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COHERENT PARITY VIOLATION*

A Review of Optical Activity with Massless and Massive Particles.

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ABSTRACT

Recent theoretical speculations about parity violating effects in the forward scattering of massless and massive particles are reviewed at an elementary level. These phenomena are analogous to optical activity, whose history is also briefly reviewed. Order of magnitude estimates for the rotatory power are presented, and the feasibility of experiments with neutron beams is discussed.

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This is intended to be an elementary review of ideas connected with parity violation in forward, coherent scattering. The subject is over 150 years old. It is not my intention to give a complete survey, but to introduce the reader quickly to recent theoretical speculations. The recent interest in phenomena of this kind is mainly due to advances in our knowledge about weak interactions. The experimental confirmation of neutral current interactions at CERN and NAL has renewed interest in other weak processes expected theoretically. These "new" weak interactions can be observed either in coherent or noncoherent phenomena; this review deals only with coherent processes.

This review is based on talks which were supposed to be accessible to a wide audience. Thus order of magnitude estimates of various effects are stressed. The main danger of such estimates, in advance of experimental knowledge, is that one has overlooked a factor of zero which is also present. The estimates quoted are within a factor of ten of what I believe to be the correct answer. All formulae below should not be taken more seriously than that. The other self-imposed limitation is to restrict the discussion to scattering from non-crystaline media: atomic and molecular fluids. One word about units: I use the system, widespread in high energy physics, in which $\hbar=c=1$. When estimating numerically a formula in the CGS system a sprinkling of $\hbar, c$ factors will convert the inverse masses into Compton wavelengths of the corresponding particles.

1. Prehistory: Optical Activity with Light

At the beginning of the last century (Arago 1811, Biot 1812) it was discovered experimentally that some substances are optically active. This was at a time of debate about the nature of light: particles or waves? The recognition of two independent states of polarized light helped to settle the issue, for a century, in favor of transversely polarized waves. Biot recognized that when travelling through an optically active medium (labelled right handed sugar in Fig. 1) plane polarized light emerges with its plane of polarization rotated by an angle with respect to the plane of polarization of the incident wave. Clearly the medium can tell the difference between right and left. In modern language this is a parity violating effect, and I believe this accounts for some of the original excitement.

It can be seen from Fig. 1a that a plane polarized wave is not an eigenstate of propagation through an optically active medium. The plane wave rotates into another plane wave. The eigenstates of propagation through an active medium are helicity states. This was recognized by Fresnel, who discovered helicity states for light (Fresnel 1817, see also Jacob and Wick 1959) so called right handed and left handed circularly polarized light waves. Fresnel also recognized that right handed and left handed waves propagate at slightly different speeds through active media, and this difference accounts for the rotation of polarization of plane waves (Fresnel 1823).

An important conceptual clarification was the experimental demonstration (Pasteur 1848) that optically active substances come in two species: a right turning variety and a left turning variety. Apart from their optical properties the two species are identical in their physical and chemical behavior. The crystals of the two species are in the relation of mirror images to each other. The mirror image is not superimposable on the original by rotation, and Pasteur and others, speculated correctly that the same relationship holds for the molecules of the two optically active species. From a modern viewpoint Pasteur's experiments demonstrated that it is <u>not the interaction</u> (of the light wave with the molecules) which violates parity but the target molecules themselves. The optically active molecules are not in an eigenstate of parity. The interaction is parity conserving. Indeed, the belief in parity conservation for all physical interactions remained unquestioned for over a century (Lee and Yang 1956). The fact that some molecules are quasistationary in states which are not invariant under parity is interesting in itself. This phenomenon is similar to spontaneous symmetry breaking in field theory. The hamiltonian of a sugar molecule is parity conserving yet right handed sugar is not an eigenstate of parity.

