brightness distribution. In view of uncertainties in the model, in the reference intensity of the night sky and in the calibration of the plate, our estimate of the Crab precursor's mass of 12 $M_\odot$ is indicative only.

Observations of the halo, such as photoelectric confirmation of its extent, distribution and brightness, spectral confirmation of its emission spectrum and detection of its anticipated large velocity dispersion, and polarization measurements are needed to elucidate its nature.

We thank Peter Krug for measuring the plate, which was obtained by Tim Hawarden.

Received 27 August; accepted 27 October 1981.

1. Chevalier, R. *Supernovae* (ed. Schramm, D.) 53 (Reidel, Dordrecht 1977).
2. Arnett, W. D. *Astrophys. J.* **195**, 727 (1975).
3. van den Bergh, S. *Astrophys. J. Lett.* **160**, L27 (1970).
4. Bessell, M. *Publ. astr. Soc. Pacif.* **91**, 603 (1979).
5. Allen, C. W. *Astrophysical Quantities*, 3rd edn (Athlone, London, 1974).
6. Toor, A., Palmieri, T. M. & Seward F. D. *Astrophys. J.* **207**, 96 (1976).
7. Scargle, J. D. *Publ. astr. Soc. Pacif.* **82**, 388 (1970).

Spin directions of interfering beams in quantum interferometry

A. Zeilinger*

Atominstitut der Österreichischen Universitäten, A-1020 Wien, Austria

It is shown here that, in a fermion interferometer experiment, the notion of the relative orientation of the interfering beams can be given a sensible meaning—information may be extracted about the spin directions without destroying the interference pattern. This is done on a gedanken-experiment level by introducing into, say, a neutron interferometer Stern–Gerlach magnets with detectors placed into their respective 'down'-spin beam paths. Similar considerations apply to experiments where spinor behaviour has been demonstrated in systems with higher spin.

In interferometry experiments with non-zero spin particles interesting effects arise due to the wave function (or probability amplitude) of the interfering beams being nonscalar. One effect concerns the sign change of a spinor wave function under 2π-rotations[1,2]. This was verified by neutron interferometry experiments[3–7], in which an incident beam was split coherently into two wave trains one of which was passed through a static magnetic field where it experienced Larmor precession and hence spin rotation. The spinor property was then found as a variation of the intensity of the recombined beams with a fringe period of multiples of 4π of the rotation angles. The values of the rotation angles were calculated from the magnetic field strengths using the known value of the neutron magnetic moment.

The interpretation of this type of experiment has been widely debated[8–12]. Moore[8], in discussing Bernstein's proposal[2] to use Larmor precession to implement the desired rotation, claims that in this experiment it would not be possible to observe directly that anything is actually rotating.

Byrne[9] has explicitly demonstrated the differences between spinor and vector wave interferometry. He showed that, in a spinor experiment, it is not possible to observe simultaneously the interference pattern and to obtain information about the relative spin directions of the constituent beams from measurements on the recombined beam. Byrne concludes that the notion of relative rotation ceases to have a meaning as it corresponds to nothing which is measurable. Thus he dismisses the interpretation that the experiments have provided a direct observation of the sign reversal of a spinor wave function subjected to a 2π rotation as unsatisfactory because, for any fermion the relative rotation of the spins in the two beams and the interference pattern are mutually incompatible observables.

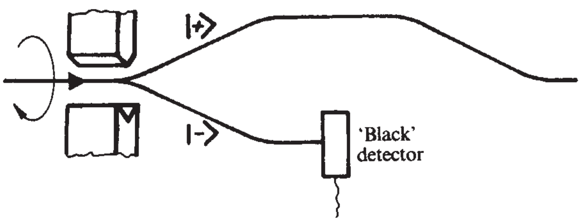

Fig. 1 Modified Stern–Gerlach arrangement with a black detector in one beam path.

However, it is possible to conceive of experimental schemes where information may be extracted from the beams interfering about their spin directions without destroying the interference pattern. In our experiments unpolarized incident neutrons were used for intensity reasons only. We consider here polarized incident neutrons that are able to trace the behaviour of the interfering spin states.

