CAN EXPERIMENTAL SCIENTISTS, DATA EVALUATORS AND COMPILERS, AND NUCLEAR DATA USERS UNDERSTAND ONE ANOTHER?

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The International Atomic Energy Agency organizes conferences on a wide variety of scientific subjects, all of which are of fundamental importance for the development of nuclear power. These include the technology of fuel elements, their stability in neutron fields, and chemical reprocessing as well as reactor physics, mathematical computational methods and the problems of protection and dosimetry. The problem of microscopic nuclear data, an essential aspect of reactor work, is just one of these many subjects. On the other hand, it should be remembered that the possibility of releasing nuclear energy was established in the first place by obtaining nuclear data on the fission process occurring in the uranium nucleus following the capture of a neutron and on the escape of the 2-3 secondary fission neutrons. In early nuclear power work the information provided by nuclear data was of considerable, even of decisive, importance. For example, the information available on the neutron balance in fast reactors showed that such reactors could operate as breeders and thus that it was worth while developing them. Strictly speaking, it is of course difficult to speak of a knowledge of nuclear data at this early period. It is perhaps more accurate to speak of the understanding of and the feeling for such data which grew up on the basis of the existing physical ideas on the fission of the nucleus, radiative capture and neutron scattering. Experimental data were very scanty but for that reason they were particularly valuable.

In comparison with this early period the situation has now changed fundamentally and the amount of information available has grown enormously. Even now, however, the position is far from satisfactory. Our present knowledge of nuclear data is insufficient from the point of view of performing reactor calculations with an adequate degree of reliability - and this at a time when large-scale plans for the development of nuclear power are being worked out and implemented in various countries throughout the world!

In order to develop nuclear power to the levels provided for in these programmes, plans are being elaborated in connection with uranium mining, ore concentration, chemical reprocessing and other branches of industry, which make up an appreciable proportion of a country's total economic effort.

The reliability of the calculations relating to these industrial operations is at present severely limited by the uncertainties existing in the field of nuclear data. From the point of view of the development of nuclear power, therefore, it is imperative that efforts should be made to obtain nuclear data of the greatest possible accuracy.

The task of obtaining more accurate nuclear data is a three-fold one. Such data have to be measured; they have to be collected and evaluated and recommended values for reactor calculations have to be worked out; they have to be checked in calculations of macroscopic reactor experiments. This is a very broad field of activity and one which requires an appropriate division of labour and specialization. The success of such a complex undertaking depends on the progress made in each of the specialized fields and also on effective co-ordination between them. Unfortunately, these are conflicting requirements. In achieving greater and greater progress in their own particular sectors, specialists tend to lose the ability to understand the work and the problems of their fellow specialists. There is no longer any common language, and co-ordination becomes a problem.

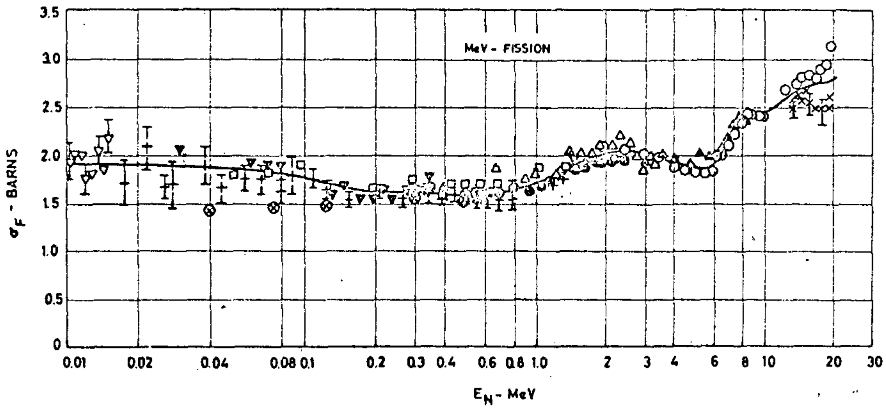
Unfortunately, we have often noticed that experimental scientists fail to extract from their experiments information which could be of great value to data users. For example, physicists working with selectors generally cease measurement work as soon as their apparatus stops resolving separate resonances. As a result of this, data users fail to obtain extremely important information on average cross-sections in the range between one and several dozen keV. It should be added that data users have only themselves to blame - they do not understand the experimental possibilities and fail to ask the right questions.