2. Wave Particle Duality: Optical Activity with Neutrons? (Kabir 1971, Podgoretskii 1966)

By the beginning of this century the duality between the wave and particle pictures for light began to emerge. Light can be thought of as being composed of massless particles travelling at high speed. In this picture the polarization of the wave corresponds to the spin of the particle. In the particle picture the optical rotation experiment looks, with a little license, as shown in Fig. 1b. Since the wave particle duality extends also to massive particles like electrons or neutrons, one is tempted to ask: what happens if we replace the polarized photon with a polarized massive particles? Kabir conjectured that polarized neutrons would rotate their polarization when travelling through an optically active medium. Podgoretskii had asked the same question somewhat earlier. Of course, if the polarization of the neutron does rotate the next question is: how many miles of sugar are needed for a one degree rotation? Neutrons of course can also interact weakly without conserving parity and this can lead to a rotation of the polarization by scattering from atoms rather than molecules (Michel 1964, Stodolsky 1974). In what follows we shall discuss the order of magnitude of these various phenomena.

3. What Does One Have to Compute?

When travelling through a medium composed of scatterers the propagation of a wave can be described by an index of refraction. The index of refraction is related to the forward scattering amplitude f(0) which describes the scattering of the wave by the atoms or molecules of the medium. The scattering amplitude f(0) has the dimensions of length (the cross section is proportional to $|f(\theta)|^2$). In an optically active medium the index of refraction of right handed waves is different from the index of refraction of left handed waves (Fresnel 1823), and therefore the forward scattering amplitude of right handed waves $f_R(0)$ differs from the forward scattering amplitude of left handed waves $f_L(0)$. In terms of these quantities, the rotatory power (in radians per centimeter) of a medium composed of N scatterers per cubic centimeter, for waves of wavelength λ, is given by*

$$\Phi = N \cdot \lambda \cdot \mathrm{Re}\left[f_L(0) - f_R(0)\right] \tag{1}$$

Formula (1) is a transcription of Fresnel's relation between the optical rotatory power Φ and the indices of refraction n_R, n_L for right handed (R) and left handed (L) waves. As stated in formula (1) it is the real part of the forward scattering amplitude which governs the phase of the wave and therefore the phase mismatch between R and L waves which accounts for the rotation Φ. If $\mathrm{Re}\, f_L(0)$ differs from $\mathrm{Re}\, f_R(0)$ then, in general the imaginary parts are going to be different from each other as well. The imaginary part of the forward scattering amplitude governs the attenuation of the wave, when passing through the medium.
If $\mathrm{Im}\, f_L(0) \neq \mathrm{Im}\, f_R(0)$ one of the two components R, L will get more attenuated than the other one. In optics this effect is well known (Cotton 1895) under the name of circular dichroism. The formula analogous to (1), giving the net

*For photons Eq. (1) has an extra factor of 2^{-1} on the R. H. S.

longitudinal polarization Ψ per centimeter, is for small Ψ

$$\Psi = N \cdot \lambda \cdot \mathrm{Im} \left[f_L(0) - f_R(0) \right] \quad . \tag{2}$$

In order to compute Φ or Ψ one has to find the spin dependent part of the forward scattering amplitude $f_S = f_L(0) - f_R(0)$.

In quantum mechanics the scattering amplitude $f_{R,L}$ is a matrix element of an operator between the initial and final state. In forward scattering the final state is identical to the initial state, and

$$f_{\substack{R \\ L}}(0) = < \substack{R \\ L} A | \hat{O} | \substack{R \\ L} A> \tag{3}$$

where by A we represent all quantum numbers describing the state of the target and of the beam apart from the helicity of the beam. If $f_R(0) \neq f_L(0)$ then either a) the state of the target is not an eigenstate of parity $P|A> \neq \pm |A>$ or b) the interaction operator $\hat{O}$ is not invariant under parity: $P\hat{O}P^{-1} \neq \hat{O}$. Both these possibilities can be realized when scatterings neutrons from a medium as we shall discuss. With light, unless electromagnetic interactions as we know them are incorrect, only the first alternative holds.

It is amusing to note that it is possible to construct examples of states which are not invariant under parity which nonetheless do not rotate polarized (neutron or light) waves, after averaging over all orientations of the incident beam. In other words, while the occurrence of spin rotation for isotropic media signals a violation of parity the converse is not necessarily true.