We look for a measurement procedure which changes neither the amplitudes nor the relative phase of these beams—a measurement without wave packet reduction. In quantum mechanics, such a measurement is possible if the quantum system under investigation is in an eigenstate of the observable defined by the measuring apparatus. For spin measurement, we consider for example, a Stern–Gerlach experimental arrangement in which we place into one of its separated beam paths a black (100% absorbing) detector (Fig. 1). To restore the beams to their initial paths, we place behind the first Stern–Gerlach an inverted second one. If the incoming beam is in the eigenstate corresponding to the detector-free path no event will be registered in the detector. The restriction that the amplitude at the detector never vanishes exactly due to the nonlocality of wave packets, can be reduced by increasing the separation of the beams. Similar considerations apply to the non-existence of exactly 100% absorbing detectors. Thus, the result that we did not register events in the detector together with the knowledge that particles have passed through the Stern–Gerlach gives us information about the spin observable of the incident beam.

In the more general case where a spin rotation device is placed in front of the Stern–Gerlach, the particles are no longer in an eigenstate of the Stern–Gerlach. Therefore, events will be registered in the detector. For simplicity we assume the incident beam to be polarized in a direction normal to its propagation direction and the magnetic field to rotate the spin around that propagation direction. The spin direction of the beam can then be found by rotating the Stern–Gerlach around the neutron propagation direction to that angular position where the counting rate in the detector vanishes. This spin direction is a macroscopically observable quantity—the angular position of the Stern–Gerlach. Many other geometrical arrangements can be envisaged on a gedanken-experiment level because for slow particles such as thermal neutrons the spin can be made to point in any direction relative to the propagation direction.

Formally we may describe our arrangement by a projection operator of the form $P = |s\rangle\langle s|$, where $|s\rangle$ is the +eigenstate of the Stern–Gerlach. If that operator acts on the incident state $|s\rangle$, that state is reproduced.

In an interferometer experiment of the type shown in Fig. 2 an incoming wave is split into two partial waves by a semireflecting mirror. These waves follow two distinct paths within the interferometer. Furthermore, in one beam path a magnetic field is arranged to rotate the spins. To observe the spin directions of these interfering beams we place a modified Stern–Gerlach arrangement into each interferometer beam path. In both arrangements we again place a detector into one of its beam paths, say, the 'down' spin beam path, leaving the 'up' beam path through each Stern–Gerlach free. If we start the experiment with arbitrary angular settings of the analysing direction of the Stern–Gerlach magnets we will again register particles in

---

[*] Present address: Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.

0028-0836/81/500544—03$01.00

the detectors. The count rate in each detector will be lower in the interference experiment because the amplitude of each separated interferometer beam is lower than the amplitude of the incoming wave. But the fact that particles are registered means that the corresponding partial wave is not in the 'up' eigenstate of the Stern–Gerlach in that partial beam.

Both Stern–Gerlachs are now rotated independently of each other until we arrive at a position where neither detector registers a single event. At that point, the amplitude of the corresponding partial wave in the 'down' eigenstate of the Stern–Gerlach vanishes. However, we can still observe the interference pattern of the recombined beams, because our Stern–Gerlach arrangement does not enable us to determine which path is followed by the particle in the interferometer. Hence, both the null-effect spin measurements and the interference fringe observation allow us to conclude that the particles are in a coherent superposition of the two 'up' states defined by the two different Stern–Gerlachs. Or $|\psi\rangle = |S_1\rangle + |S_2\rangle$, where $|S_1\rangle$ and $|S_2\rangle$ are the 'up' eigenstates of the Stern–Gerlachs in the beam paths 1 and 2, respectively.

As the analysing directions of the Stern–Gerlachs are macroscopically observable quantities we conclude that the relative spin directions of the interfering beams are operationally meaningful quantities. This also applies to the relative rotation of the interfering beams because, in principle, we can trace the effect of the spin rotation device in arbitrarily small steps. We still have to consider whether the introduction of our spin-measurement devices may destroy the relative phase of the interfering beams.

Nevertheless, when considering—on the gedanken-experiment level—the use of the Stern–Gerlach magnets the inhomogeneous magnetic fields may lead to a destruction of the coherence of the interfering beams[13]. But other spin measurements can be envisaged where this is not the case. For thermal neutrons, diffraction at perfect crystals in external homogeneous magnetic fields[14] and refraction at wedge-shaped magnetic fields[15] both lead to a separation of the spin states while retaining their coherence properties. These schemes also offer the advantage that in contrast to a gedanken-experiment they are actually realizable experimentally along the lines of the existing technology of perfect crystal neutron optics.

