are the values of the quasi-vacuum, ω and ρ trajectories at $t = 0$. The coefficients of the powers of E are functions of the residua of the corresponding poles.

A correction for the screening of the neutron by the proton in the deuteron has been applied to the values for pn obtained from the difference $\sigma(pd) - \sigma(pp)$.[5,6]

To the best χ^2 correspond the following values of the required parameters:

$$q = 0.31 \pm 0.18,\quad \rho = 0.66 \pm 0.15,\quad \omega = 0.50 \pm 0.06,$$
$$a = 22.33 \pm 1.04,\quad b = 17.88 \pm 2.50,\quad c = 1.96 \pm 0.72,$$
$$e = 18.61 \pm 0.84,\quad f = 10.71 \pm 2.79,\quad g = 20.08 \pm 13.58,$$
$$h = 8.24 \pm 12.37,\quad k = 39.75 \pm 2.38,\quad l = 38.89 \pm 5.94,$$
$$n = 26.42 \pm 3.37,\quad r = -0.69 \pm 0.58$$

(the dimensions of the parameters a, b, c, etc., which are not given, can be easily established from Eqs. (1) — (7).

Using relations of the type[7,8]

$$\sigma(\pi K)\,\sigma(NN) = \sigma(\pi N)\,\sigma(KN), \tag{8}$$

we obtain, for $E \to \infty$

$$\sigma(\pi\pi) = 12.5 \pm 1.2\ \text{mb};\quad \sigma(\pi K) = 10.5 \pm 0.9\ \text{mb};$$
$$\sigma(KK) = 8.7 \pm 1.1\ \text{mb}.$$

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[1] von Dardel, Dekkers, Mermod, Vivargent, Weber, and Winter, Phys. Rev. Letters 8, 173 (1962).

[2] Lindenbaum, Love, Niederer, Ozaki, Russel, and Yuan, Phys. Rev. Letters 7, 185, 352 (1961).

[3] Baker, Cool, Jenkins, Kycia, Phillips, and Read, Preprint BNL-6492, Upton, 1962.

[4] Ashmore, Cocconi, Diddens, and Wetherell, Phys. Rev. Letters 5, 576 (1960).

[5] Diddens, Lillethun, Manning, Taylor, Walker, and Wetherell, Phys. Rev. Letters 9, 32 (1962).

[6] R. J. Glauber, Phys. Rev. 100, 242 (1955).

[7] V. N. Gribov and I. Ya. Pomeranchuk, JETP 42, 1141 (1962), Soviet Phys. JETP 15, 788 (1962).

[8] G. Domokos, Preprint Joint Inst. Nuc. Res. D-922, 1962.

Translated by H. Kasha
341

SOME METHODS FOR POLARIZATION AND ANALYSIS OF POLARIZATION OF INTERMEDIATE ENERGY NEUTRONS

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GETTING information about the spin state of levels of the compound nucleus which are formed after neutron capture is a very important problem in the study of nuclear structure. The most general method for determining spins of levels is the use of beams of polarized neutrons and targets containing polarized nuclei.[1] Many experiments with thermal[2,3] and resonance[4,5] neutrons have been done by this method. A necessary part of the equipment is a neutron polarizer.

The familiar methods for polarizing thermal and resonance neutrons are based on the use of interference between magnetic and nuclear scattering of the neutrons, which in principle cannot be pushed to neutron energies greater than 30—50 eV, and in practice not above 10—12 eV because of the sharp drop in intensity.

The present note discusses some possibilities for polarization and analysis of polarization of neutrons with resonance and higher energies, based on the spin dependence of the nuclear interaction. These methods, which were known in principle long ago,[6] have become attainable because of the successful development of the dynamical method for polarization of protons[7-10] and the method of polarizing He^3 nuclei by optical pumping.[11]

Upon transmission of unpolarized neutrons through a target containing polarized nuclei with spin ½, the transmitted beam has a polarization equal to

$$f_n = \text{th}\left[\tfrac{1}{4} f_N n(\sigma_s - \sigma_t) d\right], \tag{1}*$$

where f_N is the nuclear polarization, n is the number of nuclei per cc, d is the target thickness and σ_s and σ_t are the neutron-nucleus interaction cross sections in the singlet and triplet states, respectively.

For protons, the polarization cross section, $\frac{1}{4}(\sigma_s - \sigma_t)$ is

$$\frac{1}{4}(\sigma_s - \sigma_t) \approx \frac{16{,}7\,(1 - E/7000)}{(1 + E/134)\,(1 + E/4000)}\ \text{b}, \tag{2}$$

where E is the neutron energy in keV (it is assumed that 1 eV < E < 3 MeV).

Since the polarization cross section of the protons is practically constant for neutron energies up to several tens of keV, the neutron polarizations will also be constant over this energy region. The degree of polarization of the neutrons which is attainable is sufficient for physics experiments. For example, we mention that using a crystal of $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$ of thickness d = 2 cm, for $f_N = 0.5$ [8] the neutron polarization would be $f_n = 0.54$; the intensity of the transmitted beam is 10% of the incident beam.