4. Light Scattering from Twisted Molecules

To warm up we estimate the rotatory power of a medium composed of twisted molecules. Light is scattered by the electrons in these molecules. The scattering amplitude of light by an electron is the so-called classical radius of the electron: e^2/mc^2. This is the only length which one can construct from the classical quantities e, m, c. To obtain a difference between the f_L amplitude and f_R scattering amplitude one must absorb the photon by electric dipole radiation and re-emit by magnetic dipole radiation (or vice-versa), which have opposite parity. Magnetic dipole amplitudes are smaller than electric dipole amplitudes by a factor $ka \sim \frac{a}{\lambda}$ where a is the molecular size and λ the wavelength of the radiation, so that:

$$f_S = f_L(0) - f_R(0) \simeq \frac{e^2}{mc^2} \cdot ka \tag{4}$$

and

$$\Phi = N \cdot \lambda \cdot f_S \simeq N \cdot \lambda \cdot \frac{e^2}{mc^2} \cdot ka \simeq N \cdot \left(\frac{\hbar}{m_e c}\right)^2 \tag{5}$$

In the last step, I took as typical molecular size $a = \hbar^2/me^2$ which brought in Planck's constant. For typical densities $N \sim 10^{21}$ molecules/cm^3, Eq. (5) gives $\Phi \sim 1$ rad/cm. This is the correct order of magnitude, which is known experimentally. The dependence of Φ on the wavelength, the "dispersion" of the rotatory power is not given in Eq. (5). As the wavelength λ increases relative to molecular size the rotary power Φ has to vanish (Boltzmann 1874). The theory of optical activity is an elaborate field of study in molecular physics; the general scale of rotatory power is correctly given in Eq. (5).

5. Light Scattering from Atoms

The discovery of parity violation in weak interactions started speculations about optical activity with atoms. *A priori*, there could exist a weak, parity violating interaction between electrons and protons (Zel'dovich 1959). So far there is no evidence for this interaction. This possibility gained support after the discovery of neutral currents: hadronic transitions induced by neutrinos unaccompanied by muons. Theories which predict neutral currents also predict a weak electron-nucleon interaction (see for example Weinberg 1967 and Salam 1968 which are leptonic models of such theories). If such an interaction exists then, in an atom it would give rise to a small mixing of negative parity states into positive parity states and vice versa (Zel'dovich 1959). The existence of such a mixing would be revealed in parity violating experiments, in particular in forward, coherent scattering of light (Zel'dovich 1959) from hydrogen atoms. More recently, Khriplovich emphasized the advantage of looking at heavy atoms, and gave an estimate for the size of the effect in $T\ell$ vapor (Khriplovich 1974). With angular momentum conservation, the parity violating interaction between an electron in an atom and the nucleus of η nucleons is of the form (Bouchiat and Bouchiat 1974):

$$H_W \sim G\frac{\vec{\sigma}\cdot\vec{p}}{m}\,\delta^3(\vec{r})\,\eta \tag{6}$$

where G is the Fermi weak coupling constant and $m, \vec{p}, \frac{1}{2}\vec{\sigma}$ are the electron mass, momentum and spin. With this interaction the (amplitude of) admixture of the wrong parity component $P_{1/2}$ into the state $S_{1/2}$ of a hydrogenic atom of nuclear charge Z has the order of magnitude:

$$\text{Wrong parity amplitude} \sim (Gm^2)\,\alpha^2 Z^2 \eta \tag{7}$$

and therefore one expects a rotatory power:

$$\Phi \simeq N\cdot\lambda\cdot\left(\frac{e^2}{mc^2}\right)\left[Gm^2\,\alpha^2 Z^2 \eta\right] \tag{8}$$

For a gas of heavy atoms $Z \sim 80$, $\eta \sim 200$ at 10^{19} atoms/cm^3 at a wavelength of 10^{-4} cm formula (8) gives $\Phi \sim 10^{-8}\,\text{cm}^{-1}$ which is within a factor of ten of the value quoted by Khriplovich, who takes into account relativistic corrections not mentioned here. Although the expected effect is small it is measurable, and experiments are in preparation to detect this rotation (Sandars 1975). A non-zero effect would demonstrate either the existence of a parity violating electron-nucleus interaction, or a direct parity violation in the interaction of light with matter. There is no need to emphasize the importance of such information.

6. Forward Neutron Scattering: Weak Interactions

The neutron participates in weak interactions, which are parity violating. One might thus expect that in forward neutron scattering through matter, there is a weak, parity violating spin dependence. The existence of such an effect does not hinge on the existence of neutral currents: the weak, charge changing process:

$$np \rightarrow pn$$

is sufficient to produce such a parity violation (Michel 1964, Stodolsky 1974).

