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Vector analyzing power measurement of pion scattering from polarized ^{7}Li in the region of the Δ_{33} resonance

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The inclusive vector analyzing power iT_{11} of $\pi^+ \rightarrow {}^7$Li elastic scattering and inelastic scattering to the 0.47 MeV excited state was measured at several angles for T_π = 134, 164, and 194 MeV. The polarization effects were found to be small but non-zero, the trend of the data is well described by a coupled channels calculation. The results of the calculation are more sensitive to variations of the nuclear structure input than to variations of the reaction mechanism.

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Since the advent of the meson factories considerable progress has been achieved in the understanding of pion nuclear reactions. However, this understanding is based on measurements of cross sections which are mainly sensitive to the spin-independent part of the reaction amplitudes. On the other hand, it is well known from nuclear and particle physics that spin observables may provide a much more sensitive test of theoretical models.

In pion physics the only access to spin information is via polarized nuclei. Pion scattering off polarized nuclear targets became possible only a few years ago when significant nuclear polarization could be achieved by the dynamic nuclear polarization technique. Since then measurements were reported on the vector analyzing power for pion elastic scattering from the nuclei ^{3}He [1], ^{6}Li [2], ^{13}C [3,4], and ^{15}N [5,6]; for pion inelastic scattering from ^{6}Li [2] and ^{15}N [6], and the single charge exchange reaction on ^{13}C [7].

When comparing the experimental data on the vector analyzing power to theoretical calculations which involve different reaction models and different nuclear structure input, a great sensitivity to the latter was observed (except for the charge exchange reaction). In the case of $\pi^+ \rightarrow {}^3$He scattering (the ^{3}He nucleus may be considered well understood) excellent agreement between theory and experiment was achieved. In the cases of $\pi^+ \rightarrow {}^{13}$C scattering and $\pi^+ \rightarrow {}^{15}$N scattering, the opposite is true. Theory predicts large values of iT_{11} in certain angular regions, but the experimental values are consistent with zero. This large discrepancy is not yet understood. For pion elastic and inelastic scattering (to the first excited state) off ^{6}Li sizable vector analyzing powers were observed which could be qualitatively described by theory.

The six- and seven-nucleon systems play a special role in nuclear physics. Unlike the few nucleon *s*-shell nuclei, the properties of which do not depend substantially on the spin-orbit interaction and the role of the Pauli principle in their structure is comparatively modest, in six- and seven-nucleon systems the number of nucleons is sufficient to exhibit important typical properties of heavier nuclei, i.e., Pauli principle, substantial spin-orbit splitting of levels, interaction of the valence nucleons with the α-particle core, important contributions of short range correlations of particles etc. Therefore, the nuclei ^{6}Li and ^{7}Li may be considered a "laboratory" for the theoretical investigations; and correspondingly their nuclear structure was probed extensively in strong and electromagnetic interactions. Within this wealth of data there have been relatively few experiments on the interaction with pions. After having observed the great sensitivity of the iT_{11} data in $\pi^+ \rightarrow {}^6$Li scattering to the nuclear structure of ^{6}Li, we have now extended these measurements to the neighboring nucleus ^{7}Li.

Experimentally, the measurement of $\pi^+ \rightarrow {}^7$Li has advantages and disadvantages. The advantages are reasonably large cross sections and a target vector polarization of about 50%. The disadvantages are the narrow energy separation of ground and first excited states in the ^{7}Li nucleus, which required an inclusive measurement with the magnet pion spectrometer, and the more complicated

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spin structure of ^{7}Li (spin $\frac{3}{2}$). This necessitated a careful consideration of the data taking procedure.