At about the same time that the neutron interferometer experiments were performed it was realized[16] that the spinor behaviour can also be observed in a spin 1 system. This exploits the fact that the wave function of a two-state system—except for the photon and similar degenerate cases—changes sign under a 2π rotation. Thus, if in a three-state system the populations of two levels are inverted twice by properly phased electromagnetic high frequency pulses, their state function acquires the -1 phase factor. That phase factor may be revealed by observing interferences between one or both of these two states and the third state. There is also experimental evidence[16] for that behaviour based on radio-frequency transitions between hyperfine energy levels in TlF. The same effect can be demonstrated experimentally by exploiting NMR transitions[17–19]. There, systems can be found where a continuous transition between spin $\frac{1}{2}$ and spin 1 behaviour may be seen depending on a continuous variation of the relative amplitudes of excitation of transitions between 2 or 3 levels.

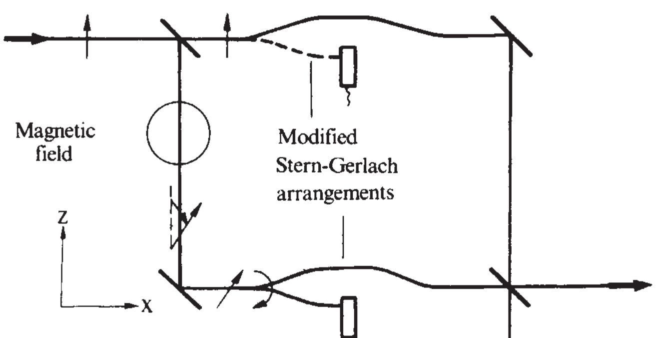

Fig. 2 Fermion interferometer gedanken-experiment with modified Stern–Gerlach arrangements in both beam paths. The magnetic field produces a spin rotation around the x-direction. A corresponding rotation of the lower Stern–Gerlach ensures unattenuated passage.

Even for the above type of experiment we could consider a spin direction which is rotated while the relative population of two levels is changed. To apply our spin-measurement scheme we consider, again on a gedanken-experiment level, a further Stern-Gerlach magnet which separates spatially all three incoming states. Later while one of these states is left unaffected we may recombine the other two states and subject them to the same measurement procedure as above. Thus we may introduce transitions between these two states and we may use one of our modified Stern-Gerlach arrangements to determine the spatial direction for which this two-state subsystem is in an eigenstate. After recombination with the unaffected third state the interference effects may still be observed. Thus, here too it is possible to assign a meaning to the notion of a spatial direction, the rotation of which is associated with the 4π periodicity of the phase factor.

The approach presented here is to some extent complementary to Renninger's considerations of a measurement without disturbance of the measured system[20], a concept which has been extended to the spin case by Yoshihuku[21]. The difference is that in Renninger's case the wave packet is actually reduced by the measurement while we consider a measurement without wave packet reduction. Note that there exists a non-vanishing probability that in our modified Stern-Gerlach experiment we may not observe particles in the 'down' detector even if the spin is not in the 'up' eigenstate of the Stern-Gerlach. Evidently that probability can be reduced by increasing the number of particles passing through the apparatus and by carefully orienting the direction of the Stern-Gerlach. Therefore the spin direction can only be determined within a certain error. Our gedanken-experiment shares this this inherent statistical nature with other quantum measurements and, to some extent, with classical measurements. Nevertheless, in an interferometer experiment this is a minor point as our modified Stern–Gerlachs actually produce the beams in their respective 'up' eigenstates: the 'down' states are absorbed by the detectors.

The action of our modified Stern–Gerlach magnets including the absorbing detector in one beam path can be described by the projection operator

$$P_{\mathrm{Op}} = \tfrac{1}{2}(I + \mathbf{n}\boldsymbol{\sigma}) \tag{1}$$

Here, $\mathbf{n}$ is a unit vector pointing in the analysing direction of the Stern–Gerlach and $\boldsymbol{\sigma}$ is the Pauli spin matrix vector. A state is in the 'up' eigenstate of the Stern–Gerlach if

$$\psi = P_{\mathrm{Op}}\psi \tag{2}$$

If we write ψ as the spinor

$$\psi = \mathrm{e}^{\mathrm{i}\epsilon}\begin{pmatrix} a \\ b\,\mathrm{e}^{\mathrm{i}\phi} \end{pmatrix} \tag{3}$$

Equation (2) implies that

$$\mathbf{n} = (2ab\cos\phi,\ 2ab\sin\phi,\ a^2 - b^2) \tag{4}$$

that is $\mathbf{n}$ has to coincide with the polarization direction of the particles described by ψ.