In the case at hand it is clearly the interaction which is parity violating rather than the initial target state. An order of magnitude of the expected effect may be constructed using the scale set by the weak interaction coupling constant G:

$$\hat{f}_S \sim G m_n \frac{\vec{\sigma} \cdot \vec{p}}{m_n} Z_A \tag{9}$$

where Z_A is the axial vector charge of the nucleus, essentially the number of protons and m_n, $\vec{p}$ and $\frac{1}{2}\vec{\sigma}$ are the neutron mass, momentum and spin. The rotatory power of matter composed of heavy atoms at normal densities is:

$$\Phi \sim N \lambda f_S \sim N G Z_A \sim 10^{-8} \text{ rad/cm} \quad . \tag{10}$$

where I have taken $N \sim 10^{22}$ at/cm^3 and $Z_A \sim 100$. The estimate (10) is identical to those published in the literature (Michel 1964, Stodolsky 1974). Stodolsky also stated the associated effect in absorption, and the possibility of deducing the sign of G from the sign of Φ. This could be very useful to confirm or rule out theories for weak interactions based on intermediate bosons in which the sign of G is expected to be positive.

7. Forward Neutron Scattering from Twisted Molecules

The parity violation in forward neutron scattering can also occur if the target is not in an eigenstate of parity—e.g., the nucleus of an "active" atom in a handed molecule. To understand this it is useful to discuss a simple model (Kabir et al. 1974), of a single spinless nucleus of mass M bound in a parity violating (anisotropic) harmonic oscillator well:

$$H = \underbrace{\frac{\vec{p}^{\,2}}{2M} + \frac{1}{2} M \left(\omega_1^2 x^2 + \omega_2^2 y^2 + \omega_3^2 z^2\right)}_{\text{invariant under parity}} + \underbrace{\ell xyz}_{\substack{\text{odd under}\\ \text{parity}}} \tag{11}$$

A similar model has been proposed much earlier (cf. Condon 1937) to describe the motion of an electron in an optically active molecule. Here, the hamiltonian (11) describes the zero point motion of a nucleus, in such a molecule. To visualize this motion it is convenient to think of the nucleus moving on a handed spiral, as in Fig. 2. How does the spin of the forward scattered neutron find the handedness of the orbital motion of the nucleus? A possible mechanism is shown in Fig. 2. This is a resonant mechanism: the incident polarized neutron is absorbed in the nucleus and carried along for a while. Since the nucleus is initially spinless, the spin of the neutron becomes the spin of the intermediate nuclear resonance. Due to spin-orbit coupling the resonance rotates its spin and, when the neutron is re-emitted its spin has been turned a little. This mechanism is "operative" when the lifetime of the nuclear resonance is comparable to the period of oscillation of the nucleus on the "spiral." The mechanism giving rise to spin orbit coupling in the second stage (on Fig. 2) is the coupling of the spin magnetic moment of the resonance to the magnetic field generated by the orbital motion of the nucleus. The resulting spin dependence of the forward scattering amplitude is easy to estimate:

$$f_S = f_L - f_R \sim f_{nucl} \cdot \frac{\frac{\mu_{spin} \cdot \mu_{orbit}}{r^3}}{\hbar \bar{\omega}} \cdot (kr) \tag{12}$$

where the spin magnetic moment of the resonance μ_{spin} is roughly $(e\hbar/m_n c)$, the orbital magnetic moment $\mu_{orbit} \sim (Z e\hbar/Mc)$ in an orbit of size $r \sim \sqrt{\hbar/M\bar{\omega}}$ and the factor kr accounts for the p-wave emission (or absorption) of the neutron. The scale of the forward amplitude f_S is set by the scattering amplitude from a free nucleus f_{nucl}. Replacing all these factors in Eq. (12) we obtain:

$$f_L - f_R \simeq f_{nucl} \cdot Z \cdot k \left(\frac{e^2}{m_n c^2} \right) \tag{13}$$

and therefore

$$\Phi = N \cdot \lambda \cdot (f_L - f_R) = N \cdot f_{nucl} \cdot Z \left(\frac{e^2}{m_n c^2} \right) \sim 10^{-5} \mathrm{cm}^{-1} \tag{14}$$

where I took $f_{nucl} \sim 10^{-13}$ cm, $Z \sim 100$ and $N \sim 10^{22} \mathrm{cm}^{-3}$ for a heavy nucleus, with a fairly large neutron scattering amplitude.