Experimental scientists often give no thought to the question of how and where their data will be used and frequently fail to specify in their papers relevant detailed information on their experiments and their treatment of data. Without such information data evaluators and compilers are unable to compare the results of different investigations.

The purpose of meeting here at this conference - as envisaged by the conference sponsors and organizers - is to improve communication between the nuclear physicists who measure microscopic nuclear data, the physicists who evaluate the data and work out recommended values for reactor calculations, and the reactor physicists and designers who use these recommended values for reactor calculations and who perform macroscopic experiments with critical assemblies and reactors.

The work of these three groups of scientists has one ultimate aim - to increase the reliability and accuracy of nuclear physical reactor calculations. In itself, however, this community of aim is no guarantee of mutual understanding since the position of each group and its attitude to the problem of the accuracy of nuclear data are objectively different. While it is perfectly reasonable for reactor specialists to say they need accuracies to within 1% for calculations relating to reactor characteristics - which means that accuracies of approximately the same order are required for fundamental microscopic nuclear data -, it is just as reasonable for nuclear experimentalists to complain about the excessive nature of these requirements and to be sceptical about the possibilities of achieving this accuracy with present experimental methods. Despite the great efforts and advances made by experimental physicists in the development of experimental methods, the fact remains that the values obtained for a particular quantity by highly competent scientists using the most refined methods often differ from one another far more than by the margins of error indicated by the authors. This suggests that some systematic error is involved whose nature is still not clear. The real accuracy of experimental results is therefore characterized not by the error indicated by the authors but by the scatter between the results of different authors.

Attention was drawn to the present unsatisfactory position with regard to microscopic nuclear data at the Conference on Neutron Cross-section Technology held in Washington in March 1966 and also at the London Conference on Fast Breeder Reactors held in May 1966. In order to illustrate how unsatisfactory the position is, let us consider some nuclear data which are of importance for fast reactors. The latest compilation BNL-325 [1], for example, shows that for the capture cross-section of uranium-238 the scatter of points extends 20% above and below the recommended curve (the figure shows the fission cross-section for plutonium-239). In the region below 150 keV the scatter is of the same order of magnitude. It is interesting to note that the difference is particularly marked in the case of the latest data of White and co-workers [2] - these are shown in the figure by means of ringed crosses.



The scatter for the fission cross-section of uranium-235 is ~5% in the 500 keV region and it increases to 15% in the region below 100 keV.

Until quite recently it was believed that the values for $\bar{\nu}$ in the thermal region were known to within 0.5%. A recent paper of Colvin and Sowerby [3], however, indicated that the measured value for the average number of secondary neutrons occurring upon the spontaneous fission of californium-252 was about 2% less than the weighted mean value utilized in earlier work. This 2% difference applies to all other fissionable isotopes since the $\bar{\nu}$ of californium is used as a standard. Moreover, in view of the large scatter in the values of different authors in the relative plot of the curve $\bar{\nu}$ (E) as a function of incident neutron energy, the above uncertainty assessment of about 2% can be considered as extermely optimistic.

As for the scientists who evaluate nuclear data with a view to their utilization in reactor calculations, they are faced with the problem of recommending definite values for all quantities to reactor specialists despite the fact that the experimental data are subject to considerable uncertainty. The interesting thing is that they in fact manage to do this very successfully in a number of cases. For example, the accuracy of calculations relating to fast reactors - made up mainly of uranium-238 and uranium-235 - is surprisingly good if use is made of the 26-group system of constants developed in the

USSR in 1962-63 by the late Professor Bondarenko and co-workers [4]. At that time there was no possibility of checking this system of constants on large-scale critical assemblies. Nevertheless the wide range of the ZPR-III [5] and BFS [6] assemblies is described by this system of constants with an overestimate of k_{eff} of 1.5 on the average and never more than 3% [7]. This is remarkable if one considers that the uncertainties relating to current microscopic nuclear data mentioned above - not to mention the uncertainties which existed in 1962 - should have given rise to an inaccuracy in the k_{eff} value of not less than 10-15%. At first glance this would appear to be mere luck. The real reason for this agreement becomes clear, however, if one remembers that the cross-section values selected were checked in a number of macroscopic experiments. The investigations in question were highly accurate experiments specially conducted to study the distribution of capture and fission numbers in blocks of depleted uranium. Consequently, the relative cross-section values, which really determine the neutron balance and hence the effective multiplication factor, were selected correctly. This example illustrates how very important it is to stage suitable macroscopic experiments and to take account of the results of such experiments when selecting values to be recommended for nuclear reactor calculations. This is a good example of the so-called feedback of the results of macroscopic experiments with microscopic cross-sections.

