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ELASTIC NEUTRON SCATTERING STUDIES AT 96 MeV ON ELEMENTS OF INTEREST FOR TRANSMUTATION

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Elastic neutron scattering from ^{12}C, ^{14}N, ^{16}O, ^{28}Si, ^{40}Ca, ^{56}Fe, ^{89}Y and ^{208}Pb has been studied at 96 MeV in the $10-70$ degree interval, using the SCANDAL (SCAttered Nucleon Detection AssembLy) facility. The results for ^{12}C and ^{208}Pb have recently been published, while the data on the other nuclei 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. 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 measurement on a nuclear target.

Elastic neutron scattering is of utmost importance for a vast number of applications. Besides its fundamental importance as a laboratory for tests of isospin dependence in the nucleon-nucleon, and nucleon-nucleus, interaction, knowledge of the optical potentials derived from elastic scattering come into play in virtually every application where a detailed understanding of nuclear processes are important.

Applications for these measurements are nuclear waste incineration, single event upsets in electronics and fast neutron therapy. The results at light nuclei of medical relevance (^{12}C, ^{14}N and ^{16}O,) are presented separately. In the present contribution, results on the heavier nuclei are presented, among which several are of profound relevance to accelerator-driven systems for transmutation.

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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, nuclear medicine, and effects on electronics. 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.

The nuclear data needs for transmutation of nuclear waste in general and spent nuclear fuel in particular are outlined in refs. [1, 2, 3], while the needs for neutron therapy of cancer tumours are reviewed in ref. [4], and upsets in electronics are discussed in ref. [5, 6]. In the present work, a programme on elastic neutron scattering at 96 MeV is presented, which deals with all these applications.

Neutron-scattering data are also important for a fundamental understanding of the nucleon-nucleus interaction, in particular for determining the the isovector term [7]. 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 previous 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 [8]. In addition, a few measurements in the $0-20^\circ$ 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. Recently, results on neutron scattering from ^{12}C, ^{40}Ca and ^{208}Pb in the $65-225$ MeV range from Los Alamos have been published [9]. The energy resolution is comparable to the present work, but the angular range is limited to $7-23^\circ$.

2. Experimental setup

The neutron beam facility at The Svedberg Laboratory, Uppsala, Sweden, has recently been described in detail [10], 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 [10]. It consists of two identical systems, placed to cover $10-50^\circ$ and $30-70^\circ$, respectively. 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 ΔE plastic scintillator that 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

Angular distributions of elastic-neutron scattering from ^{12}C and ^{208}Pb at 96 MeV incident neutron energy are presented in Fig. 1. The data are compared with phenomenological and microscopic optical-model predictions in the left and right 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 [11] 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 [12].

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 (σ_T) [13] and the reaction cross section (σ_R) [14, 15]. This σ_T - σ_R method, which is expected to have an uncertainty of about 3 %, has been used to normalize the ^{12}C data. The ^{208}Pb(n,n) data have been normalized relative to the ^{12}C(n,n) data, knowing the relative neutron fluences, target masses, etc. The total elastic cross section of ^{208}Pb has previously been determined with the σ_T - σ_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 σ_T - σ_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.

A novel technique for normalization, which is based on relative measurements versus the *np* scattering cross section [16], has also been tested and was found to have an uncertainty of about 10 %.

The data are compared with model predictions in Fig. 1, where the left and right panels show phenomenological and microscopic models, respectively. The models are described in detail in refs. [17] and [18].

When comparing these predictions with data, a few striking features are evident. First, 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. Second, all models fail to describe the ^{12}C data in the 30 – 50° range. The models predict a saddle structure, which is not evident from the data.

