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0° polarization transfer in (p,n) reactions from ^{6,7}Li and ^{9}Be near 55 MeV

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We have measured the transverse and the longitudinal polarization transfer coefficients $K_y^{y'}$ and $K_z^{z'}$ at 0° in the (p,n) reactions from ^{6,7}Li and ^{9}Be for proton energies near 55 MeV. Except for the ^{6}Li(p,n)Be reaction, where $K_y^{y'}(0°) = -0.33 \pm 0.04$, all transfer coefficients are < 0.20 and thus not very suitable for the production of polarized neutrons.

In order to search for a source of monoenergetic polarized neutrons around 50 MeV,[1] we have investigated the polarization transfer in (p,n) reactions from several light target nuclei at 0°. Apart from the most promising case of the ^{2}H(p,n)2p reaction, which is presented in detail elsewhere,[2] we have also studied the (p,n) reactions from ^{6,7}Li and ^{9}Be. Together with the ^{3}H(p,n)^{3}He case these reactions are the only ones known to produce monoenergetic neutrons with useful intensities in this energy range (cf. Ref. 1, and references therein). Although the neutron yields (for the same width of the high-energy peak) are lower by a factor 2 to 5 as compared to the ^{2}H(p,n) reaction, the ease with which these targets can be handled would still make them good candidates, provided that the polarization transfers are large enough. We would like to point out here that at energies $\gtrsim 400$ MeV the polarization transfer values approach the limit for the free pn interaction, $K_z^{z'}$ being large and rather independent of the target nucleus chosen.[1] Since in principle the neutron polarization can be produced via the transverse or the longitudinal transfer, we have measured both transfer coefficients at 0°.

Since the polarized neutron facility used here has been described in detail elsewhere,[1] we shall only outline its main features, concentrating mostly on the preparation of the longitudinally polarized proton beam, which is not given in Ref. 1.

Figure 1 shows the main features of our setup. Polarized protons from the Schweizerisches Institut für Nuklearphysik (SIN) injector cyclotron are focused into the polarimeter POL, where the polarization components P_y^{p} and P_x^{p} of the protons are measured continuously via elastic scattering from a thin carbon foil. After the deflection magnet $D1$ the beam is refocused onto the neutron production target T which is mounted in a chamber inside the shielding S. Another deflection magnet $D2$ deflects the proton beam into a Faraday cup FC. Neutrons produced at 0° pass through a 1.5 m long collimator C and hit the liquid ^{4}He analyzer target L He. The L He target (5 cm diameter) subtended a solid angle of 7×10^{-5} sr at a distance of 4.2 m from the production target. Scattered neutrons were detected in two plastic scintillation detector pairs which were placed symmetrically left/right (for measuring $K_y^{y'}$) or up/down (for measuring $K_z^{z'}$) with respect to the neutron beam at a distance of 0.7 m.

In the following we will first discuss the $K_y^{y'}$ measurements and then turn to the more complicated $K_z^{z'}$ measurements. $K_y^{y'}$ connects the proton polarization P_y^{p} with the neutron polarization P_y^{n} by the relationship

$$P_y^{\mathrm{n}} = K_y^{y'} P_y^{\mathrm{p}} \ . \tag{1}$$

P_y^{p} was extracted from the left/right asymmetry ϵ_y^{p} of the proton polarimeter POL using the super-ratio method:

$$\begin{aligned} P_y^{\mathrm{p}} &= \frac{\epsilon_y^{\mathrm{p}}}{A_y^{\mathrm{p}}(E,\theta)} = \frac{1}{A_y^{\mathrm{p}}(E,\theta)} \frac{1-\alpha}{1+\alpha} \ , \\ \alpha &= \left[\frac{N_L^{+} N_R^{-}}{N_L^{-} N_R^{+}} \right]^{1/2} \ . \end{aligned} \tag{2}$$

Here $N_L^{\pm}$ ($N_R^{\pm}$) corresponds to the number of counts in the left (right) side detector, obtained with a ± sign of the beam polarization. In our case the sign was reversed every few seconds by switching between different rf transitions at the polarized ion source. $A_y^{\mathrm{p}}(E,\theta)$ was obtained from a two-dimensional spline fit to the p-^{12}C data of Ref. 3.

