Neutron scattering measurements at intermediate energies

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Abstract

The study of elastic neutron scattering at intermediate energies is essential for the understanding of the isovector term in the nucleon-nucleus interaction, as well as for the development of macroscopic and microscopic optical potentials at these energies. The techniques used for neutron scattering measurements is presented in this paper, as well as the difficulties encountered. The few facilities that have been used are reviewed, and a newly installed setup for such measurements in Uppsala is described. Finally, the normalization problem is specifically addressed.

1 Introduction

The basic aim of studying elastic and inelastic neutron scattering at intermediate energies is to determine the isovector term in the nucleon-nucleus interaction. Furthermore, Coulomb repulsion of protons creates a neutron excess in all stable nuclei with $A > 40$, and incident protons and neutrons interact differently with this neutron excess. An isovector coupling term was introduced into the optical model by Lane [1] with the form

$$U_N(E) = U_0(E) + (4/A)U_1(E)\vec{t}\cdot\vec{T},$$

where $\vec{t}$ is the isospin of the projectile and $\vec{T}$ is the isospin of the target. The diagonal terms of the $\vec{t}\cdot\vec{T}$ matrix display the differences between proton-nucleus and neutron-nucleus elastic scattering, i.e.,

$$U_N(E) = U_0(E) \pm \epsilon U_1(E) + \Delta U_c,$$

where $\epsilon = (N-Z)/A$ and $\Delta U_c = 0$ for neutrons.

This expression shows that the proton-nucleus optical potential contains both an isovector term, U_1, and a Coulomb correction term, ΔU_c, that accounts for the reduced kinetic energy of the proton - compared to a neutron of the same energy - inside the nucleus. In a relativistic approach, this Coulomb correction is unambiguously linked to the central vector potential. Once ΔU_c is known, the isovector potential U_1 can be deduced by a comparison of neutron and proton elastic scattering from the same $T \neq 0$ nucleus at the same energy.

Since long, there is a common prejudgement in nuclear physics that the isovector term depends on $(N-Z)/A$, but this is open to question. One serious problem is found when using the Ohio-State Dirac phenomenology for proton-nucleus scattering to calculate the neutron total cross section. Such calculations describe the ^{16}O total cross section almost perfectly, while serious discrepancies for ^{208}Pb provide compelling testimony for the further need to investigate the isovector nucleon-nucleus interaction [2].

There has been notable progress lately in theoretical studies of elastic scattering of nucleons from nuclei at intermediate energies. The early hope of nuclear physics, namely that nuclear forces derived from the analysis of nucleon-nucleon data could be used to predict nuclear many-body phenomena, is maybe finally being realized. In recent calculations [3], the only input is the nucleon-nucleon force and the wave functions of the target nuclei. The *NN* potentials (below pion production threshold) now seem to be good enough so that uncertainties in these calculations largely reflect the uncertainties in the nuclear densities. In particular, analyses of proton data, together with accurate neutron scattering data, may at long last be able to yield information regarding the relative distribution of charged and uncharged matter in nuclei.

The vast majority of the existing data are for proton scattering, and to perform the mentioned analysis, neutron scattering data of reasonable precision are needed. Neutron elastic scattering at small angles is of special interest, because the Coulomb bump masks the nuclear amplitude in the proton case. Data for larger angles are important to test the limits of the first-order theory, and to pin down the diffraction structure with increased confidence. In a future, neutron spin observables would be most welcome to complement the extensive proton measurements.

Several different fields of nuclear physics would benefit from better knowledge of the optical potentials, irrespective of whether any new physics phenomena will be found. The lack of precise neutron optical potentials is a serious constraint to both (p,n) and (n,p) studies in this energy domain. Taddeucci *et al.* [4] ascribe a $20-30\%$ uncertainty in the calculation of absolute (p,n) cross sections to uncertainties in the optical potentials. Given the situation with the debate on the missing Gamow-Teller strength, any improvement in the extraction of physics results from the data would be utterly useful.

A second field where such potential data would be of large interest is the high-priority (e,e′pn) program at CEBAF, for which uncertainties in the analysis arise from the poor knowledge of the neutron potentials. For similar reasons, quasi-elastic experiments could also make use of better information about neutron potentials.

Finally, many applications would benefit from a better knowledge of neutron scattering cross sections. The greatest potential is probably in the development of ADTT (Accelerator-Driven Transmutation Technologies), which can be used to transmute long-lived nuclides in, e.g., used nuclear fuel or atomic bomb material, into short-lived radioactive waste, or to produce energy. An important medical application of neutron physics is the development of fast neutron cancer therapy. Clinical studies are in progress at about 20 centres around the world. The reason is that better results have been obtained with this modality for some specific types of slowly-growing tumours. One important problem is, however, the lack of fundamental neutron cross sections, which makes the dose planning difficult and uncertain.

