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Research Using Ultracold Neutrons at the ILL

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Abstract

In this talk I will make no effort to give an exhaustive, detailed description of the well-published results of recent work with ultracold neutrons (UCN) at the ILL. Instead, there will be a biased selection of some topics in which the author happens to be most interested, though in some cases more as a spectator from a considerable distance than as an actor. The selection includes the recent lifetime experiment using a Fomblin-coated bottle, the continuing search for an electric dipole moment of the neutron and some ideas on high precision neutron optics experiments.

1. Introduction

The Institut Laue-Langevin has probably the strongest source of ultracold and very cold neutrons available in the world at this time. This source was designed and built by a handful of motivated scientists and engineers at the ILL and at Garching, with help in terms of ideas coming from another handful of idealists dispersed all around the world. It would not have been realized without additional help in terms of financial support provided by funding organizations upon the recommendation of a further handful of individuals willing to take the risk.

Institutes like the ILL can create the fertile ground for the growth of these or other internal and external ideas, by providing in-house scientific expertise, technical support and, especially, by exercising skill in the enormously difficult task of coping with a bunch of physicists with wild ideas. The ILL has a remarkably good reputation in all these respects, and it was indeed the atmosphere of openness and flexibility that made the development of an unconventional installation like the UCN source possible.

The present report contains short reviews of some of the various activities that have been and are being conducted at the UCN source of the ILL: a precise measurement of the neutron lifetime; the continuing search for the neutron's electric dipole moment; and slow-neutron optics. UCN optics includes attempts at neutron microscopy and the precise analysis of reflection and diffraction data for mirrors and gratings. A theoretical analysis is presented which may enable a novel interpretation of elementary wave-optics experiments in the framework of recent field theoretic approaches.

2. A measurement of the neutron lifetime

A precise value for the lifetime for beta-decay of the free neutron is called for by a number of theoretical models in astrophysics, particle physics and cosmology. We mention only the calculations of Schramm and Kawano [1] which, within the framework of the standard big bang model, relate the primordial ratio of helium to hydrogen in the universe, $\alpha_{He-H} \approx 1/4$, to the number of low-mass ($m_\nu \lesssim 10$ MeV) neutrino generations, N_ν, and to the neutron lifetime, τ_n. A simplified version of the reasoning is as follows: At a temperature $T \gtrsim 10^{10}$ K the weak interaction kept the neutron and proton populations in thermodynamic equilibrium [$n/p = \exp(-Q/T)$] according to their difference $Q = 1.3$ MeV in rest mass. But then the neutron and proton populations decoupled until at a later time the temperature became low enough ($T \approx 10^9$ K) for the formation of helium nuclei. During this time window of some tens of minutes duration the neutron population decreased not at the rate it would have done if thermodynamic equilibrium had still persisted but at the slower rate determined to a significant extent by the beta-decay of the free neutron. The number of He-nuclei formed after this period of free decay was then determined by the number of neutrons that had survived beta-decay. The speed of the drop in temperature, and hence the length of the time window, depends on the rate of expansion of the universe at that time which, in turn, is determined by the number of types of relativistic radiation. This radiation is made up of photons, electrons and the low-mass neutrinos. A detailed analysis proceeding along these lines establishes a quantitative relation between τ_n, α_{He-H} and N_ν.

The experiment by Mampe *et al.* [2] was based on the following basic considerations:

a) The β-decay of thermal neutrons is conventionally studied by measuring the number of charged particles (electrons and/or protons) emerging from a beam of neutrons with precisely known characteristics in terms of intensity and geometry. This procedure calls for precise <u>absolute</u> measurements both of neutron intensity and of charged particle flux. On the other hand, ultracold neutrons trapped in a neutron bottle decay like a radioactive gas, thus a <u>relative</u> measurement of survival rate, after various storage times and for the <u>neutrons only</u>, is sufficient.

b) This proposition constitutes a valid approach if the neutron gas disappears from the bottle <u>only</u> as a result of the β-decay <u>or</u> if additional loss processes are well understood and can be taken into account sufficiently well. The most crucial source of additional losses is imperfect reflection of the neutrons from the walls of the trap. The magnetic neutron storage ring of Paul's group [3] (where there are no material walls) and storage in cavities with solid oxygen or other low-loss materials used for wall coating at low temperature [4] are examples of attempts to eliminate the wall losses to a large extent. In the experiment by Mampe *et al.* [2] as well as the previous, pioneering experiments by Konvintsev *et al.* [5] the following alternative strategy was chosen: Separate the β-decay from the additional losses by varying the bottle geometry and, thus, the ratio between volume and surface of the bottle. (Obviously, the loss rate due to wall collisions increases with surface area while the rate of β-decay does not.) This procedure will work better the smaller the additional losses are in relation to β-decay and the better our understanding and control of the loss mechanisms is.