P_y^{n} was determined similarly in the neutron polarimeter using elastic neutron scattering from the active, liquid ^{4}He target[4] at angles $\theta_{\mathrm{c.m.}} \geq 135°$, where the analyzing power is $\gtrsim 0.90$. Equations (2) apply by exchanging the superscript "p" for "n". $A_y^{\mathrm{n}}(E,\theta)$ then represents the analyzing power in n-^{4}He scattering.

For the measurement of $K_z^{z'}$ the spin precession solenoid SOL was implemented and excited such that the initially vertical spin orientation was precessed by 90° into a horizontal spin orientation. The exact value of the current needed was determined by observing the zero crossing of the asymmetry ϵ_y^{p} as a function of current. The horizontal beam polarization P_x^{p} after precession was

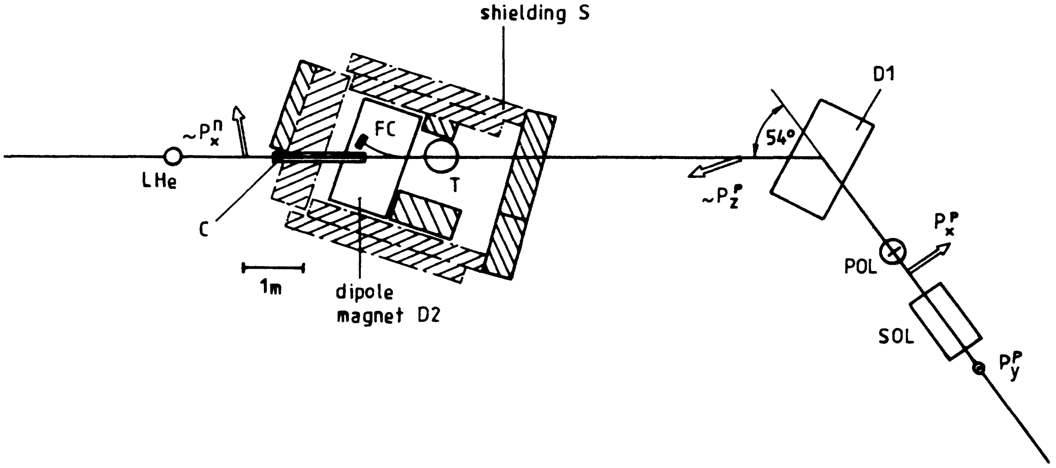

FIG. 1. Layout of the SIN polarized neutron facility. The symbols denote spin precession solenoid (SOL), proton polarimeter (POL), deflection magnets ($D1$,$D2$), neutron production target (T), Faraday cup (FC), shielding (S), neutron collimator (C), and liquid ^{4}He target (L He). The proton and neutron spin orientations are indicated by arrows for the case of a longitudinal polarization transfer reaction with $K_z^{z'}=-1$.

measured continuously during the experiment using an "up" detector at POL. Passing through $D1$ the proton spin is subsequently precessed by 102.3°. This reduces the longitudinal polarization component slightly to $P_z^p=\cos(102.3°-90°)P_x^p=0.9769P_x^p$ and introduces a small transverse component δP_x^p. After production the neutron spin is precessed by 90° in the horizontal plane by the dipole magnet $D2$. This way the interesting longitudinal component $P_z^n=K_z^{z'}P_z^p$ is transformed into a transverse component of the same magnitude, which then can be measured in the neutron polarimeter; with the side detectors now set to up/down (instead of left/right) positions. The small transverse component $\delta P_x^n=K_x^{x'}\delta P_x^p$ is transformed into a longitudinal component, which cannot be measured due to parity conservation. For the determination of $K_z^{z'}$, Eqs. (1) and (2) apply similarly as in the $K_y^{y'}$ case; however, the symbols y and y' have to be replaced by z and z' in Eq. (1) and by x in Eq. (2). Note that $A_y^n\equiv A_x^n$.

For targets we used 95.6% enriched ^{6}Li (440 mg/cm^2), natural Li (500 mg/cm^2), and a 370 mg/cm^2 thick ^{9}Be foil. The corresponding energy losses for 55 MeV protons are 5.0, 5.0, and 3.6 MeV. The Li targets were mounted in Cu housings with 10 μm Havar windows. The contamination due to the windows was measured to be $<10^{-3}$ in the neutron peak region.

With the neutron polarimeter the following four parameters were recorded in coincidence and stored on tape event-by-event.

