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Analyzing powers for neutron elastic scattering at forward angles

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Accurate neutron analyzing powers have been obtained using a new pulsed polarized neutron facility. Data are presented for elastic scattering of 14-MeV neutrons from ^{40}Ca, ^{54}Fe, ^{65}Cu, ^{120}Sn, and ^{208}Pb between 18° and 36°. Our data exhibit no evidence for the anomalously large values which were reported previously at 20°.

[NUCLEAR REACTIONS ^{40}Ca, ^{54}Fe, ^{65}Cu, ^{120}Sn, ^{208}Pb$(\vec{n},n)$, $E=14.0$ MeV; measured $A_y(\theta)$, $\theta=18°-36°$; compared to previous results.]

Analyzing power data are essential in order to investigate the spin dependence of the nucleon-nucleus interaction. Owing to the difficulties in performing experiments with polarized neutrons, such data are scarce for neutron scattering at energies above 4 MeV. A new combination of experimental techniques developed at Triangle Universities Nuclear Laboratory (TUNL) enables us to make neutron analyzing power measurements quite accurately. Analyzing powers $A_y(\theta)$ for 14-MeV polarized neutrons scattered from ^{40}Ca, ^{54}Fe, ^{65}Cu, ^{120}Sn, and ^{208}Pb at angles between 18° and 36° are reported here. Previous measurements in the 10- to 16-MeV region consist primarily of the data of Galloway *et al.*[1] At the scattering angle $\theta=20°$, their measurements show unexpectedly large values which are in strong disagreement with optical model calculations[1] using standard parameters. Our measurements, which are briefly reported here, do not give evidence for such large analyzing powers. Before presenting results, however, we point out the improvements permitted by our new system and comment on some of the corresponding aspects in the work of Galloway *et al.*

There are three major requirements for performing accurate analyzing power measurements with fast neutrons. First, a transversely polarized beam of neutrons is needed, and usually the neutrons are produced in a charged particle reaction. At TUNL we employ polarization transfer in the ^{2}H$(\vec{d},\vec{n})^3$He$_{g.s.}$ reaction at 0°. With the high 90% polarization transfer, the 70% polarized deuteron beam provided by the TUNL Lamb-shift polarized ion source for this work resulted in a 63% polarized neutron beam at 0°. Furthermore, both the differential cross section and the neutron energy for this source reaction decrease rapidly for angles away from 0°, thus providing very favorable background conditions for the side detectors. The Galloway group, as well as most others, have used light-ion reactions with *unpolarized* incident beams to produce polarized neutron beams at some particular reaction angle. Unfortunately, in such source reactions useful polarizations typically occur for angles where the differential cross sections and neutron energies are somewhat lower than at other reaction angles. The detectors must therefore be shielded against a background neutron flux which is large relative to that generated in our method.

Second, scattered neutrons of the desired energy must be detected and background events minimized. In both Galloway's method and ours, neutrons are detected by observing the recoil protons in organic scintillators. In such recoil spectra the energy resolution can be poor, and backgrounds are difficult to unfold. Time-of-flight (TOF) spectra are superior in both of these respects. Our recent development of an efficient pulsing system for the polarized ion source allows us to employ the $^2H(\vec{d},\vec{n})^3He_{g.s.}$ polarization transfer reaction *and* time-of-flight spectroscopy while still retaining sufficient intensity to conduct neutron polarization measurements to a high accuracy in a reasonable time.[2] The improvement permitted by our new method can be illustrated through the following comparison. One type of background is always determined by measuring the yields with the scattering sample removed. The open symbols in Fig. 1 represent one of our (TOF) spectra for scattering 14-MeV neutrons from ^{208}Pb through 20°. The spectrum obtained with the ^{208}Pb sample removed is represented by the solid symbols. The background in the region of the elastic peak contributes 7% of the total counts at this angle. In contrast, in the methods used by Galloway *et al.* this percentage was three to ten times larger at the same angle.

Third, in $A_y(\theta)$ measurements, instrumental asymmetries in the detection system must be eliminated. Both our system and that of Galloway *et al.* use two detectors located at equal scattering angles on opposite sides of the axis of the incident neutron beam. To remove instrumental asymmetries due to different geometries and efficiencies for the two detectors, in a typical neutron measurement the role of the left and right detectors must be interchanged during the measurement. At TUNL we alternate the orientation of the spin of the deuteron beam at the ion source, thereby alternating the polarization axis of the incident neutron beam; this effectively interchanges left and right scattering in the target area while leaving the detectors (and their massive shields) fixed throughout a measurement of $A_y(\theta)$. Galloway *et al.* do not flip the neutron spin, but rotate the detectors and their shielding about the incident neutron beam axis. This is difficult to perform in neutron experiments without introducing instrumental asymmetries because effective neutron collimators and shields are necessarily large and heavy.