With a target polarization perpendicular to the scattering plane, the differential cross section of pion scattering from a spin 3/2 nucleus (i.e., ^{7}Li) can be expressed as

$$\sigma = \sigma^0 \left(1 + \sqrt{\frac{18}{5}} p_z iT_{11} + p_{zz}\Theta_{zz} + p_{zzz}\Theta_{zzz} \right), \quad (1)$$

$$\Theta_{zz} = -\frac{1}{2}T_{20} - \frac{\sqrt{3}}{2}T_{22}, \quad (2)$$

$$\Theta_{zzz} = -\frac{3}{2}\left(\sqrt{\frac{5}{3}} iT_{31} + iT_{33} \right). \quad (3)$$

These relations are obtained by extending the Madison convention [8] to the spin 3/2 case. The vector and tensor polarizations are calculated from the relative occupation number n_i of the states as follows:

$$p_z = \frac{1}{3}(3n_{\frac{3}{2}} + n_{\frac{1}{2}} - n_{-\frac{1}{2}} - 3n_{-\frac{3}{2}}), \quad (4)$$

$$p_{zz} = n_{\frac{3}{2}} - n_{\frac{1}{2}} - n_{-\frac{1}{2}} + n_{-\frac{3}{2}}, \quad (5)$$

$$p_{zzz} = \frac{1}{3}(n_{\frac{3}{2}} - 3n_{\frac{1}{2}} + 3n_{-\frac{1}{2}} - n_{-\frac{3}{2}}). \quad (6)$$

In the polarized target, the occupation of states is given by the Boltzmann statistics. This results in an internal dependence of the polarizations: the tensor polarizations can be calculated from the vector polarization. The vector analyzing power iT_{11} is extracted from a set of equations (1) generated by measuring relative cross sections σ^i at different vector polarizations p_z^i.

In principle four measurements at different polarizations are necessary to determine the vector analyzing power iT_{11} from a set of equations of type (1). However, the contribution of the p_{zzz} term in Eq. (1) to the cross section is small. For $p_z \leq 0.5$, $p_{zz} = 3/4p_z^2$ and $p_{zzz} = 3/20p_z^3$ are good approximations. The theoretical limits of Θ_{zzz} were found to be ± 2.64 by searching for its extrema in the helicity amplitude representation [9]. For $p_z = 0.25$, this gives a maximum contribution of about 0.6% of the p_{zzz} term to the cross section. Therefore, only three polarization settings were used to determine iT_{11}; the uncertainty resulting from the omission of the third order term was included in the error bar. This was done by treating the theoretical knowledge of Θ_{zzz} like a measurement with error bars of 0 ± 2.64, and by including this error in the cross section error by Gaussian error propagation. The three polarization settings were chosen to be zero and around ± 0.25 to keep the contribution of the third order term to the overall error small. Measurements at maximum positive polarization (around 0.45) were done as a consistency check. When using $p_{zz} = 3/4p_z^2$, omitting the third order term and writing σ' instead of σ (the error of σ' includes the error of σ and the uncertainty due to the third order term), Eq. (1) becomes

$$\sigma' = \sigma^0 \left(1 + \sqrt{\frac{18}{5}} p_z iT_{11} + \frac{3}{4} p_z^2 \Theta_{zz} \right). \quad (7)$$

Now the vector analyzing power is determined by fitting a second order polynomial in p_z to $\sigma'(p_z)$.

The experiment was carried out at the $\pi M1$ pion channel at the Paul Scherrer Institut (PSI); the setup was described in detail earlier [6,2]. The target material consisted of approximately 98% ^{7}Li enriched LiH in the form of frozen beads of approximately 1 mm diameter. The required paramagnetic centers in the target material were produced by irradiating the probe with electons. A rectangular (15 × 15×5 mm) brass cell was used to contain the material and simultanously served as mixing chamber of a ^{3}He /^{4}He dilution refrigerator. Polarization was induced by microwave irradiation in a magnetic field of 2.5 T. The target polarization was measured by comparing the dynamically enhanced ^{7}Li NMR signal with the thermal equilibrium signal. This was done periodically. Typical signals are shown in Fig. 1. Target polarizations of up to +48% and −27% were achieved.