In this paper the techniques of measuring neutron scattering at low energy will be discussed, as well as the difficulties involved in extending such measurements to the $60-200$ MeV region. The few facilities that have been used for such measurements are reviewed, and a new spectrometer for neutron scattering, recently installed at the The Svedberg Laboratory (TSL) in Uppsala, will be presented. At the end, problems related to the normalization of neutron scattering data are discussed.

2 Low-energy measurements

By low energy, we mean in this paper energies below 20 or 30 MeV. In this energy region, it is possible to detect and perform spectroscopy of the scattered neutrons, using time-of-flight (ToF) techniques, with moderate flight paths. In the lower end of the interval, the flight paths could be kept at a few meters, while still maintaining a reasonable energy resolution. Thus, it is possible to rotate the detector, with its shielding, around the scattering sample, to measure angular distributions. At the high-energy end, however, this tends to become unpractical, and a beam swinger, with which the incident beam angle could be changed by rotating a set of magnets, is preferably used. Several spectrometers of the first kind have been utilized over the years, while only a few beam swinger arrangements have been built. A few examples of both types of spectrometers will be described here.

The Studsvik high-resolution, low-background ToF facility [5] (see Fig. 1) has been used to measure differential neutron elastic as well as inelastic scattering cross sections for a large number of elements ($A = 9-209$) at incident energies up to 22 MeV. This facility was a complete reconstruction of the older spectrometer used in the energy region up to 8 MeV. The beam pulsing equipment, the gas target system, and the neutron detectors, as well as the shadow bar system, were redesigned. Thus, monoenergetic neutrons were produced with the T(d,n) reaction, using a 1 cm long target cell, filled with tritium gas to a pressure of up to 4 atm. The Van de Graaff accelerator delivered bursts of deutrons with a pulse width of about 1.5 ns and an average beam current of 3μA. The deutron bursts were further compressed to less than 0.3 ns, with maintained intensity, by a post acceleration buncher. The detector system consisted of two NE213 liquid scintillators, which were separated by 5° and positioned at a distance of 4 m from the scattering sample in a heavy shielding, consisting of iron, lead, and lithium-loaded paraffin. The arrangement was placed on an arm, which could be moved on a horizontal circular track, with its axis in line with the scattering sample. The spectra of scattered neutrons were measured in steps of 2.5° or 5° in the angular interval $10^\circ - 160^\circ$.

To illustrate the quality of the measured data at 21.6 MeV, neutron elastic scattering angular dis-

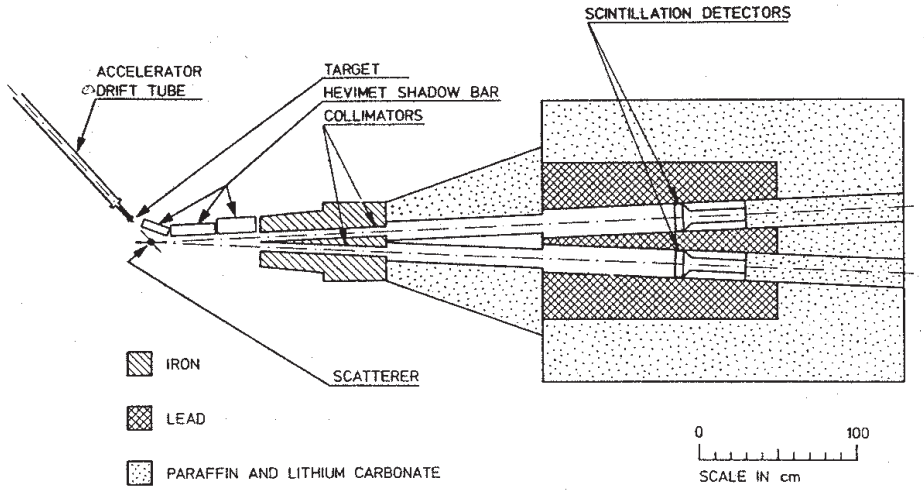

Figure 1: The Studsvik neutron scattering facility [5].

tributions for some elements are shown in Fig. 2 [6, 7, 8]. The total time resolution in these experiments

