International Conference on Nuclear Data for Science and Technology 2007
DOI: 10.1051/ndata:07372

# Elastic neutron scattering at 96 MeV

Angelica Öhrn[1,a], Joakim Klug[1], Jan Blomgren[1], Cecilia Gustavsson[1], Philippe Mermod[1], Leif Nilsson[1], Stephan Pomp[1], Michael Österlund[1], Udomrat Tippawan[2], Alexander Prokofiev[3], and Gennady Tutin[4]

[1] Department of Neutron Research, Uppsala University, P.O. Box 525, 75120 Uppsala, Sweden
[2] Fast Neutron Research Facility, Chiang Mai University, Thailand
[3] The Svedberg Laboratory, Uppsala University, Sweden
[4] Khlopin Radium Institute, St. Petersburg, Russia

**Abstract.** A facility for detection of scattered neutrons in the energy interval 50–130 MeV, SCANDAL (SCAttered Nucleon Detection AssembLy), has recently been installed at the 20–180 MeV neutron beam line of the The Svedberg Laboratory, Uppsala. Elastic neutron scattering from $^{12}$C, $^{56}$Fe, $^{89}$Y and $^{208}$Pb has been studied at 96 MeV in the 10–70° interval. The results from $^{12}$C and $^{208}$Pb have recently been published, while the data from $^{56}$Fe and $^{89}$Y are under analysis. The achieved energy resolution, 3.7 MeV, is about an order of magnitude better than for any previous experiment above 65 MeV incident energy. The present experiment represents the highest neutron energy where the ground state has been resolved from the first excited state in neutron scattering. A novel method for normalization of the absolute scale of the cross section has been used. The estimated normalization uncertainty, 3%, is unprecedented for a neutron-induced differential cross section measure ment on a nuclear target. The results are compared with modern optical model predictions, based on phenomenology or microscopic theory. Applications for these measurements are nuclear waste incineration, single event upsets in electronics, dosimetry and fast neutron therapy.

## 1 Introduction

The interest in high-energy neutron data is rapidly growing, since a number of potential large-scale applications involving fast neutrons are under development, or at least have been identified. These applications primarily fall into three sectors; nuclear energy and waste, effects on electronics and nuclear medicine.

For all these applications, an improved understanding of neutron interactions is needed for calculations of neutron transport and radiation effects. The nuclear data needed for this purpose come almost entirely from nuclear scattering and reaction model calculations, which all depend heavily on the optical model, which in turn is determined by elastic scattering and total cross section data.

Neutron scattering data are also important for a fundamental understanding of the nucleon-nucleus interaction, in particular for determining the isovector term [1]. Coulomb repulsion of protons creates a neutron excess in all stable nuclei with $A > 40$. Incident protons and neutrons interact differently with this neutron excess. The crucial part in these investigations has been neutron-nucleus elastic scattering data to complement the already existing proton-nucleus data.

Above 50 MeV neutron energy, there has been only one measurement on neutron elastic scattering with an energy resolution adequate for resolving individual nuclear states, an experiment at UC Davis at 65 MeV on a few nuclei [2]. In addition, a few measurements in the 0–20° range are available, all with energy resolution of 20 MeV or more. This is, however, not crucial at such small angles because elastic scattering dominates heavily, but at larger angles such a resolution would make data very difficult to interpret.

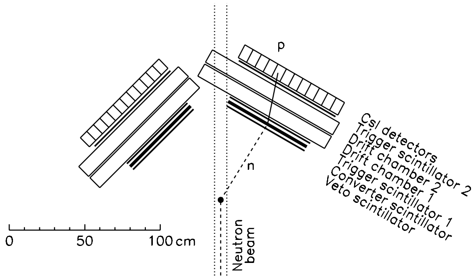


**Fig. 1.** A schematic layout of the SCANDAL setup. A typical event is indicated.

## 2 Experimental setup

The neutron beam facility at the The Svedberg Laboratory, Uppsala, Sweden, has recently been described in detail [3], and therefore only a brief description is given here. The 96 ± 0.5 MeV (1.2 MeV FWHM) neutrons were produced by the $^{7}$Li(p,n) reaction by bombarding a 427 mg/cm$^{2}$ disc of isotopically enriched (99.98%) $^{7}$Li with protons from the cyclotron. The low-energy tail of the source neutron spectrum was suppressed by time-of-flight techniques. After the target, the proton beam was bent into a well-shielded beam dump. A system of three collimators defined a 9 cm diameter neutron beam at the scattering target.