(1) The time difference t_α between a recoil-α signal in the L He target and the cyclotron rf signal. This determined the neutron energy. Since the proton beam burst width was typically 0.8 ns at 72 MeV and 1.5 ns at 54 MeV, the resulting uncertainty was about ±1 MeV.

(2) The recoil-α pulse height.

(3) The time difference t_n between a recoil-α signal and a signal from any of the plastic detectors. Since the overall time resolution for t_n was typically 0.6 ns, this information could be used successfully to discriminate against prompt γ's and inelastic ^{4}He(n,n')^{4}He events (cf. also Fig. 2).

(4) The pulse height in the plastic detectors.

In the analysis cuts were set on all parameters. As an example for the cutting procedure we show in Fig. 2 the t_n spectrum for the ^{9}Be(p,n) case at $E_p=72.4$ MeV. The top curve represents the raw spectrum, showing from left to right pulser events, prompt γ's (around channel 355), and elastic and inelastic n-^{4}He events, which are unresolved. The lower curve shows the result of tight cuts on parameters 1, 2, and 4. Also indicated are the final integration limits (about 2.5 ns wide) which were used to extract the quantities $N_L^{\pm}$ and $N_R^{\pm}$. For all targets the cut on t_α was chosen to contain the whole high-energy neutron peak, i.e., from the maximum energy to ~6 MeV below the peak energy. Since this cut also contains neutrons leading to excited states in the residual nuclei which may have a different polarization transfer, the transfer

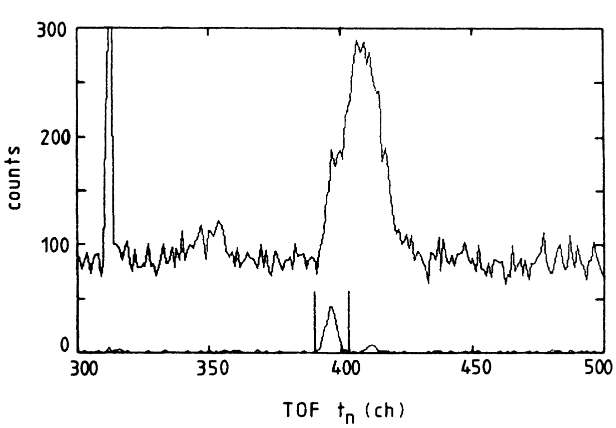

FIG. 2. t_n spectra for the ^{9}Be(p,n) reaction at 72.4 MeV. For details refer to the text.

coefficients obtained this way may depend on the lower cutoff limit. This should be kept in mind when comparing the results of different experiments.

The neutron polarization P_y^{n} (P_x^{n}) was obtained by dividing ϵ_y^{n} (ϵ_x^{n}) by the proper analyzing power $A_y^{\mathrm{n}}(E,\theta)$ which was calculated from phase shifts for p-^{4}He scattering,[5] where the Coulomb phases were removed. In principle one should use p-^{4}He phase shifts which have been properly corrected for Coulomb effects. However, in the back-angle maximum these corrections are considered to be negligible.[6] Next, P_y^{n} (P_x^{n}) was corrected for finite geometry and multiple scattering effects in the L He target[7] and divided by the proton polarization P_y^{p} (P_z^{p}) as obtained from POL. The results for ^{6,7}Li were corrected for the isotopic contents of the targets using the cross-section data of Ref. 8 and $K_y^{y'}=-0.02\pm0.04$ for ^{7}Li at 50 MeV from Ref. 9.

The final transfer coefficients for the different targets are listed in Table I as a function of the mean proton energy $\bar{E}_{\mathrm{p}}$ (defined as the energy at the target center). The quoted uncertainties contain the statistical errors and the uncertainties of the corrections mentioned above. The normalization uncertainties of the analyzing powers in p-^{12}C and p-^{4}He scattering add another ~3%.[3,5] It is difficult to estimate the uncertainty which is due to the fact that excited state neutrons with unknown polarization are included. The problem is further compounded by the strong energy dependence of the n-^{4}He differential cross section. Assuming a smooth variation $|\Delta K| \simeq 0.4$ across the integration range, we obtained an upper limit of 7% for this uncertainty.

