CM-P00057247

An Absolute Detector and Producer of Nuclear Alignment

by

B.A. Jacobsohn ^{*)} and R.M. Ryndin ^{**)}

CERN - Geneva

^{*)} Present address: University of Washington, Seattle, Wash. U.S.A.

^{**)} Present address: Joint Institute for Nuclear Research, Dubna,
U.S.S.R.

I. Introduction

A succinct method of examining some consequences of parity invariance for reactions initiated by particles in flight has been discussed by Bohr ¹⁾. In this brief note, we wish to call attention to the consequences of the application of the Bohr symmetry argument to a special type of reaction

with the indicated spins and parities. Certain of these have already been discussed in Bohr's paper. However, since reaction (1) possesses some remarkably simple and unique geometrical properties, we believe that it is useful to present some further consequences here.

As we shall see below, the reaction can, in principle, be used as a source of a known amount of nuclear alignment, an absolute detector of the same, or a source of completely linearly polarized gamma rays ²⁾. All quantities other than the dependence of cross-section on polar angle are geometrical and are fully determined.

We must confess at the outset that reactions of the above type occur but rarely in nuclear physics. For each case discussed below we mention a few possibilities; the reader will, if interested, doubtless be able to find others for himself. The very simplicity of reaction (1) makes it uninteresting to study for its own sake, and most applications will require it to be preceded or followed by another nuclear interaction, a requirement which makes its use more difficult. A partially compensating feature is, as we shall see, that one can use larger solid angles than one might expect offhand.

There is one application of process (1) which would not require it to be one of a tandem of reactions; namely, as an absolute detector of the degree of alignment achieved by an accelerator of artificially oriented deuterons.

II. Alignment Production

The demonstration of these properties can, with equal brevity, be made using either the direction of flight of particle $\underline{d}$ as quantization axis ³⁾, or the direction $\bar{n}$ along $\bar{k}_0 \times \bar{k}_1$; $\bar{k}_0$ is the initial, $\bar{k}_1$ the final relative momentum, taken positive in the direction of motion of $\underline{d}$. To facilitate the comparison with Bohr's discussion, we shall commence with the latter method, but shall then immediately rotate the quantization direction so that it points along $\vec{k}_1$.

As the result of applying a reflection in the $\bar{k}_0, \bar{k}_1$ plane, Bohr showed ¹⁾ that the matrix element for any parity-conserving reaction will vanish unless

$$P_i P_f = (-1)^{S_n^f - S_n^i}, \quad (2)$$

where $P_i P_f$ is the product of all intrinsic parities and $S_n^{f,i}$ represent the sums of all spin components along the $\bar{n}$ direction. When applied to reaction (1) proceeding from left to right, Eq. (2) implies that the normalized amplitudes which are produced for the three spin projection states are $a_{\pm 1}^{(n)} = 0$, $a_0^{(n)} = i$. (We choose the latter phase for convenience.)

Since alignments are conventionally discussed when projected along the direction of flight, we rotate the axes first through $+90^\circ$ about $\vec{n} \times \vec{k}_1$ (the original x-axis), and then through $+\varphi$ about $\vec{k}_1$. The final z-axis is thus along $\vec{k}_1$ and the y-axis makes an angle φ with $\vec{n}$. It is easy to see that the new amplitudes, which transform like the spherical harmonics Y_{1m} and for which we omit superscripts, are

$$a_{\pm 1} = \frac{1}{\sqrt{2}} e^{\mp i\varphi}, \quad a_0 = 0. \quad (3)$$

To describe the production process we take $\varphi = 0$, and see immediately that reaction (1) produces a fixed amount of d alignment, independently of primary energy and reaction angle,

$$\langle T_{20} \rangle = \frac{1}{\sqrt{2}} \langle 3S_z^2 - 2 \rangle = \frac{1}{\sqrt{2}}, \quad (4)$$

$$\langle T_{2\pm 2} \rangle = \frac{\sqrt{3}}{2} \langle S_{\pm}^2 \rangle = \frac{\sqrt{3}}{2}.$$

All other $\langle T_{JM} \rangle$ turn out to be zero. The explicit expressions for these tensor operators are given by Lakin⁴⁾, as are formulae for the effect of these alignments on subsequent reactions.

In searching for candidates for applications of this process to the production of aligned deuterons, one is handicapped in the case of light elements by the ubiquitous isotopic spin selection rule. Reactions such as $C^{12}(\alpha, d)N^{14*}$ to the first 0^+ level are known to proceed with extremely low intensity. A possibility may be $Mg^{24}(\alpha, d)Al^{26*}$. Known and well-separated 0^+ levels in heavy odd-odd nuclei seem to be rare.

III. Polarized Gamma Quanta

If, instead of considering a deuteron, we take $d(1^+)$ to be an excited level which has a gamma emission directly to a 0^+ state, it is easy to show that these photons are emitted with a pure $\sin^2\theta$ angular distribution about the $\vec{n}$ direction, and that they are completely linearly polarized, with the magnetic vector lying in the plane containing $\vec{k}$ and $\vec{n}$. A more useful result is found by summing over all directions $\vec{k}_1$. We let $\cos\beta = \vec{k}_0 \cdot \vec{k}_\gamma$, $\vec{E}_1$ be a unit vector along $\vec{k}_\gamma \times \vec{k}_0$, $\vec{E}_2 = \vec{k}_\gamma \times \vec{E}_1$, and I_1 and I_2 be the intensities polarized with magnetic fields along $\vec{E}_1$ and $\vec{E}_2$. The result of the averaging is

$$I_1 \sim 1, \quad I_2 \sim \cos^2\beta. \quad (5)$$

In particular, the quanta are completely polarized for $\beta = \pi/2$. Effects due to the motion of the nucleus $\underline{d}$ have been ignored.