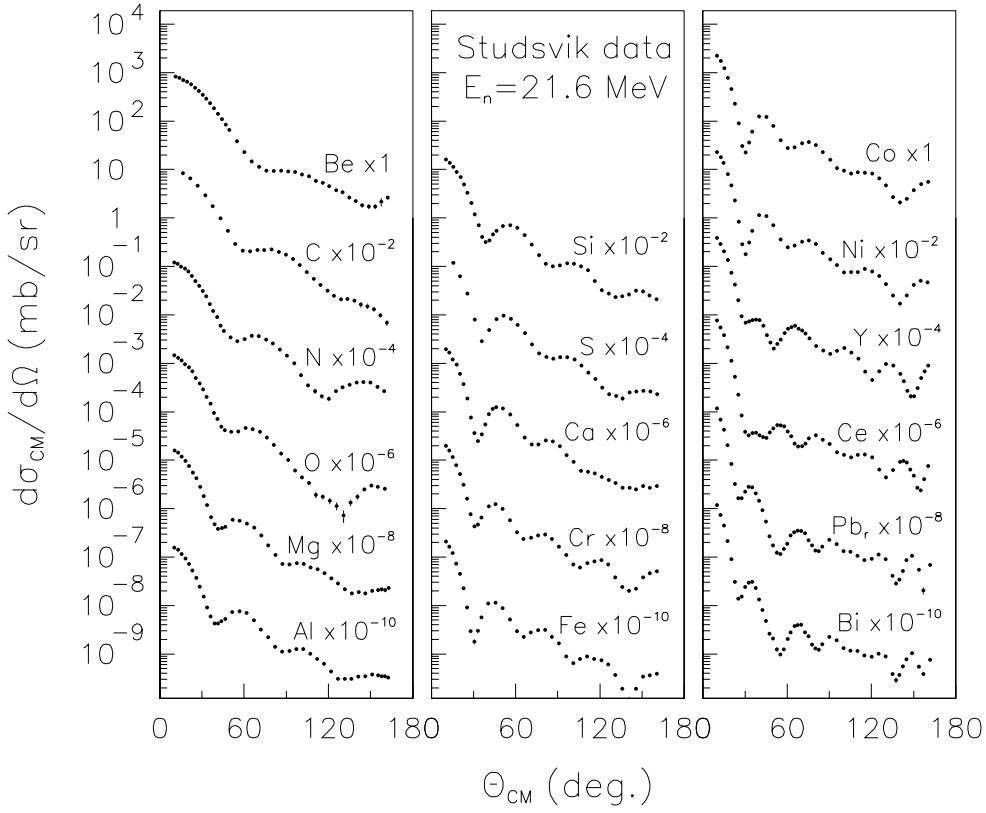

Figure 2: Data for nuclei with $A = 9 - 209$ taken at the Studsvik neutron scattering facility [6, 7, 8].

was measured to be less than 1 ns, corresponding to a total energy resolution better than 0.7 MeV at the highest energy measured.

The same type of experimental facility, but with 0.75 ns bursts of particles hitting the target, was also used for several years $(1977 - 1981)$ at the Ohio University [9], where they measured elastic and inelastic neutron scattering from a wide range of target nuclei in the angular range $15° - 155°$ for energies

up to 26 MeV. This system had, however, important limitations concerning the detector shielding and the energy resolution, especially for incident neutrons above 20 MeV, for which the available flight path of about 6 m was too short. The availability of a beam swinger magnet from the Michigan State University, provided an opportunity to design a high-resolution, low-background ToF spectrometer with one long flight path (up to ~ 30 m) in a fixed direction for neutron scattering experiments [10]. With the Ohio beam swinger facility, shown in Fig. 3, neutron elastic and inelastic scattering differential cross sections have been measured in the energy region up to 26 MeV for a large number of nuclides over a wide mass range. The quality of the data is similar to (or slightly better than) those of Fig. 2. The energy resolution was kept at a few hundred keV.

The beam swinger magnet mentioned above had earlier been part of a neutron ToF facility at the Michigan State University (MSU) Cyclotron Laboratory [11]. Neutron elastic scattering differential cross sections from ^{12}C, ^{28}Si, ^{32}S and ^{40}Ca at 30.3 and 40.0 MeV have been reported from measurements with this facility [12, 13]. The angular ranges covered were $15^\circ - 140^\circ$ and $15^\circ - 115^\circ$ at 30.3 and 40.0 MeV, respectively. The beam from the MSU Cyclotron had a typical burst width of 0.3 ns. Neutrons were produced by the ^{7}Li(p,n)^{7}Be reaction and the scattered neutrons were detected by a liquid-scintillation detector placed $5 - 9$ m from the scatterer in a fixed direction. The overall energy resolution in the measurements was 0.7 to 1.4 MeV.

3 Towards higher energy...

One could say that a clear interest to go to higher energies with high quality scattering measurements was first outspoken in connection with the Neutron-Nucleus Conference, held at Burr Oak in Ohio, 1984 [14]. During this conference, several speakers stressed the importance of such measurements for many areas of nuclear physics.

Shortly after the Burr Oak Conference, Brady *et al.* at Davis suggested to use the best known technologies from the 20 MeV region for building a dedicated facility for neutrons up to 65 MeV. The equipment included a beam swinger, previously at use at University of Colorado [15], and the scattered neutrons were supposed to be detected using ToF techniques over a fixed flight path of some 100 m. The facility was, however, never built. Simultaneously, similar discussions were going on at TSL in Uppsala, where a large beam swinger, capable of bending 200 MeV protons, was considered. The project turned out to be too costly, however. At a later stage, after the turn down of the Davis proposal, the Colorado beam swinger was being discussed also for TSL, but without result. The cause of the negative outcome was that it is extremely difficult (and thus expensive!) to extend the 20 MeV technology to be used at $100 - 200$ MeV. There are several reasons, and a few of them will be discussed here.