^{6}Li. Around 50 MeV the contribution due to neutrons from the ^{6}Li(p,n)^{6}Be* (1.68 MeV) reaction is small.[8] Assuming a simple deuteron-alpha cluster description of the g.s. of ^{6}Li, one would expect the same polarization transfer behavior as for the ^{2}H(p,n)2p reaction. Since there $K_y^{y'}=-0.38\pm0.01$ and $K_z^{z'}=-0.10\pm0.01$ for a comparable integration range,[2] our result for $K_z^{z'}$ disagrees significantly. Similarly, within the same model, we would expect that $K_y^{y'}$ and $K_z^{z'}$ are related in the following way[10] (since we are dealing with a $\frac{1}{2}+1\rightarrow\frac{1}{2}+0$ spin transition):

$$K_z^{z'}+2K_y^{y'}=-1 \; . \tag{3}$$

Again our results are not quite consistent with Eq. (3).

On the other hand, our value for $K_y^{y'}$ is in good agreement with the value $K_y^{y'}=-0.345\pm0.015$, obtained recently[11] for the ^{6}Li(p,p$'$)^{6}Li (3.562 MeV, 0^+) reaction at 0°. The 3.562 MeV, 0^+ state in ^{6}Li is the isobaric analog of the ^{6}Be g.s. Based on isospin conservation, $K_y^{y'}$ for (p,p$'$) and (p,n) reactions to analog states should be identical. Effects due to small differences in reaction Q values and exit channel optical potentials were found to be small. We conclude that the disagreement with the ^{2}H(p,n)2p reaction is not due to the inclusion of the 1.68 MeV excited state neutrons, but rather indicates that the pure deuteron-alpha cluster description is not valid.

TABLE I. Summary of results.

Target nucleus	$\bar{E}_{\mathrm{p}}$ (MeV)	$\bar{E}_{\mathrm{n}}$ (MeV)	$K_y^{y'}$	$K_z^{z'}$
^{6}Li	52.8	47.7	-0.33 ± 0.04	-0.17 ± 0.02
^{7}Li	52.8	51.1		0.07 ± 0.02
^{9}Be	53.9	52.0	-0.06 ± 0.03	
	53.5	51.6		0.14 ± 0.03
	71.0	69.1	-0.18 ± 0.02	

Reference 9 reported $K_y^{y'}$ values for ^{2}H(p,n)2p and ^{6}Li(p,n)^{6}Be, which are smaller by ~30%. The discrepancy is probably due to the poorer energy resolution and the larger integration range. In addition, the L He target acceptance angle is much larger (±6°) than in our case, so that systematic effects due to a variation of $K_y^{y'}$ and A_y with angle may arise.

^{7}Li. Our integration range contains neutrons leading to the g.s. and the first two excited states of ^{7}Be (0.43 and 4.57 MeV). Whereas the 4.57 MeV transition is practically not excited, the 0.43 MeV transition may contribute with as much as 50%.[8,12,13] Our $K_z^{z'}$ value hence represents an average over both neutron groups.

^{9}Be. Neutrons leading to the first three excited states in ^{9}B (centered around 2.6 MeV excitation energy) are not resolved from the g.s. transition neutrons. Since the excited states contribute ~40% within the integration range,[1] the transfer values measured may be strongly affected by the excited state transitions. To investigate this further we split the neutron energy cut (i.e., t_α) at 72 MeV into a lower and an upper half. For the lower half (which contains mainly excited state transition neutrons) $|K_y^{y'}|$ was larger by ~50%, whereas for the upper half (which contains predominantly g.s. transition neutrons) $|K_y^{y'}|$ was smaller by ~50%. This indicates that ^{9}Be is a poor candidate as a production target for polarized neutrons in this energy range. To our knowledge there are no previous measurements or theoretical predictions in this energy range.

With the exception of the ^{6}Li case all reactions considered here have transfer coefficients $|K_y^{y'}|, |K_z^{z'}| < 0.2$ and are therefore not very useful as sources of monoenergetic, polarized neutrons. $K_y^{y'}$ for ^{6}Li is similar to the value for ^{2}H, however, its 0° neutron production yield is lower by a factor 5. Nevertheless, it might prove useful if one is looking for a production reaction for high-resolution (<1 MeV) polarized neutron experiments, since the ^{2}H(p,n)2p reaction has an intrinsic width of ~1.3 MeV in this energy range.[1] The expected neutron yield would then be of the order of magnitude 8×10^8 neutrons/s/sr for 1 μA of proton beam. For an intense neutron beam however, i.e., 10^{10} neutrons/s/sr and a width of ~2.5 MeV FWHM,[1] we conclude that the ^{2}H(p,n)2p reaction is the only reasonable possibility around 50 MeV.

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