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Detection of Deuteron Alignment with s-wave Reactions

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Abstract. A brief review is made of some properties possessed by oriented deuteron beams with tensor moments up to rank 2. In particular, it is pointed out that angular distributions may result from aligned deuteron beams, even though the reaction may be initiated by *s*-waves and/or proceed through the contribution from a single element of the reaction matrix. Specific calculations are carried out for the 107-kev resonance in the $T(d, n)He^4$ reaction, the 430-kev resonance in the $He^3(d, p)He^4$ reaction, and the 940-kev resonance in the $C^{12}(d, p)C^{13}$ reaction. Several suggestions are made for these reactions as analyzers of deuteron alignment.

It is evident from the agenda for this symposium that many laboratories are currently engaged in the fascinating, albeit difficult, problem of producing polarized particle beams by two distinct methods, (a) polarized ion sources suitable for post acceleration to any desired energy, and (b) polarized beams of second-order intensity obtained through reactions and scattering. The present paper is concerned primarily with deuteron orientation, alignment, and polarization processes.

The theoretical aspects of orientated beams with particle spins higher than 1/2 have been formulated by DALITZ [1][1]), and applied to the case of the deuteron by LAKINS and WOLFENSTEIN [2, 3]. General treatment of the higher order tensor moments has been given by SIMON and WELTON [4, 5], and GOLDFARB [6]. Numerous other theoretical treatments [7–13] are of value in understanding the tensor orientation problem, and in particular the review articles of WOLFENSTEIN [14], DEVONS and GOLDFARB [15], BLIN-STOYLE and GRACE [16], and BREIT and MCINTOSH [17] are very comprehensive.

In contrast to the polarization of spin 1/2 particles, a physical picture for spin 1, or higher becomes considerably more complex. A particle of spin i will, in general, have non-zero irreducible tensor moments (T_q^k) up to a maximum rank of 2i. A beam of rank zero is unoriented, a beam with only odd rank components is termed polarized (rank 1 corresponds to the usual vector polarization), a beam with only even rank components we call aligned (not necessarily along a single axis),

[1]) Numbers in brackets refer to References, page 179.

and a beam containing both even and odd tensor components is said to be oriented. Thus the general orientation of a deuteron beam will have $(2\,i+1)^2$ tensor components of rank 0 (one scalar normalized to unity), 1 (the three components of a pseudo-vector, the total spin), and 2 (the five components of an irreducible tensor). If $\boldsymbol{i}$ is chosen along the beam (z) axis, then $T_1^{\pm 1} = 0$. Furthermore, the oriented states produced in simple reactions (two colliding particles in both entrance and exit channels) will have the spin and a principal axis of the tensor along the normal to the reaction plane, hence all values of $T_q^{\pm 1}$ vanish. Even so, it is apparent that considerable experimental information is required to uniquely determine all tensor components of the orientation.

Oriented deuterons may be produced from ionized atomic beams. There is, in particular, a group at the Oak Ridge National Laboratory engaged in such a project. J. E. SHERWOOD, R. F. KING, and S. J. OVENSHINE [18] have under construction a machine of the Rabi-type where selection of the appropriate atomic hyperfine states is made by means of the «flop-in» technique. Presently the expected difficulties with the ionization stage of the problem are being investigated.

Scattering and reactions are also possible sources of oriented deuterons. Elastic deuteron scattering in He^4 (at the 1.069-Mev resonance as first suggested by GOLDFARB [6, 19,] see also PONDROM [20] and PHILLIPS [21]) and C^{12}, (p, d) and (n, d) reactions, whether proceeding by compound nucleus formation or «pick-up», (He^3, d) and (He^4, d) reactions are all possible sources of highly oriented deuterons. Thermal neutron capture in hydrogen has also been suggested [22] as an aligned deuteron source. The point is that there are many ways to obtain oriented deuteron beams, and hence convenient methods of analysis are desirable. In particular, an analyzer for low energy deuterons would serve as a great impetus in the development of oriented ion sources for injection into accelerators.