The experiment by Mampe *et al*. benefitted from the previous suggestion of Bates to use Fomblin oil for wall coating and his work on UCN storage in Fomblin-coated bottles [6]. The oil is a fully fluorinated polyether combining a number of excellent properties for use as a UCN reflector: a) a very low cross section for neutron capture; b) As a film on glass substrate it forms a smooth surface which c) is stable for periods of several days in its quality as a neutron reflector, and d) hermetically seals all the gaps at moveable elements of the surface.

Although a lifetime measurement based on these ideas is conceptually simple a number of practical problems have to be addressed in the actual experiment. Most of these are due to the following conflicting demands: On one hand, it is easy to realize that the procedure of separation of radioactive decay and other losses for the neutron population is straightforward only for a gas of monochromatic neutrons in the bottle. On the other hand, sufficiently high count rates can be achieved only if a sufficiently wide spectral band of neutrons is accepted into the bottle. The wall loss rate increases with neutron velocity for two reasons: a) The frequency of wall collisions increases; b) It follows from the Fresnel formulas for an ideally flat surface bounding a homogeneous medium of semi-infinite extension that in conditions of total reflection the loss coefficient (per bounce) increases with the velocity component normal to the wall.

Since the faster neutrons disappear from the bottle at a faster rate than the slower ones the spectrum of UCN changes with time. An obvious consequence of this spectral evolution is the non-exponential decay of the neutron population which was already observed in the early work on UCN storage. A complication in the lifetime data evaluation could then arise due to the fact that the storage lifetimes are determined experimentally from survival measurements at different storage times and the spectra vary with storage time. The strategy chosen in the ILL experiment was the use of a scaling principle which provided a way to attain meaningful storage data irrespective of possible uncertainties of spectral changes with time. If the storage times, $t_n(i)$, for different bottle volumes (i,j) are scaled according to the bottle mean free paths ℓ, i.e.,

$$t_2(i)/t_2(j) = t_1(i)/t_1(j) = \ell(i)/\ell(j) = [t_2(i)-t_1(i)]/[t_2(j)-t_1(j)]$$

then the neutrons of any given velocity bin have made the same number of collisions in each volume during the corresponding times $t_n(i)$, and thus they have suffered the same wall losses. Then the spectral evolution should be the same, on the respective time scales, for different bottle volumes, and the lifetime values derived from the various storage time intervals $t_2(i)-t_1(i)$, $t_2(j)-t_1(j)$ should be reasonably independent of the details of the spectral evolution.

A more subtle effect of the temporal change of the spectrum is related to the effect of gravity on a lifetime experiment using UCN storage:

The gravitational interaction of the neutron gives rise to a variation of the spectrum with vertical distance from the floor of the bottle since the neutrons lose kinetic energy on their way up, and some flight paths will turn back down before reaching the roof. An analytic treatment of this effect by Ignatovich [7] for a monochromatic and isotropic neutron gas, on the basis of the Fresnel formulas for the reflectivity, yields a velocity and geometry dependent additive correction to the value of neutron lifetime as derived from storage experiments with varying bottle sizes by extrapolation to infinite bottle volume (where the losses due to wall collisions would vanish altogether). The correction becomes significantly more complex for a polychromatic neutron gas. It requires good models both for the initial neutron spectra in the bottles (right after filling) and of their changes with time.

For these reasons it was very important to have a good model for $\mu(E)$, the energy dependence of loss probability per wall collision, since the spectral changes are determined by this function. The authors performed measurements of specular overcritical reflectivity for Fomblin oil in the region above the total reflection cutoff, using the "UCN gravity diffractometer" described in Ref. [8]. These data are extremely sensitive to deviations from the Fresnel behavior due to a possible deviation from the simple model of an abrupt potential step representing the vacuum-oil interface. The measured reflectivity curve was in excellent agreement with the Fresnel formula, indicating that use of the elementary form for $\mu(E)$ was justified. In addition to this, direct measurements of $\mu(E)$ in the subcritical region were made, and this data also showed perfect agreement with the simple theory except very close to the edge where the observed deviations may be due to wall vibrations.

In addition to the effects of spectral changes during storage one has to deal with differences in initial spectra due to different filling characteristics for large and small bottles. These are due to the fact that different bottle volumes represent a different load for the UCN source. In some runs these slight differences were studied and minimized by adjusting the filling aperture to the bottle size.

