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Polarization of Neutrons Scattered from Li^6 and Li^7

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I. Introduction

I should like to discuss briefly some asymmetry measurements we have performed on the scattering of polarized neutrons from Li^6 and Li^7 in the few hundred keV energy region. The instigation for these measurements was a desire to extend previous data on the polarization of neutrons from the $Li^7(p,n)Be^7$ reaction to lower energies. The results as pertain to the $Li(p,n)$ reaction were presented in a short communication, and here I should like to elaborate slightly on the use of Li^6 and Li^7 as polarization analyzers.

Both of these isotopes of lithium have prominent resonances in their neutron total cross-sections near 250-keV bombarding energy. These are shown in figure 1. In both cases the resonances correspond to states formed by neutrons having one unit of orbital angular momentum. The spins and parities of the compound states are for Li^7 and Li^8, $5/2^-$ and

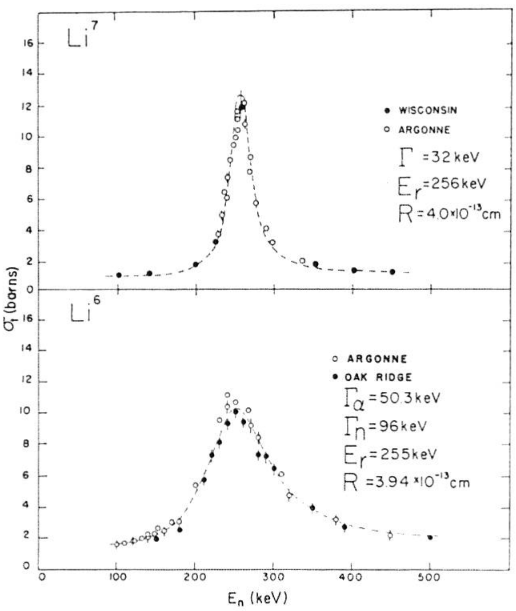

Figure 1

3^+ respectively, which means that in both cases only the larger of the two possible channel spin states are involved; i.e. 3/2 for $Li^6 + n$, and 2 for $Li^7 + n$. Cross sections calculated using the parameters given in the figure are also shown. The level parameters used are those given by WILLARD *et al.* [1][1]). If the assumption is made that all of the non-resonant cross-section arises from the interaction of s-wave neutrons with these nuclei, these data combined with other scattering data can be used to obtain information on the s-wave scattering phase shifts. In the case of Li^7 these data exist in two forms; the angular distribution of elastic scattering and the low energy coherent scattering data. In principle, the s-wave phases can be obtained from the differential cross-sections alone, but it is very difficult in practice to measure angular distributions with sufficient accuracy to provide precise phase shifts. It was pointed out by THOMAS and coworkers [2] that the coherent scattering length, which depends linearly on the two s-wave phase shifts, δ_0^1 and δ_0^2, and the low energy total cross-section, which depends quadratically on the same, admit two possible sets of phases. For one set, the parallel spin phase shift is the dominant one, with δ_0^1 being quite small. With the other set the converse is true. Differential cross-sections measured above and below the resonance energy exhibit a large asymmetry about 90°, indicating appreciable interference between the resonant scattering and the channel spin-2 s-wave scattering. This excludes the set of phases for which δ_0^2 is small and indicates that the s-wave interaction occurs predominantly in the channel spin-2 state at low energies. On the basis of just the measured asymmetry about 90° in the differential cross-sections WILLARD and coworkers [1] concluded that both channel spins were of approximately equal importance in the s-wave scattering. In any case, the presence of appreciable channel spin-2 s-wave scattering which interferes with the resonant scattering will produce appreciable polarization in the scattered neutrons. This is illustrated in figure 2, in which polarizations produced in the scattering through a c.m. angle of 90° are shown as a function of neutron energy. The positive direction of polarization is given by the vector $\boldsymbol{k} \times \boldsymbol{k}'$, where $\boldsymbol{k}$ and $\boldsymbol{k}'$ are incident and outgoing wave numbers respectively. These curves were calculated using the level parameters shown in the preceeding figure and assuming that the s-wave interaction is either entirely in the parallel channel spin state or equally strong in both channel spin states for the broken and solid curves respectively. It can be seen that $P(\theta)$ should be appreciable for Li^7 between about 250 and 400 keV. Using 280 keV neutrons from the $Li(p, n)$ reaction, WILLARD's group [3] has shown that appreciable polarization is indeed present.