Well-identified 1^+ states in even-even nuclei for use in the reaction $X(\alpha, \alpha') X^*$ are few, and again one must be on guard against isotopic spin inhibition. There is a probable 1^+ , $T=0$ level in C^{12} at 12.7 MeV which a small fraction of the time emits a gamma to the ground state. A possible level is also provided by Mg^{24} . In Zn^{66} there is a group of states, apparently 1^+ , at excitations of 3.8 to 4.9 MeV; unfortunately, those among them which have large branching ratios for the ground state gamma are listed at present as only probable (1^+).

IV. Detection of Alignment

To discuss this case, one must invert the roles of initial and final states in the discussion of Section 2 and note that, whatever might be the state of the incoming $\underline{d}$ beam, only the amplitude a_0^n can produce the reaction. After a rotation is made to bring the z -axis along $\bar{k}_1$ and appropriate averages taken over the ensemble of incoming $\underline{d}$ particles, there results the following expression for the differential cross-section:

$$\frac{d\sigma}{d\Omega} = f(E, \theta) \left\{ 1 + (2^{-1}) \langle T_{20} \rangle + (3^{-1}) |\langle T_{22} \rangle| \cos 2(\varphi - \alpha) \right\},$$

$$\langle T_{22} \rangle = |\langle T_{22} \rangle| e^{2i\alpha}. \quad (6)$$

If the $\underline{d}$ beam comes from a previous parity-conserving two body reaction and if the y -axis is chosen along the vector $\bar{n}$ associated with that reaction, then $\langle T_{22} \rangle$ must be real ⁴⁾,

We see from Eq. (6) that the total cross-section, if measured at fixed energy on the one hand with an unpolarized beam and on the other with the beam under study, will yield an absolute measurement of $\langle T_{20} \rangle$ for the latter. Furthermore, $\langle T_{22} \rangle$ can be determined from measurements which integrate over all θ at a fixed φ .

Equation (6) should be compared with a double elastic scattering at a single θ which, as Lakin ⁴⁾ has shown, also gives an absolute measurement of alignment. The latter process involves the squares of the tensor polarizations and cannot distinguish signs. Moreover, the detecting reaction must be observed at fixed polar angle.

The possibilities of using (d, α) elastic scattering as a source, and the $T(d, n)He^4$ reaction as a detector, of $\underline{d}$ alignment have recently been discussed ^{5), 6)}. Both of those methods depend on the detailed dynamics of the reactions and are not absolute in the sense discussed here. They are useful in limited energy regions near the relevant resonances.

We note in passing that, if a $\underline{d}$ -producing reaction such as (K, d) elastic scattering should fail by a small amount to conserve parity, the angle α would be linear in the parity nonconserving amplitude.

The remarks that we can make relating to the applications of this detecting reaction follow the same lines as those relevant to the alignment-producing one, modified by the fact that (d, α) reactions are experimentally easier to carry out. Two cases appropriate to the analysis of deuteron alignment have already been observed ^{7), 8)}. The reaction $Si^{28}(d, \alpha)Al^{26*}$ to the first excited state of Al^{26} at 0.23 MeV proceeds, for 6 MeV deuterons, with an intensity $\sim 10\%$ of the ground state transition. $O^{16}(d, \alpha)N^{14*}$ gives a relative yield only slightly smaller.

V. Other Spins and Parities

If the 1^+ level of particle $\underline{d}$ is replaced in the preceding analysis by 1^- , or by higher spin, the Bohr rule still has relevant predictions to make concerning selection rules. However, it is clear that in all such cases there are at least two independent amplitudes allowed, and it is impossible to express the polarization dependence of the process at all angles as a consequence of geometry alone.

It may be interesting to notice, however, that all such processes must produce 100% polarization P , where P is a generalized polarization defined by an extension of the definition given in ref. ⁴⁾,

$$P^2 = \frac{1}{2S} \sum_{J>0, M} \left| \langle T_{JM} \rangle_{e, \phi} \right|^2. \quad (7)$$

The reason for this is that the final density matrix ρ in the spin space of particle $\underline{d}$ is that of a pure state since no other spins exist over which one can average. The condition $\rho = \rho^2$ is necessary and sufficient to have $P=1$ in Eq. (7).

The authors wish to thank Prof. L. Madansky for helpful discussion, and to express their gratitude to CERN for its hospitality.

REFERENCES

- 1) A. Bohr, Nucl. Phys. 10, 486 (1959)
- 2) The implications of reaction (1) for the case that particle d is a hyperfragment have been discussed in ref. ¹⁾.
- 3) B.A. Jacobsohn and R.M. Ryndin, submitted to Phys. Rev. Letters
- 4) W. Lakin, Phys. Rev. 98, 139 (1955)
- 5) L.G. Pondrom, Phys. Rev. Letters 2, 346 (1959)
- 6) A. Galonsky, H.B. Willard, and T.A. Welton, Phys. Rev. Letters 2, 349 (1959)
- 7) C.P. Browne, Phys. Rev. 114, 807 (1959)
- 8) C.P. Browne, Phys. Rev. 104, 1598 (1956)