In the earliest treatment of this problem (Baryshevskii 1966) the tacit assumption of a rigid molecule was made. With this assumption parity violation can only occur due to the multiple scattering of the neutron from different nuclei in the molecule. This greatly reduces the size of the effect (see also Kabir *et al.* 1975).

8. How Small a Rotation of Neutron Polarization Can Be Detected?

The most accurate experiments which detect the rotation of the polarization of a neutron beam are Ramsey's well known experiments to measure the elusive electric dipole moment of the neutron (e.g., Miller et al. 1967). The rotation of the neutron polarization occurs because of the electric field through which the neutrons travel. The present limit for the electric dipole moment of the neutron is about 10^{-24} cm (Ramsey 1975), which for an electric field of 10^4 volts/cm corresponds to an energy difference of 10^{-20} eV. The corresponding precession period is 10^4 sec. In other words, if a neutron had an electric dipole moment of 10^{-24} cm, it would make a full precession in 10 hours, in the electric field mentioned above. Of course the neutrons don't hang on that long in the electric field. The measurement time in Ramsey's apparatus can be obtained by dividing the length of the apparatus ($\sim$ 1 m) by the speed of neutrons (10^2 m/sec). During a time of 10^{-2} sec the neutrons rotate their spin polarization by an angle of 10^{-6} radians. Thus it is possible, at the present time to measure a neutron angle of precession of 10^{-6} radians. (See also Mezei 1972.) This angle is in the range of the effects discussed in this review. Roughly speaking one would have to replace the electric field in the experiment by a piece of matter.

9. How to Detect the Neutrino Sea

According to rumors originating in the astrophysics community we are all immersed in a neutrino (or antineutrino) sea. The sea is very hard to detect experimentally and the corresponding cosmological theories hard to disprove. Can one detect the neutrino sea by parity violating coherent experiments? Drell asked this question from Royer who tackled it (Royer 1968). Royer found that a polarized plane wave of light will rotate its polarization slowly when travelling through the neutrino sea. The density of the neutrino sea is characterized by its Fermi energy k_F. We construct an inverse length to compute the rotatory power Φ of the Fermi sea, using the weak interaction coupling constant G and k_F:*

$$\Phi \sim G\, k_F^3\, \alpha \sim 10^{-14}\ \mathrm{rad/cm} \quad . \tag{15}$$

I have inserted a factor α to account for the dissociation of the photon into a lepton pair prior to interacting with the neutrinos, and the subsequent recombination of the lepton pair. In evaluating (15) I have assumed $k_F \sim 100$ eV. The estimate (15) agrees with Royer, apart from a numerical factor $(9\pi^4)$ which is hard to get by waving one's hands. Note that a rotatory power as small as 10^{-14} rad/cm is perhaps not impossible to detect. A plane polarized laser beam, starting on the Moon would be rotated on Earth by 10^{-4} radians. The orientation of the initial plane of polarization could be referred to the position of stars. It is not obvious how much an estimate like (15) would be changed by taking neutral currents into account. In any case the experiment might well be worth performing just in case of the neutrino sea is really here and is much deeper than expected.

The analogous observation of the neutrino sea with <u>massive</u> polarized particles has also been proposed (Stodolsky 1975). Stodolsky pointed out that a transversely polarized electron would slowly rotate its polarization while travelling through the neutrino sea. The estimate of the rotatory power of the neutrino sea for electrons is similar to (15). The factor of α is no longer present since we have a lepton to start with. If the electron sails through the neutrino sea by virtue of the motion of the solar system around the galactic center ($v/c \sim 10^{-3}$) the attendant spin rotation is of the order 1000 radians/year

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*It is amusing to note that both these concepts are due to Fermi.

for a neutrino sea of $k_F = 100$ eV:

$$G k_F^3 \cdot 3 \cdot 10^7 \frac{\text{sec}}{\text{year}} \times 3 \cdot 10^{10} \frac{\text{cm}}{\text{sec}} \times 10^{-3} \sim 10^3 \text{ rad/year} \quad .$$

Stodolsky's estimate is similar to this one. A method of this kind, involving massive particles might be sensitive to much shallower neutrino seas than $k_F \sim 100$ eV.