[1]) Numbers in brackets refer to References, page 276.

On the basis of the low energy coherent scattering data and the angular distribution measurements one would expect $P(\theta)$ to be somewhere between these two curves.

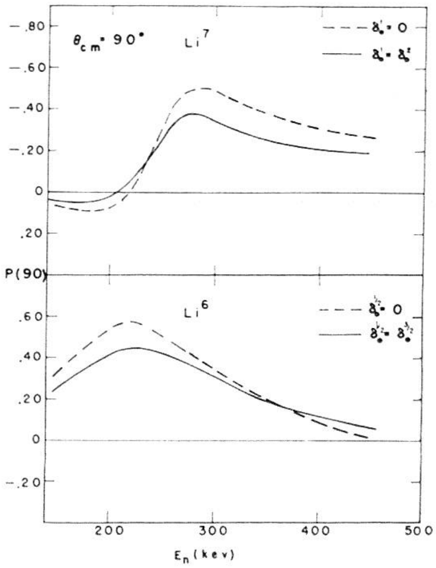

Figure 2

The situation for Li^6 is complicated by the presence of the competing (n, α) reaction. If one represents the s-wave elastic scattering again by real phase shifts consistent with the background elastic scattering cross-section, then the choice of phase shifts which reproduce the differential cross-section involves something like a statistical mixture of channel spins and the corresponding polarization is that given by the solid curve.

II. Measurements

In this investigation the asymmetries in the scattering of polarized $Li^7(p,n)$ neutrons from samples of natural lithium and Li^6 enriched to 96% have been measured. Neutrons emitted at a laboratory angle of 50° with respect to the incident proton beam and having an average energy spread of 45 keV were used. The experimental procedure used for the first set of measurements is shown in figure 3. This is the conventional arrangement for such experiments. A magnetically analyzed proton beam from the electrostatic accelerator is incident on an evaporated lithium target, producing neutrons which are collimated at an angle of 50° with respect to the proton beam by the paraffin shield. A hydrogen-filled proportional counter detected neutrons scattered to the left and right by the lithium scatterers. Most of the data were taken for a laboratory scattering angle of 88°. Cylindrical scatterers 8 cm high and 3 cm in diameter were used. The entire procedure was checked from time to time by using a carbon scatterer to ensure that no experimental asymmetries were creeping in. As is generally the case, the most serious limitation on the accuracy with which data could be obtained was imposed by the large background counting rate present when the scatterers are removed. This background, which was enhanced by the unfavorable environment in which the measurements were carried out, varied from 35 to 75% of the counting rate with scatterers present. It is necessary to apply a number of corrections to data obtained in this way. Principal among these are the corrections for the variation in neutron flux across the sample, the presence of the other isotope, and the effect of multiple scattering. The effect of multiple scattering is mitigated by the fact that the doubly scattered neutrons are on the average substantially less energetic than those which have been scattered only once, and are, therefore, detected with much less efficiency, since the pulse height discrimination used was such as to detect with zero efficiency neutrons having energies less than about 40% of the incident neutron energy.

