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NEUTRON SCATTERING STUDIES FOR THE MODEST FACILITY

Summary of Remarks Made at the Istanbul Meeting of

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I. Introductory Remarks

It is the intent to delineate certain fast neutron scattering problems that are important to applied nuclear energy programs*, are of basic physical interest and are suitable for experimental study with a modest facility. Particular attention is given to those problems requiring careful attention to technical detail, skill, and patience on the part of the experimenter and which are not overly demanding of equipment or funds. Many of these experimental procedures are of pedological value for those entering the field since attention is given to those matters which can serve to train personnel, develop skills and lead to physical understanding.

"Modest", "small" and similar terms are relative and care should be taken to establish a more absolute basis for discussion. For this purpose, the present suggestions will be oriented toward the two "bench mark" facilities outlined in Table 1. These are basic accelerators that could reasonably be found at the small institution. It is realized that accelerators alone are not research facilities. Particularly "bench mark" facility B (of Table 1) can be a part of a very sophisticated system incorporating such major equipment as extensive digital computers. Thus, in the following, it is assumed that in addition to the basic accelerator, the available facility is simple, consisting only of a modest pulse height analyzer, conventional β-, γ-ray detection equipment and a limited amount of general purpose equipment such as electronic amplifiers and high voltage supplies.

* Herein, applied need is represented by the EANDC Compilation of Requests for Nuclear Cross Sections, EANDC-55U

Table 1   Bench Mark Facilities

	Type	Ion Energy	Sources	Neutron Energy	Capital Cost
A.	Cockcroft-Walton	$\lesssim$ 0.5 MeV	d(d,n)	$\sim$ 2.0 - 2.5 MeV	$\geq$ $ 30,000
			t(d,n)	$\sim$ 14.0 MeV	
B.	Van de Graaff	$\lesssim$ 3.0 - 4.0 MeV	Li^7(p,n)	$\lesssim$ 1.8 MeV	$\geq$ $200,000
			t(p,n)	$\lesssim$ 2.5 MeV	
			d(d,n)	$\sim$ 3.0 - 5.0 MeV	
			t(d,n)	$\sim$ 14.0 -17.0 MeV	
			Others	-------	

The group entering the field should not be deceived by the accomplishments of some "small" laboratories based upon a limited national or population foundation. Some of these groups are extremely sophisticated and among the most competent in the world. While they are examples of what can be achieved, the group entering the field must take care not to be overly ambitious and to plan a program commensurate with the institutional and regional technological base and needs.

II. Elastic Neutron Scattering

1. General Program

Through the advent of fast timing techniques elastic neutron scattering measurements have largely become engineering problems most productively attacked with specialized, complex and highly automated facilities.[1] Under these conditions, information acquisition, processing and interpretation are multi-dimensional problems in numerical manipulation and analysis best carried out with complex computational equipment. In view of the above, it would seem unwise for a group of modest capability to embark upon a major and general effort in elastic neutron scattering. Too often they would find that months of work were expended acquiring information inferior to that obtained in a few hours with a specialized and automated laboratory.

2. Elastic Scattering Near 14 MeV

The above comments do not necessarily apply to elastic scattering measurements requiring special attention to specific detail. For example, scattering at neutron energies near 14 MeV can be productively studied using the simple Cockcroft-Walton Generator ("bench mark" facility A of Table 1).

The results will not be of particular applied value. However, they can provide an excellent physical comparison with such concepts as the optical model[2] and, in selected cases, can be easy to interprete as the observed phenomena is essentially all a "shape" effect. The observed angular structure of the differential cross sections is often very pronounced and is sensitive to details of the potential employed in the calculations. There have been a large number of measurements near 14 MeV. To be of value, additional work must be carried out with particular care giving detailed attention to accuracy, angular resolution and multiple scattering. Measurements of this type do offer an opportunity for developing competence in such technologies as fast time-of-flight measurements without the engineering complexities inherent in the operation of large facilities.

3. Scattering Standards

Another area in which the modest facility can make a significant contribution is the determination of precision scattering standards. Such measurements are demanding of skill and motivation rather than massive equipment and thus are an opportunity for the modest institution. The applied nuclear energy programs are generally requiring greatly improved precision in scattering cross sections; there are requests for accuracies of 2-3%.* With present technologies, these accuracies are only achievable with reference to the primary scattering standard $p(n,n)$ or to a self calibrating total cross section measurement. In most cases neither of these approaches is convenient and resort is made to a secondary scattering standard, often the C(n,n) process. Even at incident neutron energies of $\lesssim 1$ MeV, these secondary standards are not reliable to better than $\sim 8\%$.[3] At higher incident

* See request No. 269, EANDC-55U, for example.

neutron energies, the situation becomes worse. Convenient secondary scattering standards should be available from 0.1 to 10.0 MeV with precisions of 1-2%. Determinations of such standards are within the scope of "bench mark" facility B (Table 1). Technical problems such as scattered neutron resolution are not usually limiting factors. Skill and the willingness to give the work detailed care in measurement and interpretation are governing factors. The large and well endowed institutions have not been willing to commit the latter factors so necessary to success. A modest facility could make an important contribution by doing so. Before undertaking such an endeavor it would be well to solicit the assistance and cooperation of a major facility. Such assistance is particularly desirable, if not necessary, in the area of data correction where extensive computations will be required in order to properly account for such important factors as multiple scattering. These factors can affect the measurements by as much as 10%, a factor well in excess of desired and useful accuracy.