Disregarding the details of the physics of the beam splitters we can use phenomenologically for the beams inside the interferometer the four-component spinor

$$\psi_{\mathrm{IF}} = \begin{pmatrix} \psi_1^+ \\ \psi_1^- \\ \psi_2^+ \\ \psi_2^- \end{pmatrix} = \mathrm{e}^{\mathrm{i}\epsilon}\begin{pmatrix} a_1 \\ b_1\,\mathrm{e}^{\mathrm{i}\phi_1} \\ a_2\,\mathrm{e}^{\mathrm{i}\chi} \\ b_2\,\mathrm{e}^{\mathrm{i}(\chi+\phi_2)} \end{pmatrix}$$

where, say, ψ_1^+ is the amplitude in the $+z$-direction in beam 1 and so on. The normalization condition is $a_1^2 + b_1^2 + a_2^2 + b_2^2 = 1$. This four-component spinor describes the states inside the interferometer, the beams leaving the interferometer are superpositions of its various amplitudes.

In analogy with the above case, the projection operator describing the case where two modified Stern–Gerlachs are in the interferometer, one in each beam path, may be given as

$$P_{\mathrm{IF}} = \frac{1}{2}\begin{pmatrix} I+\mathbf{n}_1\boldsymbol{\sigma} & 0 \\ 0 & I+\mathbf{n}_2\boldsymbol{\sigma} \end{pmatrix} \tag{6}$$

The condition that this operator leaves the wave function invariant

$$\psi_{\mathrm{IF}} = P_{\mathrm{IF}}\psi_{\mathrm{IF}} \tag{7}$$

implies again that

$$\mathbf{n}_i = \frac{1}{a_i^2+b_i^2}(2a_ib_i\cos\phi_i, 2a_ib_i\sin\phi_i, a_i^2-b_i^2) \tag{8}$$

Or, equivalently, the analysing directions of the individual Stern–Gerlachs have to be oriented parallel to the respective beam polarization directions. The particle state is then left invariant, in particular the relative phase χ in equation (5) between the two interferometer beams is unchanged. Therefore the interference pattern may still be observed.

I thank Professors H. Bernstein, J. Byrne, M. A. Horne, H. Rauch and A. Shimony for critical and useful discussions and Drs A. G. Klein and O. Schärpf for critical reading of the manuscript. Financial support was by Fonds zur Förderung der wissenschaftlichen Forschung (Austria), project no. 4230.

Received 17 June; accepted 24 September 1981.

1. Aharonov, Y. & Susskind, L. *Phys. Rev.* **158,** 1237–1238 (1967).
2. Bernstein, H. J. *Phys. Rev. Lett.* **18,** 1102–1103 (1967).
3. Rauch, H. *et al. Phys. Lett.* **54**A (1975) 425–427.
4. Rauch, H., Wilfing, A., Bauspiess, W. & Bonse, U. *Z. Phys.* **B29,** 281–284 (1978).
5. Rauch, H. & Zeilinger, A. *Hadr. J.* **4,** 1280–1294 (1981).
6. Werner, S. A., Colella, R., Overhauser, A. W. & Eagen, C. F. *Phys. Rev. Lett.* **35,** 1053–1056 (1975).
7. Klein, A. G. & Opat, G. I. *Phys. Rev. Lett.* **37,** 238–240 (1976).
8. Moore, G. T. *Am. J. Phys.* **38,** 1177–1180 (1970).
9. Byrne, J. *Nature* **275,** 188–191 (1978).
10. Bernstein, H. J. in *Neutron Interferometry* (eds Bonse, U. & Rauch, H.) 231–240 (Oxford University Press, 1979).
11. Mezei, F. in *Neutron Interferometry* (eds Bonse, U. & Rauch, H.) 265–272 (Oxford University Press, 1979).
12. Bernstein, H. J. & Zeilinger, A. *Phys. Lett.* **75A,** 169–172 (1980).
13. Bohm, D. *Quantum Theory,* 593 (Prentice-Hall, New York, 1951).
14. Zeilinger, A. & Shull, C. G. *Phys. Rev.* **B19,** 3957–3962 (1979).
15. Just, W., Schneider, C. S., Ciszewski, P. & Shull, C. G. *Phys. Rev.* **B7,** 4142–4145 (1973).
16. Klempt, E. *Phys. Rev.* **D13,** 3125–3129 (1976).
17. Stoll, M. E., Vega, A. J. & Vaughan, R. W. *Phys. Rev.* **A16,** 1521–1524 (1977).
18. Stoll, M. E., Wolff, E. K. & Mehring, M. *Phys. Rev.* **A17,** 1561–1567 (1978).
19. Kaiser, R. *Can. J. Phys.* **56,** 1321–1332 (1978).
20. Renninger, M. *Z. Phys.* **158,** 417–421 (1960).
21. Yoshihuku, Y. *Mem. Chubu Inst. Technol.* **13-A,** 173–175 (1977).