Before considering specific reactions, there are two important special conclusions that can be drawn regarding alignment with rank 2. First of all, the general expression [4, 5, 6] reveals that reactions, or scatterings induced by s-wave deuterons with even rank tensor alignment can give rise to non-isotropic angular distributions, provided that the compound state has total angular momentum greater than 1/2, and the emitted wave of particles has orbital angular momentum greater than 0. This is in contrast to spin 1/2 particles which can have only «vector» polarization (rank 1), and hence produce only spherically symmetrical angular distributions, independent of their state of polarization.

Secondly, alignment depends upon the real part of $R_1\,R_2^*$, while odd rank polarization is a function of the imaginary part of $R_1\,R_2^*$. (Here R_i is the usual reaction matrix element.) Thus, alignment can arise

from a *single* matrix element (single level of definite spin and parity formed (and decaying) by unique values of orbital angular momentum and channel spin). Furthermore, since the unoriented angular distribution also depends upon the real part of $(R_1 R_2^*)$, the alignment resulting from a single matrix element will be independent of the dynamics of the process (compound nucleus formation, pick-up process, etc.). It will be characterized by the geometry only. On the other hand, odd rank polarization is essentially an interference phenomena and hence requires at least two different elements in the reaction matrix.

A particularly good reaction illustrating both the above conclusions was first pointed out by GALONSKY, WILLARD, and WELTON [23] (see also GOLDFARB [24]). The $T(d, n)He^4$ reaction [25] has an isolated resonance at a deuteron bombarding energy of 107 kev. This state of total angular momentum $J = 3/2^+$ is formed by s-wave deuterons and decays by d-wave neutron emission. Unoriented beam angular distributions are isotropic up to about 500 kev, and the total reaction cross section is well fitted in this region by assumption of a single level. If aligned deuterons formed in the pure spin state $m_d = \pm 1$ interact with tritium, the angular distribution of the emitted neutrons will have a 0° to 90° asymmetry ratio of 2 to 5 (in the center of mass system where the axis of quantization has been taken along the incident beam direction). If the deuterons are produced in the pure spin state $m_d = 0$, this ratio will be 4 to 1. (Note that the distribution depends upon the expectation value of m_d^2, and hence is identical for $m_d = +1$ and $m_d = -1$.) More general types of tensor alignment [6, 24] also produce large asymmetries, and because of its large cross section (5 barns at resonance) this reaction should serve as a useful analyzer of deuteron alignment from about 25-kev to 500-kev deuteron energy. It should be possible to detect very weak beams of low alignment by discriminating against the usual troublesome gamma-ray background in high efficiency neutron detectors, with pulse shape differentiation [26]. Finally, under suitable choice of the second rank tensor components of the deuteron alignment, this reaction may serve as a source of completely polarized 14-MeV neutrons.

The mirror reaction $He^3(d, p)He^4$ has also an insolated resonance of similar properties [25], except displaced to about 430 kev and reduced in peak cross section to about 0.7 barns by the Coulomb barrier. Unoriented angular distributions for this reaction are spherically symmetric up to about 800 kev, and this reaction should serve as a useful alignment analyzer from 250 kev up to the former energy. Furthermore, the higher efficiency for proton detection (100 per cent) will approximately compensate the lower cross section. Background discrimination should be extremely favorable.

These two reactions are most attractive for aligned deuteron ion source development, since it is possible to construct the apparatus at ground potential where unlimited space and power are available. The oriented beam can be accelerated to a few hundred kev in an air operated Cockcroft-Walton, or similar machine, and the asymmetry then measured in the terminal. Such a scheme is planned at Oak Ridge [18].