10. Summary

In addition to the well known coherent parity violation in the propagation of light through handed media a number of similar new phenomena have been proposed. These are all summarized in Table I. Experimental information on these effects is eagerly awaited.

11. Acknowledgements

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TABLE I

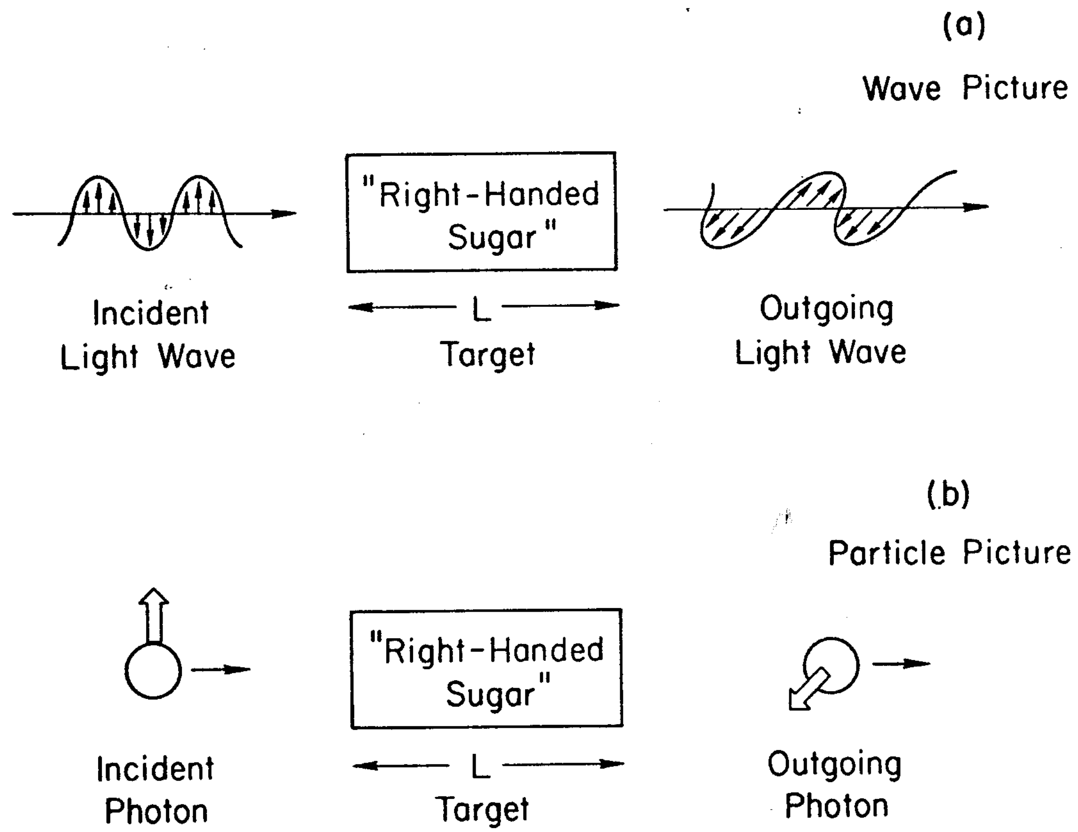
Coherent Parity Violating Effects

	Effect	Rotatory Power
a)	Light Propagation:	
	1. States of mixed parity in molecules	1 rad/cm
	2. States of mixed parity in atoms (due to neutral currents)	10^{-7} rad/cm
b)	Neutron Propagation:	
	1. States of mixed parity in molecules	10^{-5} rad/cm
	2. Parity violating weak interactions with nuclei (charged and neutral currents)	10^{-8} rad/cm

Figure Captions

1. Wave and particle pictures of optical activity.

2. The resonant mechanism for neutron optical activity.



QUESTION (Kabir, Podgoretskii)

(a) Is there an analogous effect with massive particles, say neutrons?