For calculations relating to various other reactor parameters, this system of constants does not yield the same degree of agreement. For example, the calculated value for the lifetime of prompt neutrons is, on average, 20% less than the experimental value. The reason for this, in my opinion, is that the lifetime measurement was not preceded by a macroscopic experiment, the results of which would have been strongly dependent on the absolute values for uranium-238 and uranium-235. This made it possible for the absolute values for these cross-sections, which were based on inaccurate microscopic data, to differ from the real values.

What can reactor specialists do to improve mutual understanding and to contribute to the problem of selecting values for constants which will describe all reactor processes with sufficient accuracy? They must of course continue to maintain their exacting standards with regard to the accuracy of microexperiments. At the same time, however, they must endeavour, together with the data evaluators, to ensure that a constant feedback is maintained between the results of reactor and other macroscopic experiments involving microconstants.

Reactor specialists obtain information on whole experiments, which can be carried out with good statistical accuracy. Of course, each reactor experiment has its own special features which, if misinterpreted, can give rise to systematic errors. In the experimental analysis various corrections have to be introduced, e.g. for an irregular assembly surface, for heterogeneity, for a non-spherical shape, etc. Only after these corrections have been made is it possible to make a comparison with the calculation, which is generally idealized. To make it possible for the results of such experiments to have a direct influence on the choice of the recommended nuclear data values, the calculated results of the experiments have to be presented in such a way as to make it easy to evaluate how particular changes in the constants will affect the values of the measured quantities.

To give an example, this was the case with the perturbation theory which we developed in 1963 [8]. With the help of this theory, a relative change in any of the measured parameters, e.g. ratios relating to the numbers of processes, the reactivities of the samples or the prompt neutron lifetime, can be expressed linearly through relative changes of the constants. Once a single calculation has been made of the coefficients of linear relationship for each assembly and for all the characteristics measured in each assembly, it is possible to make a general and useful contribution to the problem of improving all the recommended values of the constants by ascertaining the best agreement between the experimental and calculated characteristics of all the assemblies in question.

An example of this type of procedure is given in a paper presented at this conference [9]. This paper shows how the results of a macroscopic experiment on prompt-neutron lifetime and reactor criticality confirm an existing tendency to alter the microscopic data.

With the help of the perturbation theory technique the feedback mechanism becomes routinely operative and the complex language of this mechanism can be translated by the reactor specialists into the simpler and more accessible language of the linear relationship whose coefficients take account of all the necessary reactor details.

As has already been pointed out, the present stage of knowledge of microscopic nuclear data is such that the utilization of feedback can have an appreciable influence on the choice of recommended values. Our aim must, however, be to reach the stage where feedback no longer requires changes in the values obtained from microexperiments. To do this of course it will be necessary to learn how to measure microscopic cross-sections to within several per cent and sometimes with even better accuracies. This will mean that there will have to be complete agreement between the results of measurement of one and the same quantity obtained by different methods and authors. In other words, it is essential to eliminate systematic errors in experiments. A corresponding accuracy on the part of reactor specialists is naturally an essential requirement.

Ultimately these efforts must be aimed at eliminating the costly necessity of assembling reactor models and also at eliminating the even greater expense caused by errors in the calculation of operating periods, isotopic composition and other reactor characteristics of fundamental economic importance. To have to determine the operating period of each new reactor type or variant only after the period has actually been completed is too high a price to pay for the inaccuracy of nuclear data. The reliability of reactor dynamic studies, which are so closely bound up with safety problems, also depends on the reliability and accuracy of nuclear data. It should be re-emphasized that the arguments presented in this paper naturally presuppose that parallel progress will be made both in the methods and in the theory of reactor calculations which take into account real geometry and various other reactor effects, e.g. the resonance blocking effect. More accurate nuclear data are also required in nuclear physics.