Scattered neutrons were detected by the SCANDAL (SCAttered Nucleon Detection AssembLy) setup [3]. (see fig. 1). It consists of two identical systems, placed to cover

[a] Presenting author, e-mail: angelica.ohrn@tsl.uu.se

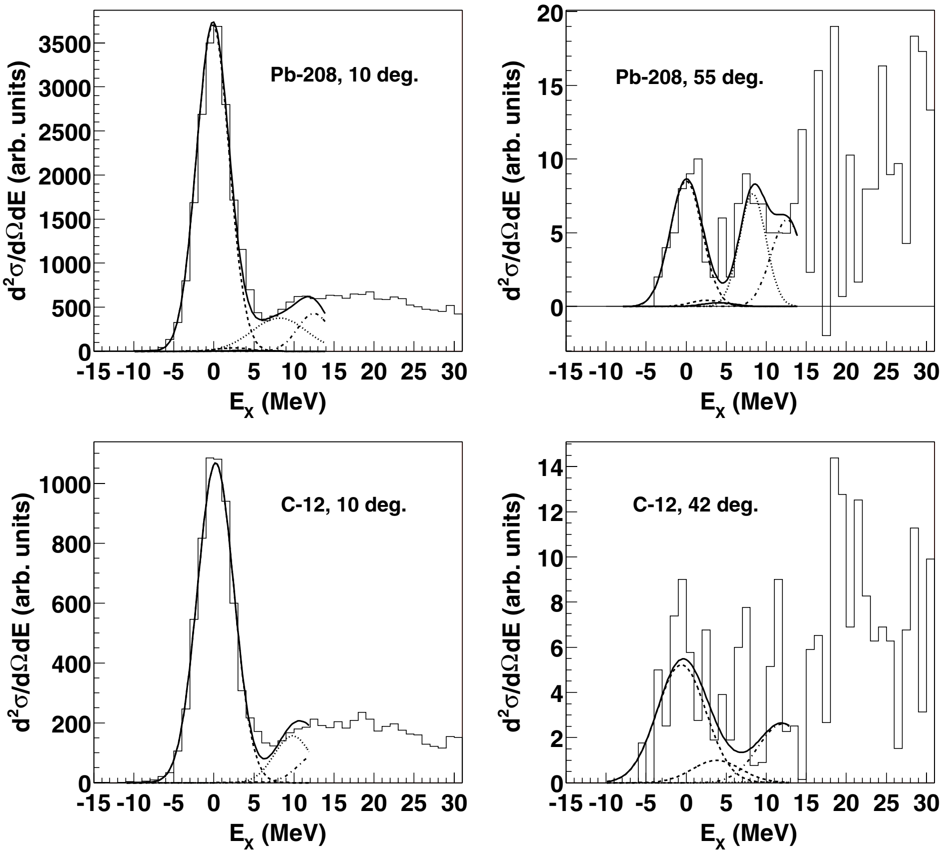


**Fig. 2.** Excitation energy spectra for elastic neutron scattering from $^{12}$C and $^{208}$Pb at 96 MeV incident neutron energy, together with gaussians representing known excited states. See the text for details.

10–50° and 30–70°, resp. The energy of the scattered neutrons is determined by measuring the energy of proton recoils from a plastic scintillator, and the angle is determined by tracking the recoil proton. In the present experiment, each arm consisted of a 2 mm thick veto scintillator for fast charged-particle rejection, a 10 mm thick neutron-to-proton converter scintillator, a 2 mm thick plastic scintillator for triggering, two drift chambers for proton tracking, a 2 mm thick $\Delta E$ plastic scintillator which was also part of the trigger, and an array of CsI detectors for energy determination of recoil protons produced in the converter by np scattering. The trigger was provided by a coincidence of the two trigger scintillators, vetoed by the front scintillator. The total excitation energy resolution varies with CsI crystal, but is on average 3.7 MeV (FWHM). The angular resolution is in the 1.0–1.3° (rms) range.