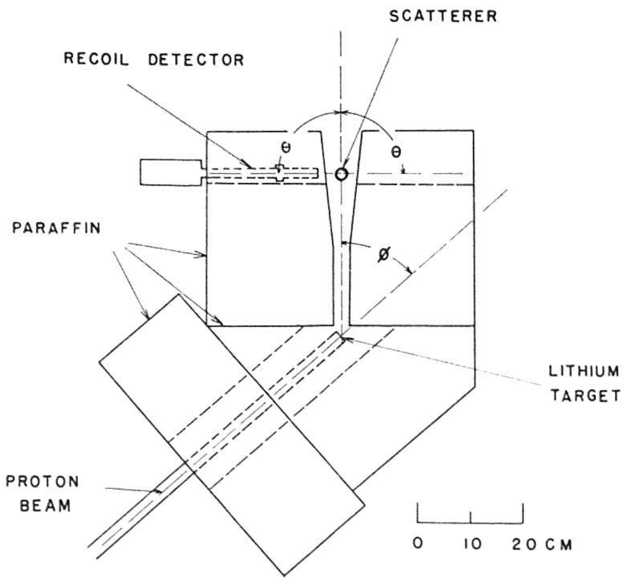

Figure 3

More recently, additional measurements have been made using a different procedure, illustrated in figure 4. With this arrangement the necessity of moving the detector from side to side is eliminated by the use of a magnetic field transverse to the direction of the neutron's flight path between source and scatterer. Instead of rotating the detector from one side to the other, the intensity of scattered neutrons is measured with the field alternately shut off and turned on to a value sufficient to permit precession of the neutron's magnetic moment through 180° as the neutrons pass from source to scatterer. The advantages of this approach have been discussed elsewhere and will not be dwelt upon here. One obvious disadvantage is that the substitution of iron for paraffin in the region between source and scatterer results in an increased neutron background at the detector. This difficulty was circumvented by increasing the distance between source and scatterer and inserting additional paraffin shielding, and by using a somewhat larger scatterer. As before, asymmetries were measured from time to

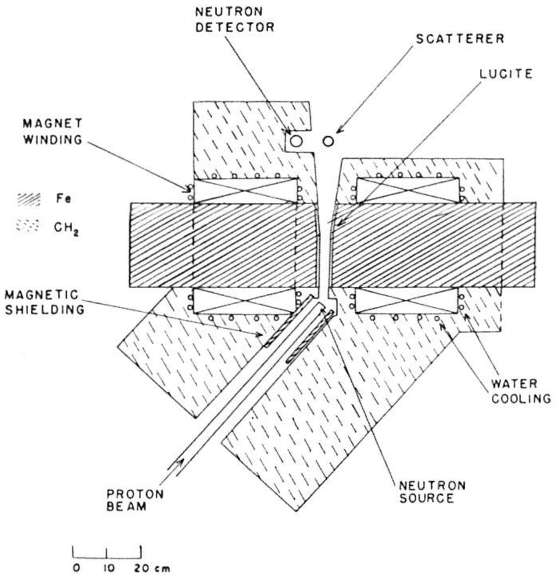

Figure 4

with time carbon to ensure that no spurious effects were being introduced by the magnetic field. An additional check was provided by measuring asymmetry versus magnetic field in one case. The results are shown in figure 5. The ordinate is proportional to the product of the polarization of the incident neutrons and the analyzing power of the Li^7 as given by the expression

$$P_1\,P_2 = \frac{\dfrac{L}{R} - 1}{\dfrac{L}{R} + 1}\,. \tag{1}$$

Here L/R refers to the ratio of the scattered intensities measured with the magnet alternately off and on. The $P_1\,P_2$ as defined above is, of course, the correct one only when the magnetic field rotates the neutron spins through 180°. The points were obtained from the measured asymmetries using Eq. (1), while the shape of the curve represents the $P_1 P_2$

calculated from the asymmetries expected on the basis of the measured values of the magnetic field. For the point farthest to the right, the field strength was that required to rotate the neutron spin vector through 360°. The correspondence between the points and the curve indicates that the neutron spins are being rotated by the magnetic field as expected.