Detection of monsoon inversion by TIROS-N satellite

M. S. Narayanan & B. M. Rao

Meteorology Division, Space Applications Centre,
Ahmedabad-380053, India

Colon[1] and Ramage[2] have investigated the thermal stratification of the summer monsoon air and presented evidence of a well-defined temperature inversion in the lower atmosphere over the Arabian Sea. This inversion is low (base between 900 and 800 mbar) and strong over the western Arabian Sea and weakens and rises (base at ~700 mbar) towards the coast of India and is not observed east of 70 °E, especially during the active monsoon[3]. The presence of dry warm continental air from Africa and Arabia above the maritime air is thought to be associated with this inversion. This inversion is very important to the rain producing potential of the monsoon current because once the inversion is destroyed there is a favourable stratification for rapid release of moisture upwards leading to precipitation. Observations of the western Arabian Sea inversion features have previously been reported only from *in situ* ship radiosonde and aircraft dropsonde measurements. Although the basic accuracy and the vertical resolution of the present-day satellite sensors cannot delineate the small-scale variations of temperature[4] such as monsoon inversions we have detected these features from just the TIROS-N derived sea-surface temperatures and the 1,000–850 mbar layer-mean temperatures using a simple differencing procedure. From these temperatures and simultaneous satellite-derived mid-tropospheric water vapour content, we show here the close link between the extent of inversion regions and the convective processes with the Indian monsoon at its different phases.

The present data pertain to the Monex-period (1 May–31 July 1979) TIROS-N satellite results of 14.00 h LT supplied by NOAA Environmental Satellite Service of the USA. These results (about one set in a 2.5° × 2.5° lat.-long. box) include data on the: sea surface temperature (SST); 15 layer-mean atmospheric temperature profile from 1,000 to 0.4 mbar; and 3 level total water vapour content.

The inversions are characterized by the altitude of its base, height extent and temperature departure. Well-marked (height extent >30 mbar and temperature departure >3 °C) monsoon inversions in the western Arabian Sea exhibit in the aircraft dropsonde profiles a negative lapse rate in the altitude regions between 900 and 800 mbar region, above and below which the lapse rates are similar to those of the normal profiles.

Our investigation did not reveal any inversion features from the individual temperature profiles of the satellite data set. However, we now use only the SST and the lowest layer-mean (1,000–850 mbar) temperature, referred to as T_1 and T_2 respectively.

For a temperature profile with an inversion structure at lower levels (below 850 mbar), the layer-mean temperature of the 1,000–850 mbar layer will be larger than that for normal profiles (those which follow a standard lapse rate with height). Assuming further that the sensible heat exchange between the sea and the air above is small and fairly uniform[5] (implying small air–sea temperature difference), it is to be expected that a horizontal map of the difference, ΔT, of the satellite-derived SST (T_1) and the 1,000–850 mbar layer-mean temperature (T_2), with appropriate time and spatial averaging could reveal the inversion regions. Lower values of ΔT can be interpreted as being associated with regions of inversion. From *in situ* aircraft dropsonde measurements, the values of ΔT for non-inversion profiles in the active monsoon areas range between 4 and 6 °C and in inversions these are as low as 0 °C in some cases.

Examination of the horizontal variation of the ΔT values thus obtained from satellite data also minimizes the errors that may be present in the original temperatures T_1 and T_2, whose retrieval involves assumptions of the atmospheric models in the radiative transfer computations.

The aircraft dropsonde measurements during Monex 1979 provided data for *in situ* ground truth comparisons in the Arabian Sea between long. 75° E and 55° E. However, these measurements were available up to 27 June 1979 covering only the onset and active periods of the monsoon. No *in situ* data

Table 1 Comparison of aircraft profiles with satellite data

	Aircraft profiles	Near simultaneous satellite data $\Delta T \leq 2$ °C	$\Delta T \geq 3$ °C
No. of profiles with well-marked inversion below 850 mbar	30	23	7 (for four of them $\Delta T = 3$ °C)
No. of profiles without well-marked inversion	129	0	129

0028–0836/81/500546—03$01.00