There is no doubt that more accurate information on all the cross-sections of each element will help to provide physicists with more precise ideas on the nature of neutron-induced nuclear reactions and on the structure of the nucleus in general. There are well-known examples in science of how the increase in the accuracy of data not only resulted in a shift of the decimal place, but also produced qualitatively new results. There is no reason to think that this will not be the case in the field of study under discussion. At the same time it is clear that a genuine concern for precise and reliable measurements on the part of nuclear physicists would increase the enthusiasm of and the care taken by the experimental physicists who measure nuclear data for reactors.

In this connection, I would like to give an example of how the interest taken in an investigation into the mechanism of a particular phenomenon acted as a stimulus and gave rise to a particularly careful series of measurements, the results of which were of particular value to reactor specialist users.

The investigation in question was carried out in Obninsk and was concerned with the measurement of the energy curve showing the number of secondary neutrons for ^{235}U and ^{233}U as a function of the energy of the fission-inducing neutron. Because this dependence was associated with the channelling effects of fission, it was investigated with the greatest possible care and precision.

In addition to the $\bar{\nu}$ measurements, measurements were also made of the mean kinetic energy of the fragments as well as of their mass and energy distributions. This comprehensive approach in an investigation concerned with the mechanism of a particular phenomenon increased the reliability of the results obtained [11,12].

Theoretical nuclear scientists can play an extremely important role in encouraging this all-round approach to the study of phenomena. I think it is important to overcome the scepticism which is felt as regards the possibilities of theoretical work. Of course, not everyone would agree that theory can provide quantitative predictions. On the other hand, everyone would agree that theory can yield extremely valuable results when it is carried out in close association with experimental work and acts as a stimulus to such work. Even here, of course, there is the danger of the hypnotic effect of theoretical concepts on experimentalists and, hence, on experimental results. This sort of influence is the main danger - in fact, it is the only one - involved in such collaboration. In this respect experimentalists just have to remain sceptical. However, I do not think that this danger is, in actual fact, a very great one. After all, there is the old joke about the difference between the theoretician and the experimentalist - no one believes in the results of the theoretician except the theoretician, whereas everyone believes in the results of the experimentalist except the experimentalist.

In spite of everything, data evaluators do make use of the services of the theoreticians. We all know that use is made of the optical model for interpolations and extrapolations in uninvestigated areas (energies, masses of total cross-sections, and angular distributions of elastically-scattered neutrons). Progress has also been made in developing the systematics of level density [13], which, it may be hoped, will lead in particular to an increase in the accuracy of radiative capture cross-section predictions. The possibility of making such predictions would be particularly valuable in connection with the cross-sections for the capture of neutrons by fission fragments since direct measurements are extremely difficult in this case.

One of the chief reasons for creating an intermediate specialized discipline covering data evaluation and compilation is the rapid growth in the volume of experimental information and the necessity of interpreting and processing it. A solution to the problem of processing large volumes of information is now being found thanks to the use of electronic computers for data storage and processing. Two storage and processing systems are known at the present time. One of them - the SCISRS system developed at the Brookhaven Sigma Centre - is oriented towards microscopic experiments and it stores and processes initial nuclear data. The other - a British system geared to reactor calculations - contains curves recommended for calculations. The work of the data evaluator, which is not yet mechanized, occupies an intermediate zone between these two systems.

At the Washington Conference on Neutron Cross-section Technology [14] Dr. Parker expressed his conviction that this activity could be mechanized. He maintained that if the selection of recommended cross-sections was a logical process, it could be programmed, and that if it was a non-logical process it should not be carried out at all. Apart from the fact that each new datum on cross-sections would be taken into account operationally, he argued that there would be another advantage - complete elimination of the subjective approach in the selection of recommended values since the selection algorithm could be thoroughly discussed beforehand. I should like to add that in my view this future algorithm should include the use of the perturbation theory technique described above. This algorithm will have to be explained to an electronic computer and will therefore have to be clear and logical. The scientists who discuss and create it will have to include representatives of all the various specialist fields and will have to devise a common language.

I hope that I have been able to show that a real basis exists for a proper understanding between experimental physicists, data evaluators and reactor specialist users. Obviously, in order to make real progress in this direction a lot of work will be needed not only during the present conference but also for a long time afterwards.

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