This mismatch has prompted a re-examination of the ^{12}C(n,n) cross section. Fortunately, this could be accomplished in combination with another experiment. Recently, we have studied *nd*

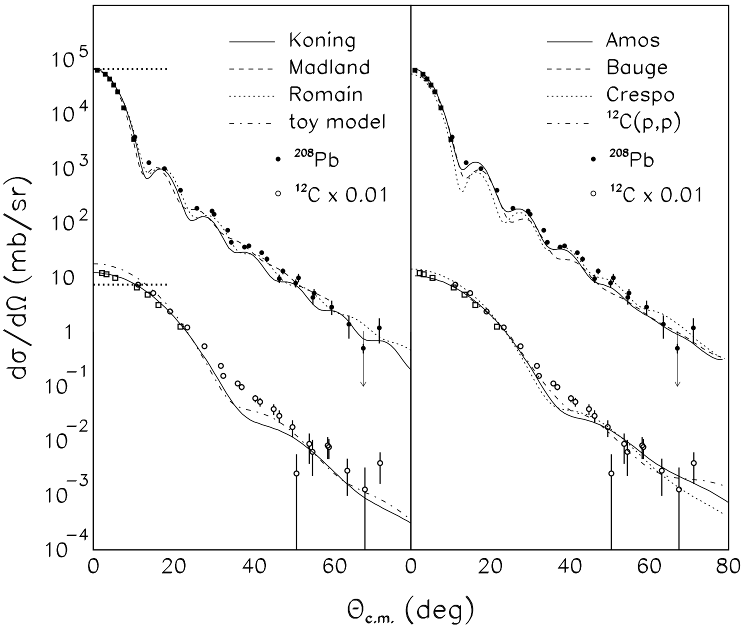

Figure 1: Angular distributions of elastic neutron scattering from ^{12}C (open circles) and ^{208}Pb (solid) at 96 MeV incident neutron energy. The ^{12}C data and calculations have been multiplied by 0.01. The data by Salmon at 96 MeV [11] are shown as squares. Left panel: predictions by phenomenological models. The thick dotted horizontal lines show Wick's limit for the two nuclei. Right panel: predictions by microscopic models, and data on elastic proton scattering from ^{12}C [22]. See the text for details, and refs. [17, 18] and references therein for a description of the theory models.

scattering at the same energy to investigate three-nucleon interaction effects. These results show clear evidence of such 3*N* forces [19, 20, 21]. In these experiments, scattering from carbon was used for normalization, as described above. The size of the target was, however, significantly larger than in the experiments above, resulting in far better statistics. This allowed more stringent analysis procedures to be used, and the results seem to indicate that the ^{12}C elastic scattering cross section is actually in agreement with the theory models. Thus, the main reason for the discrepancy above was probably due to an unbalance between the ground state and the first excited state in the analysis, resulting from the poor statistics for the excited state.

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 [23, 24]. 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 [8], where the ^{12}C data overshoot Wick's limit by about 30 %, whilst the ^{208}Pb data agree

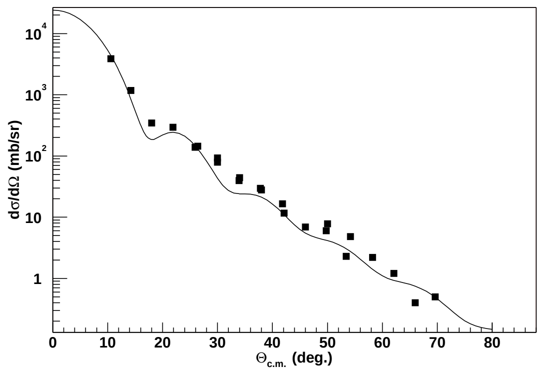

Figure 2: Preliminary angular distribution of elastic neutron scattering from ^{89}Y at 96 MeV incident neutron energy together with a prediction by the Koning-Delaroche potential [12].

with the limit.

It has recently been shown by Dietrich et al. [25] that this makes sense. Using the Koning-Delaroche potential [12], it has been shown that Wick's limit actually deviates less than 5 % from an equality for ^{208}Pb over the entire 5 – 100 MeV interval. The lightest nucleus investigated was ^{28}Si, but the systematics imply that large discrepancies for ^{12}C should be expected.