(b) If there is, how many miles L of "Right-Handed Sugar" do we need for a one degree rotation of the polarization?

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Fig. 1

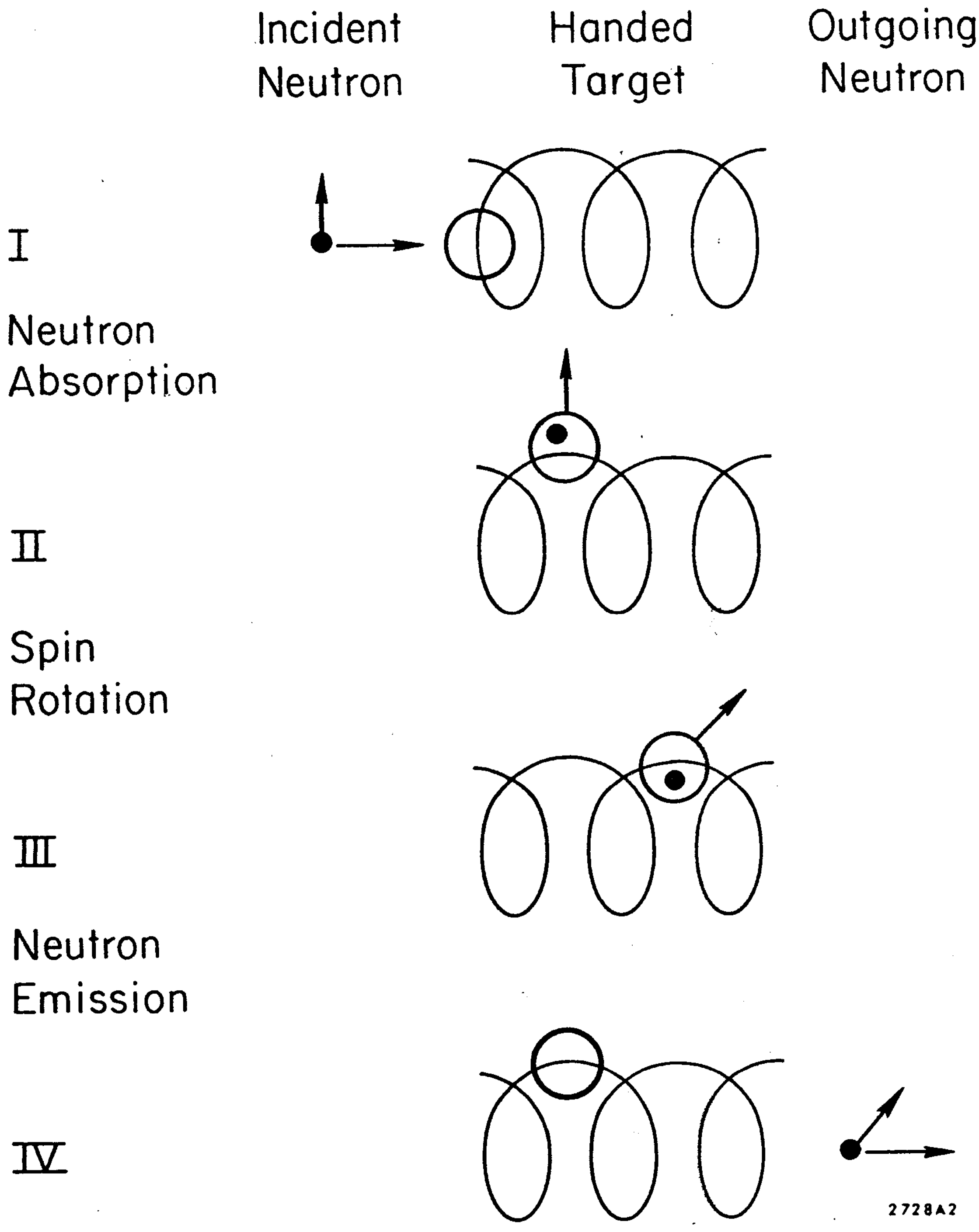
Incident Neutron
Handed Target
Outgoing Neutron
I
Neutron Absorption
II
Spin Rotation
III
Neutron Emission
IV
2728A2

Fig. 2