A number of parameters of the experiment (like temperature and vacuum conditions) were varied to check for possible systematic errors. Furthermore, detailed analytical calculations and computer simulations were performed to obtain from the actual storage data information on the parameters relevant for the spectral evolution. It turned out that the maximum correction that had to be applied to the raw-data lifetime values, due to gravity and source loading, was about one percent. The final result for the lifetime of the free neutron for β-decay was

$$\tau_n = 887.6 \pm 3 \text{ s.}$$

At the time of publication this value constituted the most precise lifetime value available either from a direct measurement or inferred from measurements of angular correlations for the decay products. The relation to previous values as well as the implications of the considerable improvement in precision were discussed in detail by Dubbers, Mampe and Döhner [9]. Among these are a rounding-off of the cosmological arguments mentioned above. Combining several recent lifetime values to a new world average of 888.6 ± 2.6 s the calculations of Schramm and Kawano [1] yield for the number of low-energy neutrino generations a value

$$N_\nu = 2.6 \pm 0.3.$$

This result is consistent with the three generations that have already been discovered, and a fourth generation of particles would appear to be very unlikely.

In the meantime two further lifetime results derived from UCN storage have been obtained and are presented at this Neutron School (Morosov *et al.* and Serebrov *et al.*). They apparently fit in the same "ballpark" as the value of Mampe *et al.* [2], corroborating the previous conclusions.

3. The electric dipole moment of the neutron

Of the three basic symmetries observed in nature (invariance with respect to parity inversion, P; to charge conjugation, C; and to time reversal, T) the time reversal symmetry is probably the most subtle. This is not only so if viewed from a philosophical platform but even from the "simple-minded" point of view of physicists used to merely describing (rather than trying to explain) nature. So far the only process found to violate time reversal invariance in the microscopic world is the decay of the long-lived K^0_L meson into two (rather than three) pions, and this rare decay mode and its implications with respect to CP and T violation have been studied extensively since its first discovery by Christenson *et al.* in 1964 [10]. T violation follows from the CPT theorem but can also be directly inferred from an analysis of the experiment [11]. Even before then Purcell and Ramsey had suggested in 1950 [12] to search for electric dipole moments (EDM) of elementary particles and nuclei as a means to test P invariance. The question whether finite EDM's of "simple systems" would as well be evidence of T violation was discussed by Ramsey in 1958 [13]. He pointed out that this was so if the EDM was thought to be due to a static electric charge distribution. If, on the other hand, magnetic monopoles existed and the EDM was caused by rotating magnetic charges then the interpretation would have to be modified to indicate a failure of the combined TM symmetry where M stands for magnetic charge conjugation.

Since the pioneering work of Smith, Purcell and Ramsey [14], many experimental searches for EDM's have been performed on the neutron, and as the techniques were refined the upper limit of a possible EDM, d_n, of the neutron was lowered by 6 orders of magnitude to the present limit of about 10^{-25} e cm where e is the proton charge. In recent years the search for EDM's of "simple systems" was extended to atoms, especially the ^{199}Hg atom (Lamoreaux [15]). While the level of experimental sensitivity is even higher for selected atoms than it is for neutrons (presently $\approx 10^{-26}$ e cm for the ^{199}Hg atom) the interpretation becomes more complex. This is because a possible EDM of a neutron could be associated with T violation in some aspect of the nuclear interaction while atoms are, in addition, sensitive to other possible T violating effects such as an intrinsic EDM of the electron or electron-nucleon interactions [15]. Furthermore, the significant screening of electric fields in atoms is a major factor which must be taken into account.

I shall not go into any details of the ILL experiment which uses stored UCN to search for an EDM of the neutron but only quote the latest result published by Smith *et al.* [16] in 1990:

$$d_n = -(3 \pm 5) \times 10^{-26} \ e \text{ cm}$$

This value is to be compared to the value

$$d_n = -(14 \pm 6) \times 10^{-26} \ e \text{ cm}$$

which was obtained by the group at Gatchina (also on the basis of the use of stored UCN) and published in 1986 (Altarev *et al.* [17]). This result was interpreted by the authors as setting an upper limit of 26×10^{-26} e cm on $|d_n|$. The ILL value seems to suggest even more strongly that a finite value for d_n has not yet been found. While these latest experiments eliminated a number of theoretical models for the EDM of the neutron others predict values which might be within reach of a next generation of EDM experiments with a somewhat improved sensitivity.

An improvement of the ILL set-up is expected from the use of a larger bottle and, especially, of polarized ^{199}Hg atoms (or, possibly, of another suitable atomic species) as a gas filling the same bottle volume as the neutrons and serving as a sensitive magnetometer. These plans were described in ref. [18]. The gas will monitor the same temporal and spatial average of the magnetic field (apart from small gravity effects) as the neutrons and thus reduce possible uncertainties in field monitoring.