Preliminary data on ^{89}Y are presented in Fig. 2, together with the Koning-Delaroche potential [12]. The data have been normalized to the model and it can be seen that it describes the shape of the data points reasonably well. The measurements on ^{16}O have been analyzed and are presented in another contribution to this workshop. Measurements on ^{14}N, ^{28}Si, ^{40}Ca, and ^{56}Fe have been completed and the data are under analysis.

4. Conclusions 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 the absolute cross-section scale is impressive.

Performance investigations have revealed that the method as such should work also at higher energies. Recently, the TSL neutron beam facility has been upgraded in intensity, making measurements at the highest energy, 180 MeV, feasible. An experimental campaign at 180 MeV does, however, require an upgrade of the CsI detectors of SCANDAL.

Acknowledgments

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References

[1] A. Koning, et al., J. Nucl. Sci. Tech., Suppl. **2** (2002) 1161.

[2] J. Blomgren, in Proceedings of Workshop on Nuclear Data for Science & Technology: Accelerator Driven Waste Incineration, Trieste, Italy, Sept. 10-21, 2001, eds. M. Herman, N. Paver, A. Stanculescu, ICTP lecture notes **12** (2002) 327.

[3] J. Blomgren, Nuclear data for accelerator-driven systems - Experiments above 20 MeV, in Proceedings of EU enlargement workshop on Neutron Measurements and Evaluations for Applications, Bucharest, Romania, October 20-23, 2004.

[4] J. Blomgren and N. Olsson, Radiat. Prot. Dosim. **103(4)** (2003) 293.

[5] J. Blomgren, B. Granbom, T. Granlund, N. Olsson, Mat. Res. Soc. Bull. **28** (2003) 121.

[6] J. Blomgren, Nuclear Data for Single-Event Effects, in Proceedings of EU enlargement workshop on Neutron Measurements and Evaluations for Applications, Budapest, Hungary, November 5-8, 2003. EUR Report 21100 EN, Luxembourg: Office for Official Publications of the European Communities, ISBN 92-894-6041-5, European Communities, 2004.

[7] See, e.g., Neutron-Nucleus Collisions: A probe of Nuclear Structure, AIP Conference Proceedings **124** (AIP, New York, 1985).

[8] E.L. Hjort, et al., Phys. Rev. C **50** (1994) 275.

[9] J.H. Osborne, et al., Phys. Rev. C **70** (2004) 054613.

[10] J. Klug, et al., Nucl. Instr. Meth. **A 489**, 282 (2002).

[11] G.L. Salmon, Nucl. Phys. **21**, 15 (1960).

[12] A.J. Koning, J.P. Delaroche, Nucl. Phys. **A713**, 231 (2003).

[13] R.W. Finlay, et al., Phys. Rev. C **47**, 237 (1993).

[14] J. DeJuren, N. Knable, Phys. Rev. **77**, 606 (1950).

[15] R.G.P. Voss, R. Wilson, Proc. Roy. Soc. **A 236**, 41 (1956).

[16] C. Johansson, et al., Phys. Rev. C **71** (2005) 024002.

[17] J. Klug, et al., Phys. Rev. C. **67** (2003) 031601(R)

[18] J. Klug, et al., Phys. Rev. C **68** (2003) 064605.

[19] P. Mermod, et al., Phys. Lett. **B 597** (2004) 243.

[20] P. Mermod, et al., Phys. Rev. C **72** (2005) 061002(R).

[21] P. Mermod, et al., submitted to Phys. Rev. C.

[22] G. Gerstein, J. Niederer, K. Strauch, Phys. Rev. **108**, 427 (1957).

[23] G.C. Wick, Atti. R. Accad. Naz. Lincei, Mem. Cl. Sci. Fis. Mat. Nat. **13**, 1203 (1943).

[24] G.C. Wick, Phys. Rev. **75**, 1459 (1949).

[25] F.S. Dietrich, J.D. Anderson, R.W. Bauer, S.M. Grimes, Phys. Rev. C **68** (2003) 064608.