III. Inelastic Neutron Scattering

General Program

As was true for elastic scattering, an extensive program of inelastic scattering studies is best pursued using complex pulsed sources and multi-dimensional fast time-of-flight techniques. Mastering of this technology requires extensive experience and appreciable resources. However, an intensive inelastic scattering program of limited and carefully selected scope is within the capability of a modest facility and can lead to significant applied and basic physical information.

2. Inelastic Scattering Near Threshold

Inelastic scattering cross sections near threshold are of pure and applied importance. Good measurements in this region combined with a few values at higher energies and quantitative calculation can fulfill many of the applied needs for inelastic cross sections. Further, the inelastic scattering process near threshold is particularly rich in dynamic and static basic structure information. A productive program in this area will require a controlled and variable energy neutron source (for example, facility B of Table 1) but will derive marginal benefit from the optimization of complex techniques such as time-of-flight (for example, a 5-8 nsec. time determination will often be as effective as a 0.5-1 nsec measurement).

Near threshold, the observation of gamma-rays from $(n;n'\gamma)$ processes can be a particularly effective way of determining structure parameters such as spin and parity and, when coupled with a direct neutron measurement at higher energies, can provide excellent applied cross section information. This is increasingly true as high resolution Ge(Li) γ-ray detectors become more generally available. These devices employed in $(n,n'\gamma)$ measurements provide an energy definition of low energy excited structure 5-10 times better than that available from the best fast time-of-flight apparatus. Further, the angular distribution of the emitted quanta is often more sensitive to characteristics of the nuclear states involved than is the case for the emitted neutron. Interpretation of the observed gamma-ray spectrum becomes rapidly more difficult as the incident neutron energy increases and the number of residual excited nuclear states rapidly increases. However, measurements of inelastic gamma-ray emission remain of applied importance at high incident neutron energies in the form of gamma-ray production cross sections.

3. Activation by Inelastic Neutron Scattering

There is an applied need for exact knowledge of the activation of specific isomers by inelastic scattering processes.* This need is based upon reactor requirements for knowledge of structural materials, fuel poisons and diagnostic tools. The information is desired both as precision cross sections and as accurate cross section ratios. The ratio measurements are particularly suitable for the modest facilities of either type A (14 MeV) or B of Table 1. The desired results can be obtained with the careful use of conventional β-, γ-ray detection equipment. Through the use of careful flux standardization the ratio measurements can be extended to yield precise cross sections.

The above type of measurement is of basic physical interest.[4] Isomers made only with difficulty, if at all, by other methods will be available for study both in formation and decay. Sensitivity for very small reaction cross sections permits the inelastic scattering from rare isotopes without the use of expensive separated samples required for direct observation of the scattered neutrons. In some instances this method, coupled with Ge(Li) detectors, provides resolution sufficient to resolve uncertainties in nuclear structure not possible by other methods. These structure problems are most prevalent in the region of deformed nuclei and can involve metastable states with life times of nanoseconds to hours or even days.

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* For example, see request numbers 394 and 406 of EANDC-55U

Whether pursued for pure or applied reasons, the activation method of inelastic scattering studies requires an endeavor oriented toward specific problems, executed with care but employing relatively simple equipment. These characteristics are often not compatible with the well defined and rigid equipment and programs of a large facility, but are well within the capability of the more modest institution.

4. Inelastic Scattering Near 14 MeV

Inelastic scattering near 14 MeV is within the capability of both the "bench mark" facilities of Table 1. It is an area of primarily basic physics interest and studies here can be used for developing technological skills, such as fast time-of-flight, that are applicable to the important applied neutron scattering problems.[5]

At energies near 14 MeV, most inelastic scattering observations will result in nuclear temperature distributions. This relatively old concept is not as well defined as one might expect. In fact, recent (p,n) studies indicate serious discrepancies in the conventional simplified picture.[6] Shell structure, deformation and other nuclear structure appears to play a more prominent part in temperature determinations than previously thought. The distinction between direct and compound nuclear processes is not well defined. To be of value, temperature measurements must be very carefully made with particular attention to the precise relative energy sensitivity of the detection equipment and to the angular distribution of the emitted particles.

At 14 MeV direct reaction mechanisms play an important part in inelastic scattering from deformed nuclei. The observed process can be well correlated with theory to provide detailed structure and deformation information. Unfortunately, the experimental determinations are not simple, often demanding emitted neutron resolutions of 400 keV or less. This is difficult but it can (and has) been done using a modest Cockcroft-Walton generator and carefully conceived post-acceleration pulsing and timing systems.[5] These are not simple techniques but are within the scope of the modest facility staffed by competent personnel and will permit a significant contribution to the understanding of the direct interaction of neutrons with the deformed nuclei.