The relative cross sections for positive, negative, and zero target polarizations were determined by analyzing the scattered pions with the magnet spectrometer SUSI at PSI. The energy resolution of the calculated missing energy spectra was about 1.8 MeV due to the thickness of the polarized target. Therefore, the ^{7}Li ground state and the excited state at 0.47 MeV could not be resolved and were measured inclusively. For all angles and energies, the peak corresponding to this doublet was clearly separated from peaks caused by pion scattering from other nuclei in the target region. Figure 2 shows typical raw missing energy spectra for positive and negative target polarization. Additionally, the spectrum at negative polarization is shown after background subtraction. The contributions of the helium coolant and the target cell to the spectra were measured in separate runs. The scattering yields and their statistical and background subtraction errors were determined by fitting the raw spectra using the background information and a Gaussian curve with exponential tail for the ^{7}Li peak. The peak shape was determined from spectra taken without helium coolant in the target region. The yields were normalized to the number of incoming pions detected by a beam definition counter to get relative cross sections.

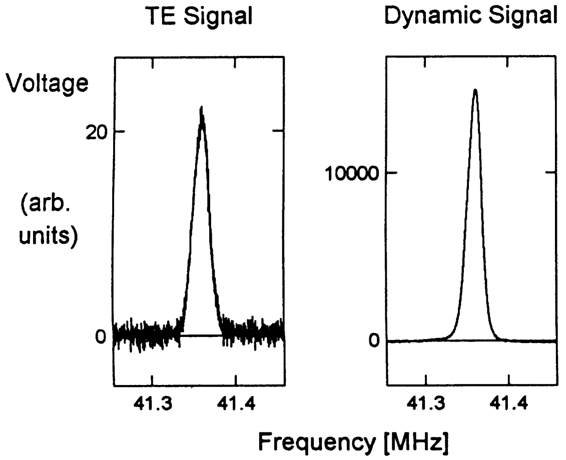

FIG. 1. Typical thermal equilibrium and dynamically enhanced NMR signals for polarized ^{7}Li.

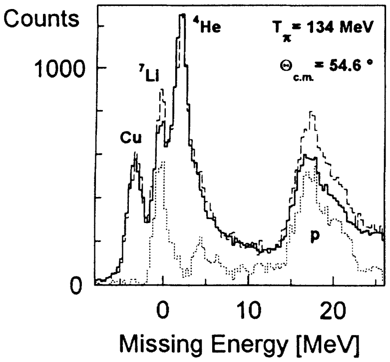

FIG. 2. Comparison of raw missing mass spectra for positive (dashed line) and negative (solid line) polarization. Additionally, the spectrum for negative polarization is shown after background subtraction (dotted line).

In Fig. 2 polarization effects can be seen in the region of the ^{7}Li doublet and in the region of elastic πp scattering. The poor resolution of the spectra in the πp region is produced by the kinematics chosen for pion scattering from ^{7}Li.

The analyzing power A_y for $\pi^+ p$ elastic scattering was extracted as a check of the polarization measurement. For this, the proton polarization in the target was calculated from the measured ^{7}Li polarization using equal spin temperatures. Good agreement with asymmetries A_y from the SAID πN phase shift program [10] was found.

Systematic errors arise from a relative 5% uncertainty in determination of the target polarization. This results in a relative normalization uncertainty of 5% in the final iT_{11} data. Other systematic errors like the uncertainty in the absolute beam flux, the number of scattering nuclei and the spectrometer acceptance do not affect iT_{11} because no absolute normalization is required for its calculation.

Figure 3 shows cross sections and vector analyzing powers at $T_{\pi^+} =$ 134, 164, and 194 MeV. Cross sections were normalized to elastic π^+ scattering from protons in the LiH target. Except for the point at 79.4°, there is reasonable agreement with a previous cross section measurement [11] at 164 MeV. The polarization effects are small but, at least for 134 and 164 MeV, significantly different from zero.

