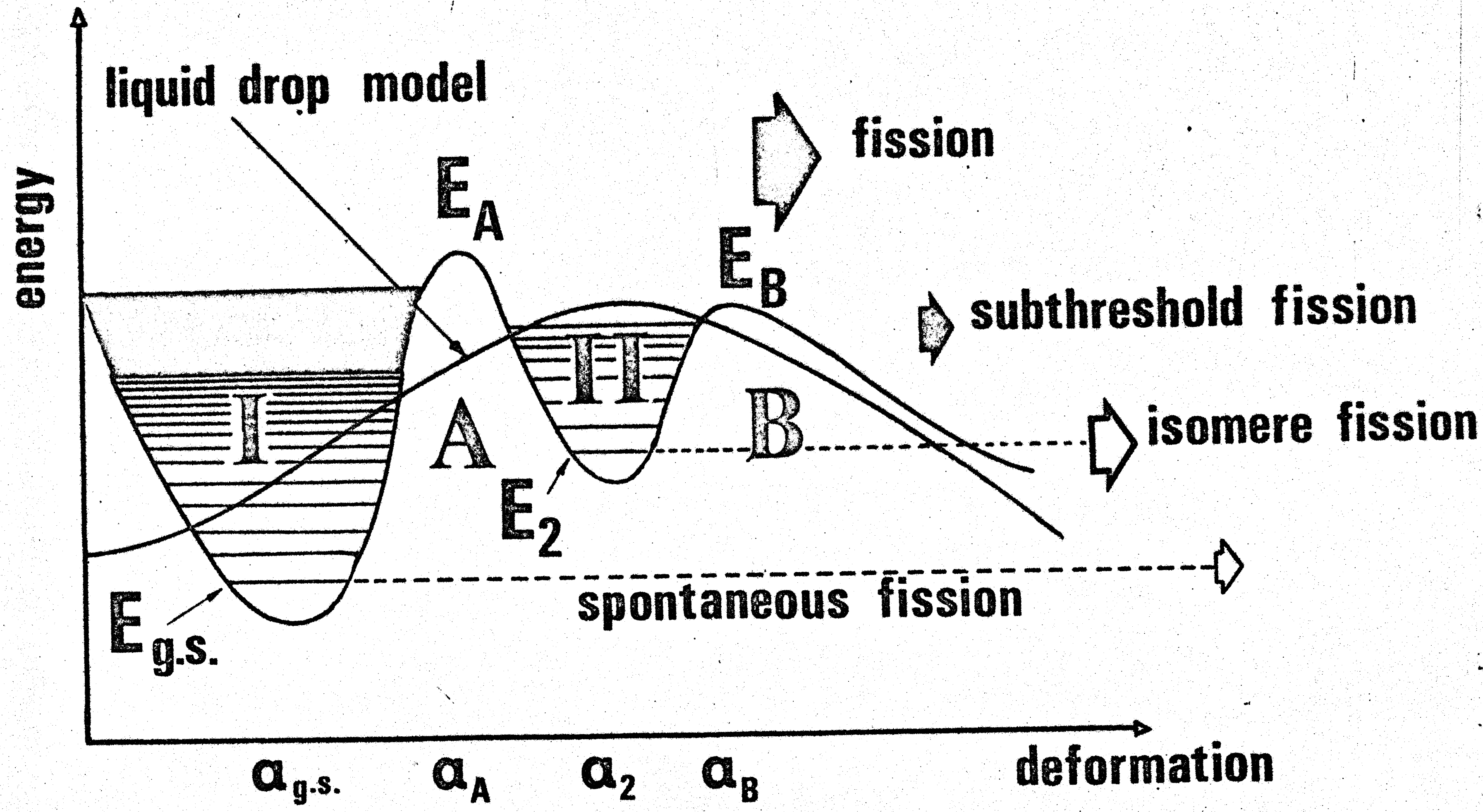

Fig.1 Double humped fission barrier.

Annex VII

Proposal

Measurements of the neutron-neutron cross section, using nuclear explosions.

Justification: Critical evaluation of all existing measurements of neutron scattering length, a_{nn} and effective range, r_{nn} demonstrates that our present knowledge is quite inadequate. $D(\pi^-,\gamma)2n$ experiments gave $a_{nn} \sim -13$ to -18.5 fm; $D(n,2n)p$ resulted in $a_{nn} = -14$ to -16.5 fm. Other reactions are unreliable. Information concerning r_{nn} is considerably worse and at this stage one can only say that a_{nn} is determined within 20% and r_{nn} within 50%. Early estimates indicate that underground nuclear explosion experiments could determine a_{nn} and r_{nn} considerably more accurately.

I am in the process of preparing a complete review of information concerning neutron-neutron effective range parameters and if desirable, it could be presented.