5. Precision Inelastic Scattering Cross Sections

The reactor programs need high accuracy (∿ 2%) inelastic cross sections particularly for the fissile and fertile nuclei.* The applied importance is great, the fundamental physical value is not so appreciable. These are "standard" problems of a most difficult nature requiring extreme skill and care. Careful attention must be given to the analysis of the measured values as such experimental perturbations as multiple scattering can result in uncertainties larger than the desired precisions. These measurements are not to be undertaken lightly even by the most competent of laboratories. They will require the best possible facilities which are "modest" only in the sense of their programmatic scope. Such a program will also require extensive computational support including the availability of massive digital computers.

The above remarks indicate that a precision inelastic cross section program is not a promising endeavor for the smaller laboratory unless it is an institution with truly outstanding capability and experience correlating its work with the support available at a very large national or regional laboratory.

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*See request No. 712 EANDC-55U, for example

IV. Flux Standards and Sources

An institution or region embarking upon a fast neutron program should give consideration to source and flux standards. These are requisite to a pure and applied research program and are essential to the utilization of neutron devices in such diverse areas as bio-medical and geological studies. Many of the applied needs for fast neutron scattering data appear as requests for neutron emission or production cross sections and are inclusive of such reaction contributions as the (n,2n') process. These cross section requests and most source calibration needs can often be satisfied using the $MnSO_4$ water bath techniques[1] and simple β^-, γ-ray detection employed with skill and care. It is noteworthy that for a number of years the best values of the Be(n,2n') cross section were obtained using the $MnSO_4$ water bath method and that some of the best present $\bar{\nu}$ values were obtained with the same technique. An institution embarking on a neutron physics program would do well to consider a $MnSO_4$ bath facility for standard calibration, flux calibration, neutron emission and production cross section measurements and precision determinations of neutron yields from reactions inclusive of fission. The fiscal cost is small and the potential of the method, particularly when coupled with facility B of Table 1, is considerable.

The above comments are oriented toward the Mn bath technique but many of them could apply to other absolute or relative flux determination methods including standard long counters, recoil counters and reaction detectors.

V. Computation and Analysis

Meaningful physical interpretation of many of the above suggested measurements requires the numerical solution of complex quantum mechanical problems.

These are best obtained with large digital computers and codes for such work are readily available through a number of regional and international code centers.* However, many modest installations do not have the requisite computational capacity. Thus it is desirable that a close working relation be established with a suitable large installation where extensive computers are available. In some cases, it is reasonable to consider the use of extensive tabulations of such quantities as optical model transmission coefficients.[7] A library of such quantities combined with the very modest capabilities of a small computer such as an IBM-1620 is sufficient to achieve useful and significant results if used with skill and patience.

The proper analysis of complex measurements is difficult as the numerical corrections are often very dependent upon the particular experimental conditions and frequently require such time consuming procedures as Monte Carlo calculations. However, tabulations of experimental corrections suitable for the more conventional geometries and experimental configurations are becoming available.[8] These should be particularly helpful if care is taken to plan and execute the measurements in a configuration that is applicable to the available tabulations of correction factors. Locally available small computers will ease the application of such tabular corrections but it is doubtful if one should attempt to generate the correction factors from first principles with small digital machines.

VI. Cooperation and Assistance

One of the most disturbing facets of the program at a modest facility, particularly in the formulative and creative stages, is the absence of experienced advisory, consulting, and even guidance personnel. Such devices

* For example, the Argonne National Laboratory Code Center

as training periods, scientific exchanges, code and data centers, etc., all have the objective of making the requisite experienced talent and information available to the smaller and often isolated facility. Unfortunately these mechanisms have not always succeeded. It is therefore recommended that the first order of business for any Group embarking upon a program in the field of fast neutron physics is the establishment of the closest possible working relationship with a major national or international laboratory. Such a relationship must be pursued on a continuing basis in such a manner as to affect the systematic growth of the smaller institution.

VII. Summary

The above remarks pertain only to a very limited area, fast neutron scattering. They do indicate that there are certain problems in this area that can form the basis of a productive program for a modest facility. Such a program can make a very significant contribution to the field of applied nuclear data and in areas not usually commensurate with the programs of major institutions. Some of these problems are stimulating and can be a vehicle for achieving a truly deep insight into many facets of low energy nuclear physics. Small groups are often well educated but under trained and deficient in experience. The problems cited above will offer the scientific staff an opportunity to gain experience with and mastery of technological skills in such a manner as to produce an exceptionally competent and well rounded staff.

Certainly, there is opportunity limited only by creativeness and initiative provided that care is taken to choose a program emphasizing the most valuable resources of the modest facility, time, patience, and skill.

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