## 3 Results and discussion

### 3.1 Data on $^{12}$C and $^{208}$Pb

Excitation energy spectra are presented in figure 2. In these spectra, gaussians representing known states are indicated. For $^{12}$C, the ground state ($0^+$) and the two collective states at 4.4 MeV ($2^+$) and 9.6 MeV ($3^-$) are shown. In the case of $^{208}$Pb, the ground state ($0^+$) and the two collective states at 2.6 MeV ($3^-$) and 4.1 MeV ($2^+$) are shown, as well as a gaussian at 8.3 MeV representing a cluster of weak states. For both nuclei, a gaussian at 12.6 MeV represents the opening of conversions due to $^{12}$C(n,p) reactions in the converter scintillator, i.e., an instrument background. As can be seen, in no case the population of excited states seriously affects the determination of the ground state cross section. Angular distributions of elastic neutron scattering from $^{12}$C and $^{208}$Pb at 96 MeV incident neutron energy are presented in figure 3. The data are compared with phenomenological and microscopic optical model predictions in the upper and lower panels, respectively. The theoretical curves have all been folded with the experimental angular resolution to facilitate comparisons with data. The data by Salmon at 96 MeV [4] are also shown.

The angular distributions presented have been corrected for reaction losses and multiple scattering in the target. The contribution from other isotopes than $^{208}$Pb in the lead data has been corrected for, using cross section ratios calculated with the global potential by Koning and Delaroche [5]. The absolute normalization of the data has been obtained from knowledge of the total elastic cross section, which has been determined from the difference between the total cross section ($\sigma_T$) [6] and the reaction cross section ($\sigma_R$) [7,8]. This $\sigma_T$ - $\sigma_R$ method, which is expected to have an uncertainty of about 3%, has been used to normalize the $^{12}$C data. The present $^{208}$Pb(n,n) data have been normalized relative to the present $^{12}$C(n,n) data,