The results are compared to theoretical predictions from Mach and Meier. The calculations are based on the momentum space coupled channel formalism of Gmitro, Kamalov, Kvasil, and Mach [12,13]. The longitudinal electromagnetic form factor of ^{7}Li can be reproduced very well using simple harmonic oscillator shell model nuclear wave functions. To determine the nuclear structure input in our calculations, we started from the shell model by van Hees and Glaudemans [14]. The s- and p-wave oscillator parameters were obtained by fitting the ground state longitudinal form factor [15]. Adopting the prescription by van Hees, Wolters, and Glaudemans [16], we multiplied the tensor and isotensor components of the effective pion-nucleus interaction by $(e_p + e_n)$ and $(e_p - e_n)$, respectively, where e_p=1.0087 (e_n=0.3763) is the effective proton (neutron) charge. This procedure simulates the core deformation in ^{7}Li.

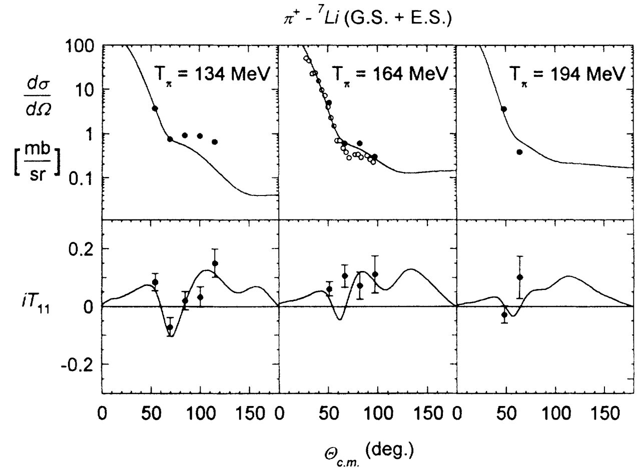

FIG. 3. The vector analyzing power iT_{11} and $d\sigma/d\Omega$ for $\pi^+ \to {}^7$Li (ground state + 0.47 MeV excited state) scattering at 134, 164, and 194 MeV. The data are from this experiment (solid circles) and from Zichy [11] (open circles). The solid lines are predictions from R. Mach and R. Meier.

The predictions of the inclusive observables for elastic scattering to the ground state (G.S.) and inelastic scattering to the first excited state (E.S.) were calculated from the exclusive observables as follows:

$$\sigma^{\text{inclusive}} = \sigma^{\text{g.s.}} + \sigma^{\text{e.s.}}, \tag{8}$$

$$iT_{11}^{\text{inclusive}} = \frac{\sigma^{\text{g.s.}} iT_{11}^{\text{g.s.}} + \sigma^{\text{e.s.}} iT_{11}^{\text{e.s.}}}{\sigma^{\text{g.s.}} + \sigma^{\text{e.s.}}}. \tag{9}$$

As one can see in Fig. 3, with the exception of the cross section for larger angles at T_π = 134 MeV, all data are quite well reproduced by the theoretical predictions. In order to learn something about the sensitivity of the calculation to the theoretical input, parameters in the first order potential (impulse approximation, off shell behavior) as well as in the second order potential (the complex parameters B_0 and C_0) and those describing the coupling between the elastic and the inelastic scattering (to the first excited state) have been varied in reasonable limits. Such variations only affect the predictions to a small extent. For instance, if the channel coupling is turned "on" or "off", the predictions differ by several percent. It should be noted that we were able to find a set of parameters B_0 and C_0 which allows us to reproduce very well both the cross section and the analyzing power at T_π = 134 MeV. However, these B_0 and C_0 are far away from the smooth energy dependence obtained for B_0 and C_0 in Ref. [13].

The insensitivity of the calculations to the reaction model is contrasted by the large sensitivity to the nuclear wave function. Varying the HO parameters a_s and a_p around the values obtained by fitting the experimental ^{7}Li form factor as a function of q^2 quickly destroys the good agreement between theory and experiment.

It would be very interesting to apply the present data as a test of new cluster model wave functions of ^{7}Li which include proper antisymmetrization.

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