As was seen above, at low energy one can obtain reasonable energy resolution by using ToF over a modest flight path. By simultaneously keeping the distance from the neutron target to the scattering sample short, i.e., a few tens of centimeters, the count rate can be comparatively high. With a total time resolution of 1 ns, one will get an energy resolution of 0.5 MeV with a flight path of 5 m at 20 MeV, while for the same resolution at 100 MeV, 60 m is needed. Even if a resolution of 2 MeV is accepted, the flight path will be 15 m, which is normally too space-consuming for rotating the well-shielded detector around the scatterer, and thus a beam swinger is called for. In addition, a large array of neutron detectors is needed to preserve a reasonable solid angle and count rate.

Another severe problem is related to the dumping of the charged-particle beam. At low energy this could easily be done by stopping the beam in a sheet of, e.g., gold immediately after the neutron-producing target material. At 100 MeV this technique is not possible, since a beam stopper of several centimeters is needed, in which maybe 99% of the beam energy will be dissipated. This will create a huge background of neutrons. A solution is to bend the beam between the target and the scattering sample, and bring it far away to a well shielded beam dump. This is a severe complication, which automatically leads to an increase in the distance target–scatterer to 1 m or more, thus resulting in a loss of count rate. Nature will, however, partly compensate for the last problem, since most neutron-producing reactions become more forward peaked at higher energies.

On the other hand, physics will introduce severe difficulties if we want to measure full angular distributions. At 20 MeV, the scattering cross section for any nucleus at $140^\circ - 160^\circ$ is of the order of ≈ 1 mb/sr, while at 100 MeV it has dropped to ≈ 10 nb/sr, i.e., 5 orders of magnitude lower! Thus, only a limited angular range can be measured. Calculated scattering cross sections at 100 MeV for ^{12}C, ^{90}Zr and ^{208}Pb in the angular region $\theta_{CM} = 0^\circ - 60^\circ$ is shown in Fig. 4, where it can be seen that the