Representative TUNL $A_y(\theta)$ data for 14-MeV neutron scattering through angles less than 40° are shown in Fig. 2. Error bars include uncertainties due to all known sources of error: counting statistics, background subtraction, multiple scattering, and beam polarization. Total uncertainties for some of the points are less than ± 0.01. We have obtained analyzing powers of quality similar to that shown in Fig. 2 at both 10 and 14 MeV for all the above isotopes, as well as for ^{58}Ni and ^{116}Sn. The combined data set exhibits a smooth dependence on angle and mass number. For comparison, the forward-angle data at 16 MeV reported by Galloway and co-workers are plotted in Fig. 3. The two sets of data are in serious disagreement at 20°: We

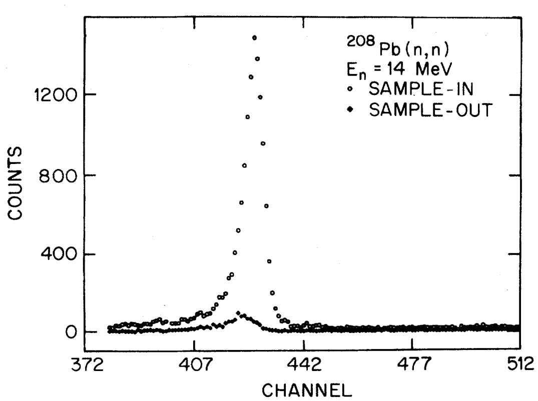

FIG. 1. Time-of-flight spectra for 14-MeV neutrons scattered for the ^{208}Pb measurement at 20°. The sample-out spectrum is shown as solid symbols.

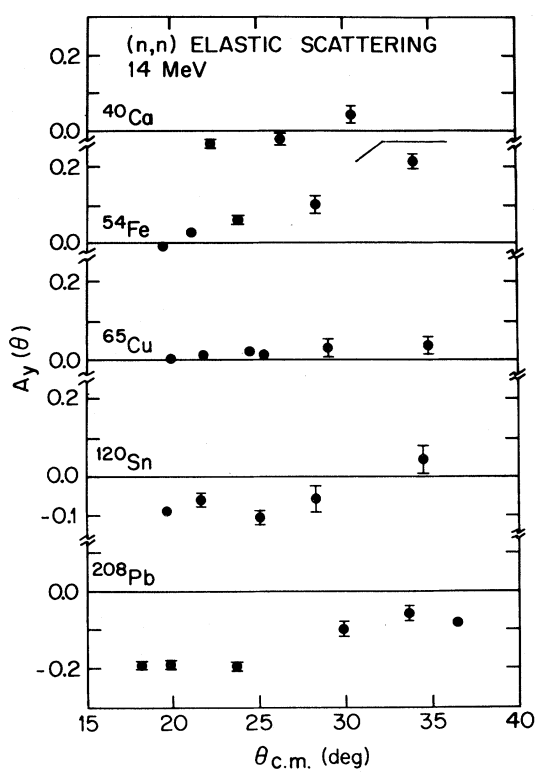

FIG. 2. Analyzing power distributions for forward angle scattering 14-MeV neutrons.

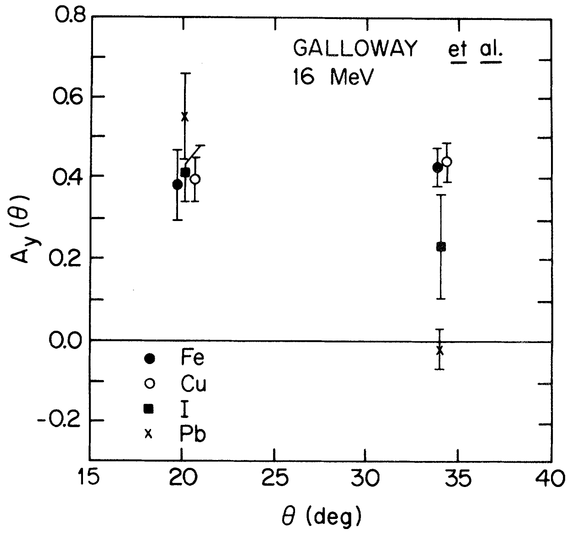

FIG. 3. Analyzing power data of Galloway *et al.* (Ref. 1).

observe no indication of large analyzing powers. Since narrow resonance structure is not observed at these high energies, the 2-MeV difference in bombarding energy cannot provide an explanation. Differences in angular resolution cannot explain the discrepancy—the apparatus of Galloway *et al.* provides an effective angular resolution of 10°, which is a factor of 2 more coarse than for our system. Therefore, we would have been sensitive to a high value for $A_y(\theta)$ at 20°, for example, associated with diffraction effects, even if it were restricted to a narrow angular range. Inelastic scattering would not affect our data; our time-of-flight resolution is about 2 ns, sufficient to allow inelastic events to be eliminated through careful selection of the analysis region for the elastic peak. Also, the Mott-Schwinger interaction, which produces a very large $A_y(\theta)$ at far forward angles, cannot account for the difference. That is, at 14 MeV the Mott-Schwinger effect is not large for the range of angles encompassed in these experiments.

In summary, none of our results suggest the anomalously large values reported by Galloway *et al.*[1] The small uncertainties shown with our data in Fig. 2 include all the known errors introduced with our technique. We acknowledge the care taken in the experiments of Galloway and co-workers, and we have not been able to detect any fundamental error in either their technique or their analysis. Some major differences between the two experimental methods are outlined above. Their method is perhaps weakest with respect to the possibility of introducing false asymmetries in the interchange of the detectors. Their large detector array must preserve strict alignment, since at these forward angles, cross sections change about an order of magnitude over a 5° change in scattering angle. This effect, the relatively poor signal-to-background ratio, and the high background flux are interrelated and probably result in the greatest sources of error in their experiments.

In conclusion, we have obtained accurate values of forward angle neutron analyzing powers for seven nuclei ranging from $A=40$ to 208. The new data are not unreasonable in view of the optical model calculations shown in Ref. 1. Our results are part of a larger set of cross sections and analyzing powers being obtained at TUNL, and a program is underway to use these data to develop a global model for neutron-nucleus scattering.

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