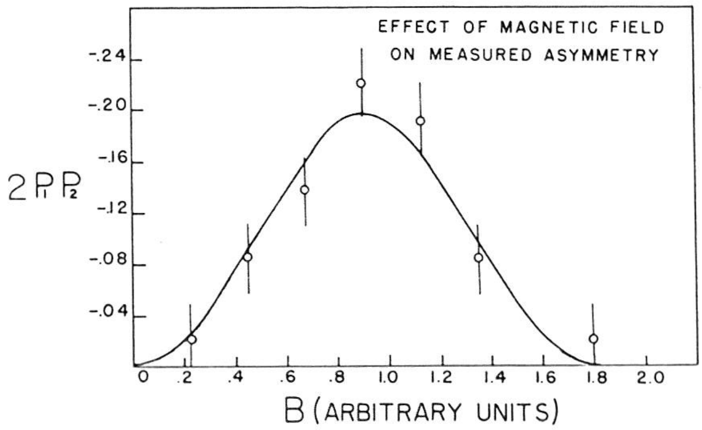

Figure 5

III. Results and Discussion

Results of the measurements for both Li^6 and Li^7 are shown in the last figure. The points represent values of P_n, the polarization of the incident neutrons, times $P(\theta)$ for the scatterer and are given as a function of neutron energy. These were obtained from the corrected experimental asymmetries using Eq. (1). In addition to statistical uncertainties, an uncertainty of about one third the value of the corrections to the data has been included in the error bars shown. The solid circles represent data obtained by rotating the neutron detector from side to side, while the open circles correspond to data taken using the electromagnet. On the right are given the ordinate scales for the curves, which are the calculated polarizations assuming the *s*-wave interaction is all channel spin-2 for Li^7, and assuming equal phases for both channel spin states in the case of Li^6. The normalization between the left and right hand ordinate scales is such that the points should coincide with the curves wherever P_n is equal to 0.40, providing the curve gives the correct value of $P(\theta)$.

If, for Li^7, the curve is assumed to represent $P(\theta)$ correctly in the energy interval between 300 and 400 keV, values of P_n close to .40 are obtained, in agreement with the results obtained using oxygen analyzers. This agreement, together with the evidence from the scattering length data discussed in the introduction, would indicate that the channel spin-2 s-wave interaction is predominant for neutron energies below about 400 keV. Consequently, $P(\theta)$ below 400 keV was taken to be given by the curve shown to within about 10%, and the data below 400 keV were used to determine P_n. The positive value of $P_n P(\theta)$ found at 190 keV suggests that P_n changes sign somewhere between 200 and 250 keV. Unfortunately, the small magnitude of $P(\theta)$ together with the large experimental uncertainties prevent any very quantitative determination of P_n at 190 keV. The change in sign of P_n is also evident in the Li^6 data, since the measured $P_n P(\theta)$ reverses sign while the analyzing power does not. This conclusion does not depend on a detailed knowledge of the s-wave phase shifts for Li^6, since the shape of the $P(\theta)$ curve, i.e. the slow variation with energy near 200 keV, is quite insensitive to the relative magnitude of the two s-wave phases. The fact that these measured points for Li^6 fall somewhat below the curve suggests the channel spin 1/2 interaction may be somewhat stronger than the channel spin 3/2 interaction.

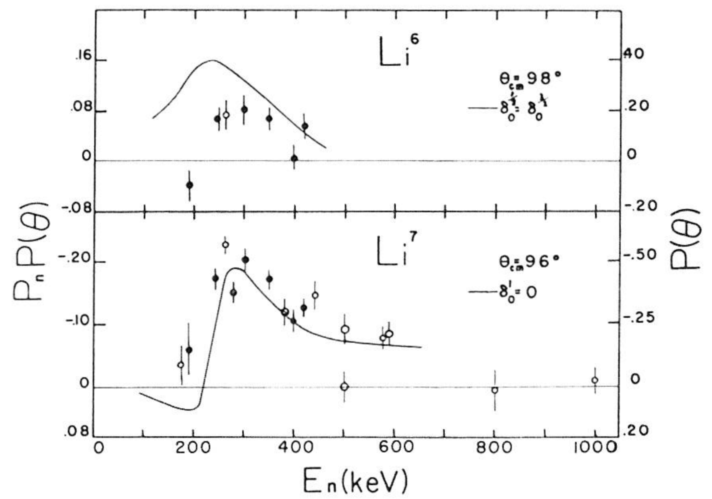

Figure 6

Over the energy interval from about 420 to 600 keV, the observed asymmetries for Li^7 are generally greater than would be expected if the curve shown really represented $P(\theta)$. The polarization of the incident neutrons is known from oxygen measurements to be about .20 in this energy region. Dividing the experimental $P_n P(\theta)$ by .20 yields $P(\theta)$ values at least twice as large as those calculated using just the 3^+ resonant phase and an s-wave phase obtained from the total cross-section. It is not immediately obvious what causes this increased polarization. Additional P-wave phases may become important at these energies. Also, the threshold for inelastic scattering to the first excited state in Li^7, which occurs around 550 keV, may affect the polarization in the vicinity of the threshold. At present however the data are too sparse and inaccurate to permit much to be said about the phases above 400 keV.

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