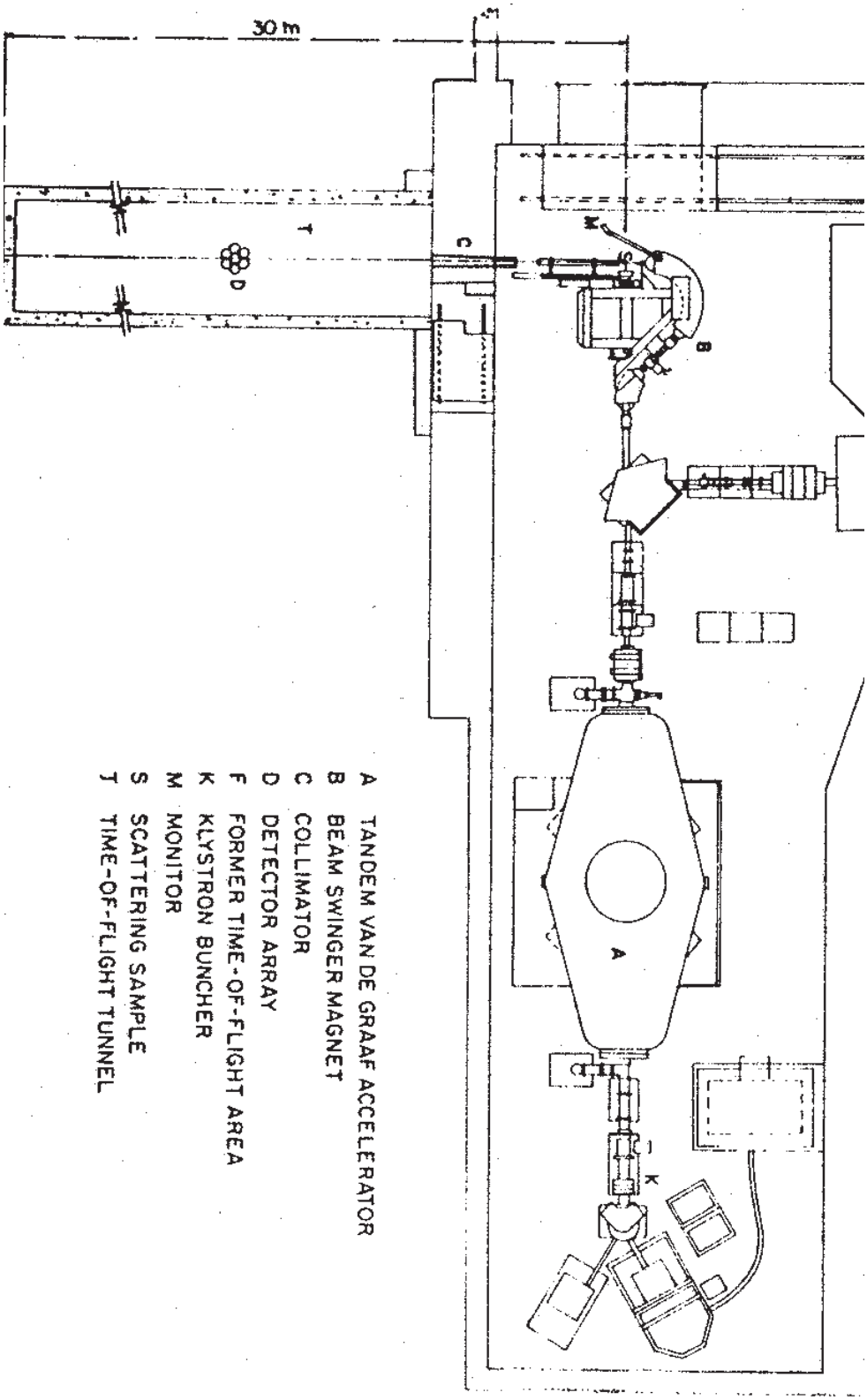

Figure 3: The Ohio University beam swinger facility [10].

cross section already at 60° is down to the order of 1 mb/sr.

One way out of these problems is to find a totally different approach. If we start by increasing the distance between the neutron producing target and the scatterer, there will be enough space for a

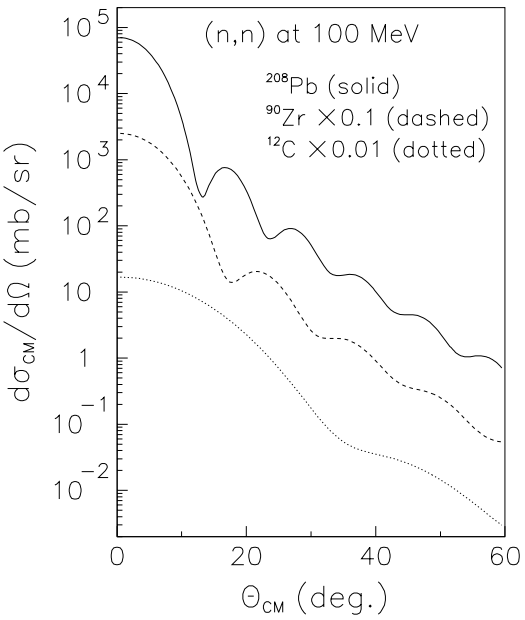

Figure 4: Calculated angular distributions at 100 MeV for ^{12}C, ^{90}Zr and ^{208}Pb.

heavy shielding of the beam dump, while at the same time the neutron beam could be collimated to high quality before entering the low-background scattering area. If we at the same time give up the ToF method, we could shorten the distance from the scatterer to the neutron detector considerably, e.g., to about 1 m. Thus we would gain back in solid angle what was lost when increasing the target–sample distance. The problem left is how to construct a neutron spectrometer without ToF. This can be done using a technique that is not feasible at low energy, namely by converting the neutrons to recoil protons in a relatively thin hydrogenous converter, and then detect the recoil protons with a ΔE-E telescope. The method could be further refined by including position-sensitive detectors for tracking of the protons. The increase in solid angle must, however, also compensate for the loss of detector efficiency, from $10-20\%$ for a typical ToF detector, to about 1%.

A detector system of the type described was first used for scattering measurements at 65 MeV by the Davis group [16, 17]. Their setup is shown in Fig. 5. Neutrons were produced with the ^{7}Li(p,n)^{7}Be reaction, which gives a full-energy peak, corresponding to the ground state and first excited state of ^{7}Be, and a rather flat low-energy tail. The proton beam was carefully dumped, and a clean neutron beam was formed with a 1.5 m thick steel collimator. The detector assembly was put in two different positions, covering the angular ranges $6^\circ - 20^\circ$ and $18^\circ - 48^\circ$, with a distance scatterer–converter of 100 and 35 cm, respectively. The overall energy resolution was 2.7 MeV. The result of elastic scattering from natural targets of C, Si, Ca, Fe, Sn and Pb is shown in Fig. 6 [17].

A similar detector setup has been used by a group at Los Alamos [18]. They used the white neutron beam at WNR, produced at 15° by colliding a 800 MeV proton beam from LAMPF with a 7.5 cm tungsten target. The energies of the incident neutrons were determined by ToF techniques over a flight path of about 90 m from the neutron producing target to the scattering facility. With this technique, the neutron intensity per unit energy is a few orders of magnitude lower than that of the Davis facility, but on the other hand, a large energy range, i.e., $45-250$ MeV, can be covered in one measurement. Due to the low neutron intensity, the data had to be binned in quite wide energy bins, i.e., $\Delta E = 10$ MeV at $60-100$ MeV, and $\Delta E = 15-50$ MeV up to 250 MeV. With this equipment, data have been collected at scattering angles in the range $7^\circ - 21^\circ$ for targets of ^{12}C, ^{40}Ca and ^{208}Pb at 10 energy bins from 53 to 225 MeV [18]. With a distance from the scattering sample to the converter of about 1 m, the energy resolution varied from 2.5 to 6 MeV depending on the incident energy and scattering angle.