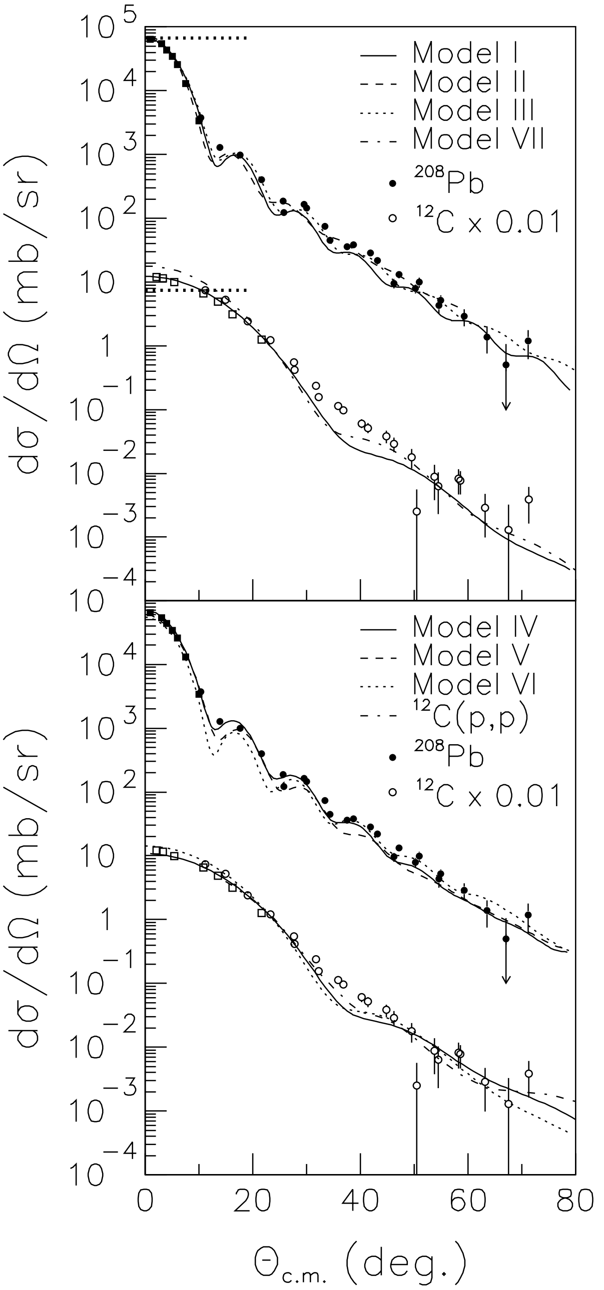


**Fig. 3.** Angular distributions of elastic neutron scattering from $^{12}$C (open circles) and $^{208}$Pb (solid) at 96 MeV incident neutron energy. The $^{12}$C data and calculations have been multiplied by 0.01. The data by Salmon at 96 MeV [4] are shown as squares. Upper panel: predictions by phenomenological models (I–III, VII). The thick dotted horizontal lines show Wick's limit for the two nuclei. Lower panel: predictions by microscopic models (IV–VI), and data on elastic proton scattering from $^{12}$C [12]. See the text for details.

knowing the relative neutron fluences, target masses, etc. The total elastic cross section of $^{208}$Pb has previously been determined with the $\sigma_T$ - $\sigma_R$ method. The accuracy of the present normalization has been tested by comparing the total elastic cross section ratio ($^{208}$Pb/$^{12}$C) obtained with the $\sigma_T$ - $\sigma_R$ method above, and with the ratio determination of the present experiment, the latter being insensitive to the absolute scale. These two values differ by about 3%, i.e., they are in agreement within the expected uncertainty.

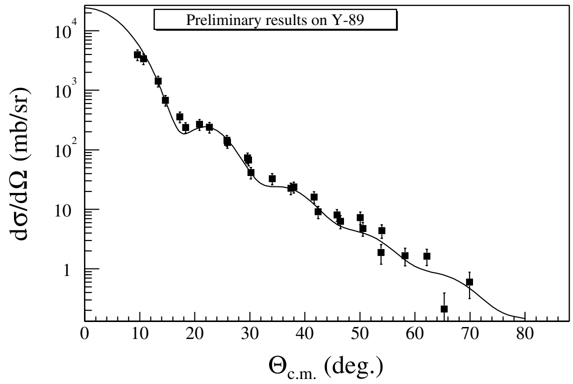


**Fig. 4.** Preliminary angular distribution of elastic neutron scattering from $^{89}$Y at 96 MeV incident neutron energy together with a prediction by a phenomenological model [5].

The data are compared with model predictions in figure 3, where the upper and lower panels show phenomenological (I–III, VII) and microscopic (IV–VI) models, respectively. The models are described in detail in refs. [9] and [10].

All models are in reasonably good agreement with the $^{208}$Pb data. It should be pointed out that none of the predictions contain parameters adjusted to the present experiment. In fact, they were all made before data were available. Even the absolute scale seems to be under good control, which is remarkable, given that neutron beam intensities are notoriously difficult to establish.

A new measurement on $^{12}$C has recently been performed. The results show good agreement with the models used above, see ref. [11].

A basic feature of the optical model is that it establishes a lower limit on the differential elastic scattering cross section at 0° if the total cross section is known, often referred to as Wick's limit. It has been observed in previous experiments at lower energies that for most nuclei, the 0° cross section falls very close to Wick's limit, although there is no a priori reason why the cross section cannot exceed the limit significantly. An interesting observation is that the present $^{208}$Pb data are in good agreement with Wick's limit, while the $^{12}$C 0° cross section lies about 70% above the limit. A similar behaviour has previously been observed in neutron elastic scattering at 65 MeV [2], where the $^{12}$C data overshoot Wick's limit by about 30%, whilst the $^{208}$Pb data agree with the limit.