A third possible choice for s-wave analysis of deuteron alignment is provided by the $C^{12}(d, p)C^{13}$ reaction, long a source of polarized protons. In particular, there is a broad (140 kev) $J = 1^+$ level at 940 kev formed by s-wave deuterons and emitting p-wave protons [25]. We have used the formalism of GOLDFARB [6] to calculate the angular distribution of protons for a deuteron beam of arbitrary orientation. The analysis is somewhat complicated by the two possible combinations of exit channel angular momenta. This is because oriented beams may, in general, interfere coherently in the exit channel spin, thus the usual simplifications in this representation are lost. We find that

$$W = W_0 \left[1 - \frac{(1/2 + \sqrt{2}\,x)}{1 + x^2}\right] \Big\{ P_{33}\, P_2^{(0)}(\cos\theta) + 2/3\,(P_{13}\cos\chi + P_{23}\sin\chi)\, P_2^{(1)}(\cos\theta) + \frac{1}{6}\left[(P_{11} - P_{22})\cos 2\chi + 2\,P_{12}\sin 2\chi\right] P_2^{(2)}(\cos\theta)\Big\}$$

where W_0 is the angular distribution of an unoriented beam (isotropic),
x is the mixing ratio of $j_{out} = 1/2$ to $j_{out} = 3/2$,
j is the vector addition of outgoing particle spin and orbital angular momentum,

$$P_{ij} \equiv \frac{3}{2\hbar^2}\left[\overline{i_i\, i_j} + \overline{i_j\, i_i}\right] - 2\,\delta_{ij}\,,$$

$\boldsymbol{i} = \hbar\,\boldsymbol{P}$ is the *vector* spin orientation of the deuteron,
χ is the angle between the y-axis used to describe the orientation of the incident beam (z-axis) and the normal to the plane of the reaction, and
$P_2^{(k)}(\cos\theta)$ is an associated Legendre polynomial.

The results in channel spin representation can easily be obtained from the unitary transformation equation of SATCHLER [27]. For example, a beam with pure channel spin zero has $x = 1/\sqrt{2}$, and pure channel spin one has $x = -\sqrt{2}$.

In the pure spin states $m_d = \pm 1$, $P_{11} = P_{22} = -2$, $P_{33} = +1$, and $P_{12} = P_{23} = P_{13} = 0$. The angular distribution then simplifies to

$$W = W_0 \left[1 - \frac{(1/2 + \sqrt{2}\, x)}{(1+x^2)} \cdot P_2 (\cos \theta) \right].$$

Similarly, the pure $m_d = 0$ state has $P_{11} = P_{22} = +1$, $P_{33} = -2$, and $P_{12} = P_{23} = P_{13} = 0$, with the resultant distribution

$$W = W_0 \left[1 + \frac{(1 + 2\sqrt{2}\, x)}{(1+x^2)} \cdot P_2 (\cos \theta) \right].$$

It is quite apparent then that this reaction will have large observable asymmetries over the deuteron energy range 800 to 1100 kev. However, the assumption of an isolated resonance used in the above calculations is not as well justified as in the first two reactions considered. There is, in fact, a broad $J = 2^-$ level at 1.16 MeV [25] which produces interference in the unoriented angular distribution. The effect of neighboring levels will be considered in a more detailed treatment to appear later.

Thus the three reactions considered in this paper will serve as convenient analyzers of second rank tensor deuteron alignment over the energy range 25 to 1100 kev. Because of their broad character, the first two reactions may be used as general analyzers of almost any energy deuterons, since the deuterons may be slowed down by foils to the effective energy interval.

Although, first considered for their utility in oriented beam ion source development, these reactions may also serve as the second stage reaction in a double «scattering» experiment, where the first stage may be, for example, (p, d) «pickup», [28, 30] or (He^3, d) stripping. In particular it may be of some interest to orient deuterons by the $C^{13}(p, d)C^{12}$ reaction and then analyze by the inverse reaction, $C^{12}(d, p)C^{13}$. In a two stage process, care must be taken in the transformation of the spin tensors from the laboratory to the center of mass system [29]. In addition, conversion of tensor components by deflection in magnetic fields [3, 29] may be helpful in unraveling the complicated tensor alignment. Experiments of this general nature are in the planning stage at Oak Ridge.

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