4 ...SCANDAL at TSL in Uppsala

A detector system for measurement of scattered neutrons in the energy interval $50-160$ MeV, SCANDAL (SCAttered Nucleon Detection AssembLy), has recently been installed at the neutron beam facility

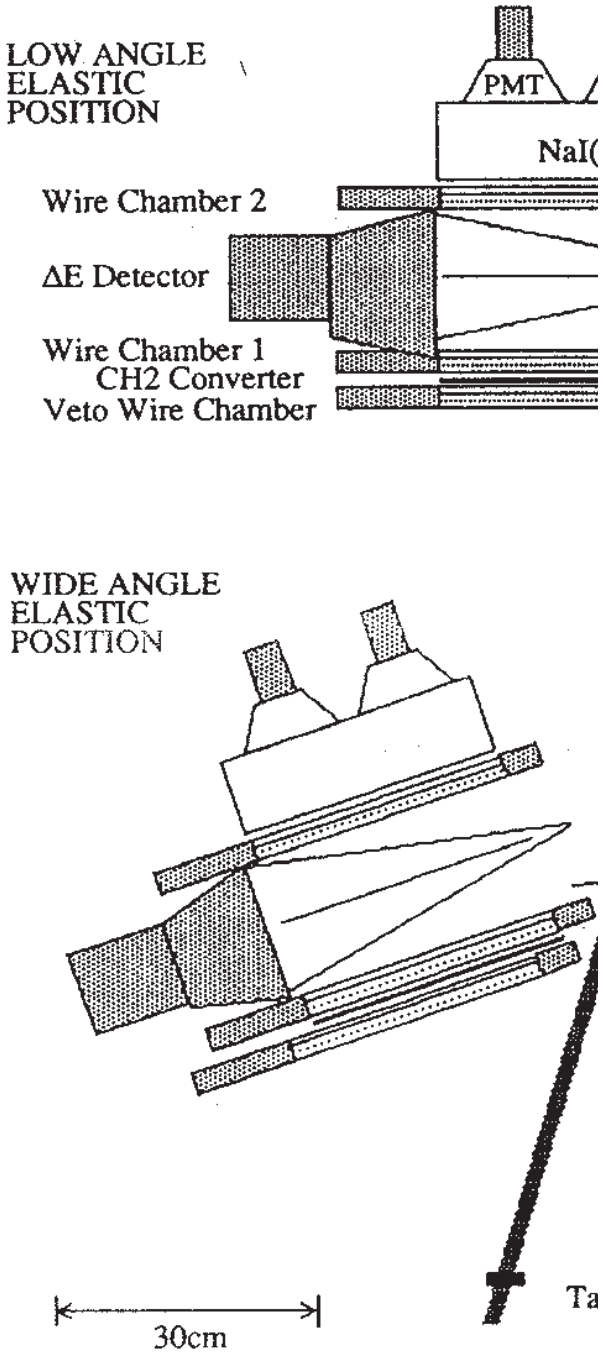

Figure 5: The neutron scattering facility at UC Davis [16, 17].