Earlier [12] it was shown that the $He^3(n, p)$ reaction at low neutron energy goes preferentially through the spin 0 channel, and $\sigma_t/\sigma_s = (2 \pm 2\%)$ as $E \rightarrow 0$. Thus, for energies up to tens of keV, if one can neglect scattering, deviations from the 1/v law, and p neutron capture, the polarization cross section of He^3 is $\frac{1}{2}(\sigma_s - \sigma_t) \approx 850\ E^{-1/2}$ barns, where E is the neutron energy in eV.

Possibly it is most promising to use polarized He^3 as an analyzer of neutron polarization. If N_+ and N_- are the numbers of interactions induced by the neutron beam in a thin layer of spin $\frac{1}{2}$ nuclei for the two directions of nuclear polarization, then

$$\frac{N_+ - N_-}{N_+ + N_-} = -f_n f_N \frac{\sigma_s - \sigma_t}{\sigma_s + 3\sigma_t}. \quad (3)$$

At low energies, for He^3, $(N_+ - N_-)/(N_+ + N_-) \approx -f_n f_N$. At energies $E > 100$ kev, when one can count proton recoils, for protons the ratio $(\sigma_s - \sigma_t)/(\sigma_s + 3\sigma_t)$ reaches 0.72 at E = 100 kev and 0.32 for E = 1 Mev.

The combination "unpolarized incident beam-polarized target-polarization analyzer" is equivalent in principle to the combination of "polarized beam-polarized target-polarization-insensitive detector" used at present for determining spins of levels. An essentially new possibility is the use of a polarization analyzer to measure the depolarization on resonance scattering of neutrons in an unpolarized target.

If the incident beam is polarized ($f_n = f_{in.}$), the polarization of the scattered neutrons is

$$f_f = (1 - 2Q) f_{in}, \quad (4)$$

where $Q = 2\sigma_{inc}/3\sigma_{sc.}$ is the probability for spin flip in a single scattering.[6]

In the case of resonance scattering, the spin flip probability Q depends on the spin of the compound nucleus:

$$Q_+ = \frac{2}{3}\frac{I}{2I+1} \text{ for } J = I + \frac{1}{2},$$

$$Q_- = \frac{2}{3}\frac{I+1}{2I+1} \text{ for } J = I - \frac{1}{2}, \quad (5)$$

where I is the spin of the target nucleus. The expression (5) is valid for $l = 0$ (s neutrons) if one can neglect potential scattering and the contribution from nearby levels with other spin values. We give values of $\alpha_\pm = f_f/f_{in} = (1 - 2Q_\pm)$ for different I:

I	$^1/_2$	1	$^3/_2$	2	$^5/_2$
α_+	0,66	0,55	0,5	0,47	0.44
α_-	0	0,11	0,17	0,2	0.22

The strong dependence of the depolarization of the neutrons on the spin of the compound nucleus J permits one to determine J to sufficient accuracy by measuring the polarization of the scattered neutrons.

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*th = tanh.

[1] M. E. Rose, Phys. Rev. **75**, 213 (1949); Nucleonics **3**, #6, 23 (1948).

[2] Bernstein, Roberts, Stanford, and Dabbs, Phys. Rev. **94**, 1243 (1954), **95**, 105 (1954). Dabbs, Roberts, and Bernstein, Phys. Rev. **98**, 1512 (1955).

[3] R. I. Schermer, Bull. Am. Phys. Soc. **8**, 70 (1963).

[4] A. Stolovy, Phys. Rev. **118**, 211 (1960), Bull. Am. Phys. Soc. **5**, 294 (1960), **6**, 275 (1961), **8**, 70 (1963).

[5] Sailor, Marshak, Shore, Reynolds, and Postma, Bull. Am. Phys. Soc. **6**, 275 (1961), **7**, 305 (1962), **6**, 502 (1961); Phys. Rev. **126**, 979 (1962), **127**, 1124 (1962), **128**, 1287 (1962).

[6] B. T. Feld, in "Experimental Nuclear Physics," ed. E. Segre, vol. II, John Wiley and Sons, N. Y., 1953.

[7] M. Borghini and A. Abragam, Helv. Phys. Acta, Suppl. **4**, 143 (1960).

[8] T. J. Schmugge and C. D. Jeffries, Phys. Rev. Letters **9**, 268 (1962).

[9] Lushchikov, Manenkov and Taran, FTT **5**, 233 (1962), Soviet Phys. Solid State **5**, 169 (1962).

[10] Chamberlain, Jeffries, Schultz, and Shapiro, Bull. Am. Phys. Soc. **8**, 38 (1963).

[11] Schearer, Colegrove, and Walters, Bull. Am. Phys. Soc. **8**, 38 (1963).

[12] A. A. Bergman and F. L. Shapiro, JETP **40**, 1270 (1961), Soviet Phys. JETP **13**, 895 (1961).

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342