### 3.2 Other nuclei

Preliminary data on $^{89}$Y [14] are presented in figure 4, together with Model I [5]. Corrections for multiple scattering remain. The model describes the shape of the data points reasonably well. Preliminary data on $^{56}$Fe [15] are presented in figure 5, together with Model I [5]. All corrections as well as the subtraction of the contribution of inelastic scattering events remain to be performed, which are the most likely reasons why the model does not describe the shape of the data points better. For normalization, both $^{89}$Y and $^{56}$Fe have been measured relative to $^{12}$Ca.

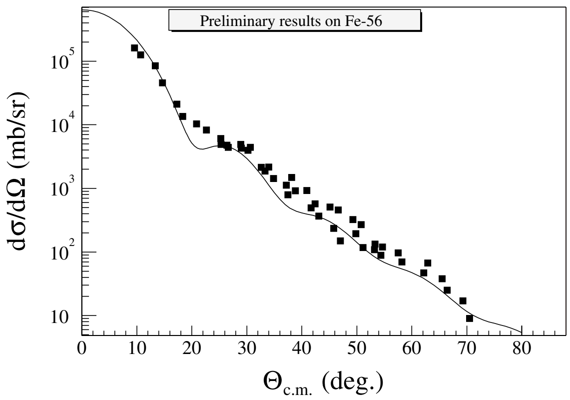


**Fig. 5.** Preliminary angular distribution of elastic neutron scattering from $^{56}Fe$ at 96 MeV incident neutron energy together with a prediction by a phenomenological model [5].

## 4 Summary, conclusion and outlook

In short, first results on elastic neutron scattering from $^{12}C$ and $^{208}Pb$ at 96 MeV incident neutron energy are presented, and compared with theory predictions. This experiment represents the highest neutron energy where the ground state has been resolved from the first excited state in neutron scattering. The measured cross sections span more than four orders of magnitude. Thereby, the experiment has met – and surpassed – the design specifications. The overall agreement with theory model predictions, both phenomenological and microscopic, is good. In particular, the agreement in absolute cross section scale is impressive.

The SCANDAL setup will be upgraded with thicker CsI crystals which will allow elastic scattering measurements at higher energies.

We wish to thank the technical staff of The Svedberg Laboratory for enthusiastic and skillful assistance. This work was supported by the HINDAS project of the 5th EU framework programme, as well as by Vattenfall AB, Swedish Nuclear Fuel and Waste Management Company, Swedish Nuclear Power Inspectorate, Barsebäck Power AB, Forsmark AB, Ringhals AB, Swedish Defence Research Agency and the Swedish Research Council.

## References

1. See, e.g., *Neutron-Nucleus Collisions: A probe of Nuclear Structure*, AIP Conf. Proc. **124** (AIP, New York, 1985).
2. E.L. Hjort et al., Phys. Rev. C **50**, 275 (1994).
3. J. Klug et al., Nucl. Instrum. Meth. A **489**, 282 (2002).
4. G.L. Salmon, Nucl. Phys. **21**, 15 (1960).
5. A.J. Koning, J.P. Delaroche, Nucl. Phys. A **713**, 231 (2003)
6. R.W. Finlay et al., Phys. Rev. C **47**, 237 (1993).
7. J. DeJuren, N. Knable, Phys. Rev. **77**, 606 (1950).
8. R.G.P. Voss, R. Wilson, Proc. Roy. Soc. A **236**, 41 (1956).
9. J. Klug et al., Phys. Rev. C **68**, 064605 (2003).
10. J. Klug et al., Phys. Rev. C **67**, 031601(R) (2003).
11. P. Mermod et al., Phys. Rev. C **74**, 054002 (2006).
12. G. Gerstein, J. Niederer, K. Strauch, Phys. Rev. **108**, 427 (1957).
13. J. Matero, Z. Phys. A **351**, 29 (1995).
14. A. Öhrn et al. (to be published).
15. M. Österlund et al. (to be published).