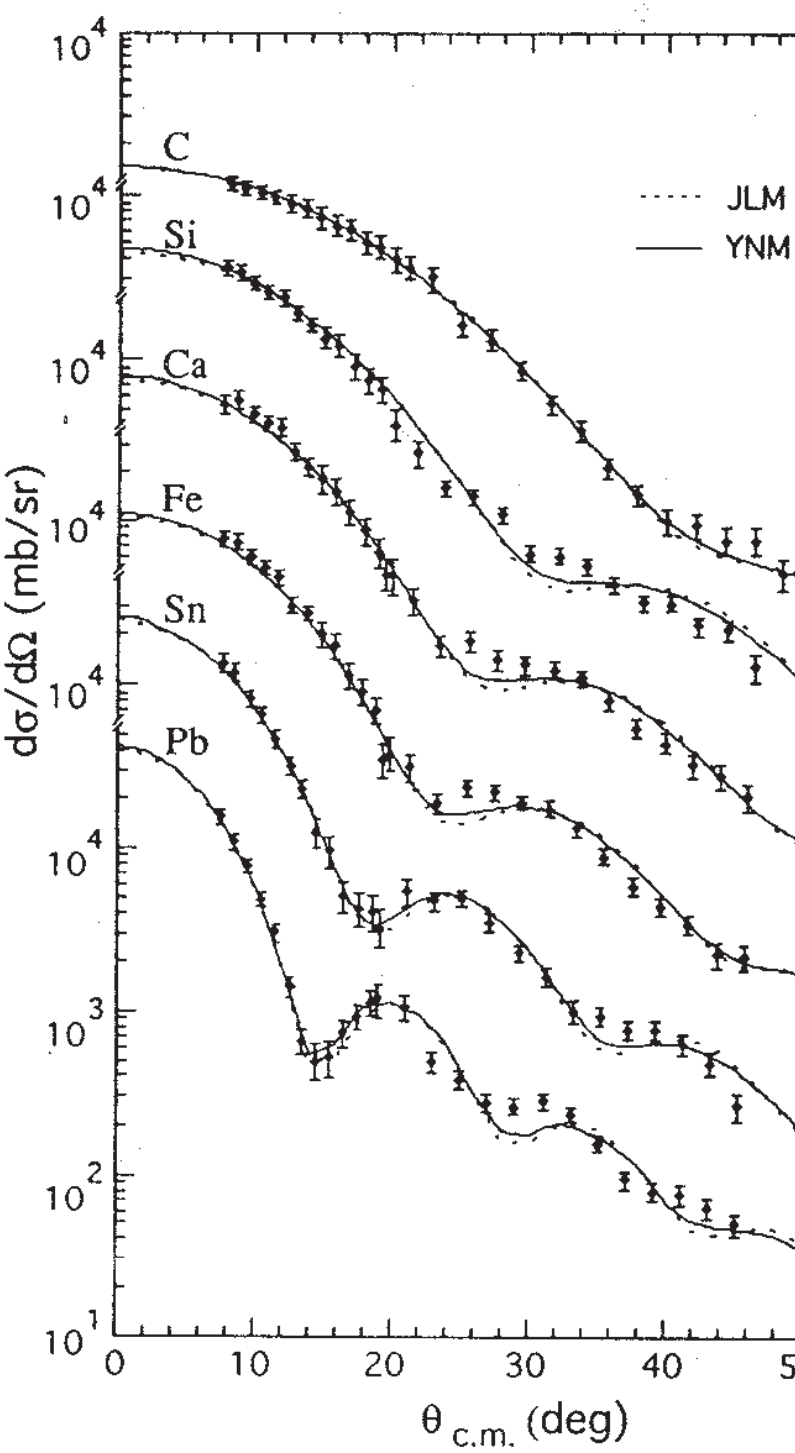

Figure 6: Neutron elastic scattering data at 65 MeV taken with the UC Davis facility [17].

at TSL. Performance tests are at present in progress. The neutron beam facility and the SCANDAL setup are shown in Fig. 7.

The detector layout is as follows: a front veto scintillator for fast charged-particle rejection, a drift chamber for slow rejection, a plastic scintillator neutron-to-proton converter, a drift chamber to reject protons from the conversion scintillator wrapping, a plastic scintillator for triggering, two drift chambers for proton tracking, a ΔE plastic scintillator, which is also part of the trigger, and an array

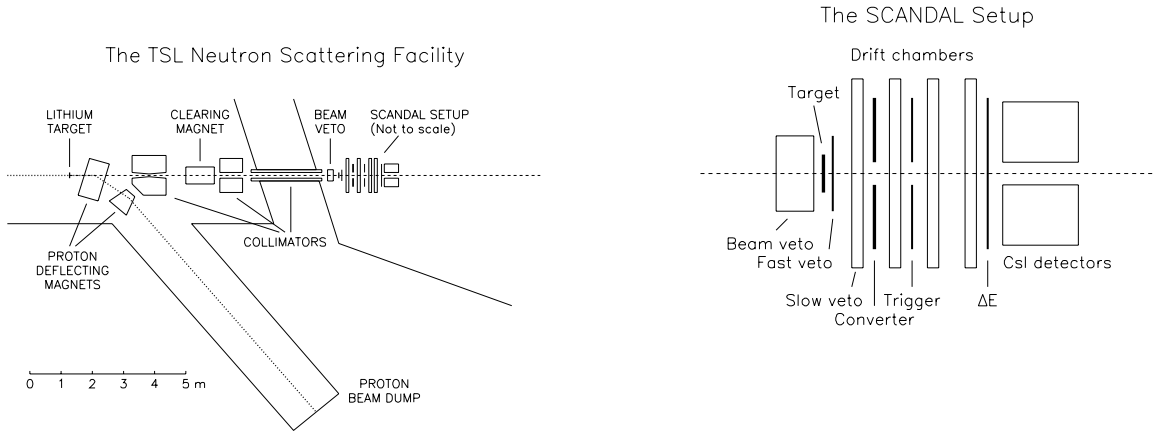

Figure 7: The Uppsala neutron beam facility (left) and the SCANDAL neutron scattering detector system (right).

of CsI detectors.

The converter is active, which has the advantage that it can be thicker, because the proton straggling on the way out of the scintillator can be measured and compensated for. With a thickness of 10 mm ($\sim 0.5\%$ efficiency), the energy loss is up to 10 MeV, giving a contribution of about 1 MeV to the resolution. Since the converter contains not only hydrogen, but also carbon, unambiguous measurements can be performed up to 12 MeV excitation energy. For higher excitation energies, the ^{12}C(n,p) channel opens in the converter, and therefore a unique identification of the target excitation is no longer possible. This is obviously not a problem for elastic scattering, or inelastic scattering to low-lying states.

The setup has 24 CsI detectors, located in two stacks which are grouped 3 by 4. These detectors are 30 cm thick, sufficient for stopping several hundred MeV protons, having a square surface area of 5×5 cm^2, and are conical such that they point to a focus 60 cm away.

The drift chambers, which are of double sense-wire type with two-dimensional readout, having a detection area of 192×960 mm^2, serve two main purposes. First, the H(n,p) cross section close to zero degrees is rather flat over several degrees in the lab system. This effect, combined with the rather large front-area of the CsI's, make the effective subtended angular range for each detector quite large. Using the drift chambers, the conversion point is well determined, and thus the remaining contribution to the angular resolution is the width of the neutron beam (or the sample). Second, they have the potential of allowing rejection of spurious events.

The energy resolution has contributions from the neutron beam, the converter, the ΔE detector and the CsI's. These contributions are estimated to be 1.0, 1.0, 0.3 and 2.0 MeV (FWHM), respectively. This makes a total energy resolution of 2.5 MeV, i.e., dominated by the CsI resolution. The angular resolution is solely due to the neutron beam (or sample) width. Assuming the sample illumination to be a square distribution with a 7 cm diameter, the angular resolution (rms) for a sample-to-converter distance of 60 cm is about 2°, and with a distance of 100 cm it is about 1°. The angular resolution is most crucial at small angles, where the cross section falls rapidly. For these angles, the cross section is also large, and thereby a narrow strip sample could be used to improve the angular resolution.

With the present setup, the solid angle is 100 msr at 80 cm distance from a point sample to the CsI's. This will be slightly smaller for an extended sample, but the decrease is marginal. With the parameters of the present setup and reasonable sample thicknesses, the total beam time required to get 1000 counts in each 1° bin for elastic scattering at 100 MeV in the angular range $5° - 60°$ from a ^{208}Pb sample of reasonble size is about 80 hours. With overhead time for adjustments, calibrations etc, this makes measurements for one target per week of beam time feasible.

The targets for this project would primarily be a set of closed-shell nuclei, e.g., ^{16}O, ^{40}Ca and ^{208}Pb. In addition, the semi-magic ^{90}Zr would be an interesting medium-weight target. Another often investigated nucleus is ^{12}C, which will be studied anyway during the commissioning.

5 How to normalize data?

The measurements with SCANDAL, or other similar setups, are only relative, since it is extremely difficult to determine the absolute efficiency, as well as the incident neutron flux, with high precision. To obtain absolute cross sections, a nucleus with well-known cross section, at least at some angle, has to be measured in parallel. Unfortunately, no such cross section exists! The best available is the *np* scattering cross section.

Recently, our group has measured *np* scattering at 96 and 162 MeV in the $70° - 180°$ (CM) region, with a very precise extrapolated value of the pion-nucleon coupling constant as the most profound result [19, 20, 21]. For these measurements our magnetic proton recoil spectrometer was used [22]. The major uncertainty in the extracted value is related to the absolute scale, which was determined by normalizing to the total cross section, which is known to better than 1%. Our normalization has, however, an uncertainty of $1.5 - 2.5\%$ from the fact that all the angular range could not be measured with the used facility. Nevertheless, we have found deviations from potential models and phase-shift analyses of the order of 10% at 180°, i.e., with the proton emitted at 0°. The huge world data base, on which these models are built, contain several discrepancies and inconsistencies, both regarding the angular shape and the normalization [23].

For the forward-angle cross section, which is of interest here, there exist very few data, and no one can say what the uncertainty is. On the basis of our experience in the backward hemisphere, we believe, however, that it can be on the 10% level, or even more. This is thus one of the major limitations of the precision that can be obtained. On the other hand, it might be possible to use SCANDAL to measure part of the forward angular distribution ($\theta_{CM} = 0° - 70°$) and join it with our previous back-angle data, thus improving the differential cross section, as well as the normalization.

6 Conclusions

The study of elastic neutron scattering at intermediate energies is essential for the understanding of the isovector term in the fundamental nucleon-nucleus interaction, as well as for the development of macroscopic and microscopic optical potentials at these energies. Also for several applications, e.g., within ADTT, medicine, etc., a better knowledge of neutron scattering cross sections would be of great value.

The difficulties in such measurements are, however, severe. The ToF method starts to be impractical for several reasons, and spectrometers based on conversion of neutrons into protons have to be employed, although the efficiency of such arrangements is in the $< 1\%$ region. Also the physics work against the experimentalists, since the cross sections at large angles tend to be extremely small. If the measurements are restricted to a limited forward angular region, they can, however, be performed.

One of the most prominent problems is the absolute normalization of the data. The only cross section that at present could be considered for that purpose is the *np* scattering cross section, which, unfortunately, has uncertainties of the order of 10% or more. A better determination of this cross section in the intermediate energy range must therefore be given the highest priority.

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