4. Some aspects of neutron optics

The most distinguished and characteristic property of waves is their capability to interfere constructively or destructively. In this sense, neutron waves do not seem to differ in any way from other types of radiation, like acoustic or light waves. Phenomena like reflection and refraction at interfaces between different media or fields, or diffraction on periodic structures or other spatial fluctuations, are all based on the collective effects of wave scattering from the atoms and nuclei constituting matter, and on the collective, coherent action of fields like gravity on the wave function, or that of magnetic induction on the neutron spin-wave function. It is only the "petites différences" like the finite - and sizable - mass of the neutron, the absence of an electric charge, the low energy, or the spin and magnetic moment that endow the neutron waves and their study and application with a special quality.

Interest in testing, and perhaps extending, wave mechanics is as old as the subject itself but the ideas of de Broglie [19] and, more recently, Bialynicki-Birula and Mycielski [20] had been almost forgotten when the subject was vigorously revived by Weinberg's theory of a non-linear extension of quantum mechanics [21]. In contrast with the previous approaches it includes a strict homogeneity postulate stating that states differing only by a normalization factor represent the same observables. Very precise experiments testing the older ideas have set stringent upper limits on the possible magnitude of a specific, the logarithmic type of, non-linearity (Shull *et al.* [22], Gähler *et al.* [23]). Even more sensitive tests of the new ideas have already been reported (Bollinger *et al.* [24]; Walsworth *et al.* [25]) or are underway.

In the present note I want to draw attention to an alternative approach. Non-linear terms in equations of motion of physics are not always due to non-linearities intrinsic to the theory but often arise as a result of coupling to the embedding media or fields which, in their turn, act back on the system under consideration. A well-know example is "non-linear optics" where the E-field polarizes the medium in which it propagates, and the polarization retroacts on the field. Most field theories of particles are based on such a framework which does not require the homogeneity postulate. Along these lines proceeds a recent discussion of a "gauged non-linear Schrödinger equation" by Jackiw and Pi [26]. In such a theory non-linear terms in a Schrödinger-like equation (in two dimensions) would be a direct consequence of coupling of the matter field Ψ to a "massive photon-like field", the Chern-Simons gauge field. Within such a framework a search for non-linearities in the equation of motion of a particle wave is tantamount to a search for a field via which the particle field acts on itself.

The non-linear gauged equation considered by Jackiw and Pi [26] reads

$$i\hbar\, \partial\Psi(\mathbf{r},t)/\partial t =$$

$$\{-(\hbar^2/2M)[\nabla - (ie/\hbar c)\mathbf{A}(\mathbf{r},t)]^2 + eA^0(\mathbf{r},t) - g\Psi^*(\mathbf{r},t)\Psi(\mathbf{r},t)\}\ \Psi(\mathbf{r},t), \quad (1)$$

where M is a mass parameter, $h = 2\pi\hbar$ is Planck's constant, c the velocity of light, g governs the strength of the non-linearity, and e measures the coupling to a gauge field described by scalar (A^0) and vector (**A**) potentials. They showed that eq. (1) for the matter field Ψ possesses vortex-like stationary solutions corresponding to freely moving, localized waves with a finite orbital angular momentum $m\hbar$ ($m \geq 1$) (in addition to the more conventional soliton-like solutions for which $m = 0$).

Using numerical methods we have found similar, stationary vortex-like solutions for the Bialynicki-Birula Mycielski (BBM) equation

$$i\hbar\, \partial\Psi(r,t)/\partial t = \{-(\hbar^2/2M)\, \nabla^2 - b\, \ell n\, [a^n\, |\Psi(r,t)|^2]\}\, \Psi(r,t), \qquad (2)$$

both in two and three dimensions ($n = 2$ or 3). Here b (> 0) describes the strength of the self-interaction and a is an arbitrary positive constant with the dimension of a length. The BBM equation was chosen because its properties and soliton-like solutions (the "gaussons") are well known but it may be assumed that similar solutions can be found for other forms of non-linearities (like the more standard type $-g|\Psi|^2\Psi$, and for 3 dimensions as well as for 2).

While details of the analysis will be published elsewhere we will sketch here only the basic ideas and final results. We seek stationary wave solutions to eq. (2) of the form

$$\Psi(r,t) = a^{-1} \exp[1 - E/(2b)]\, \chi(R)\, e^{im\varphi} \exp(-iEt/\hbar), \qquad \text{for } n = 2$$

and

$$\Psi(r,t) = a^{-3/2} \exp[3/2 - E/(2b)]\, \chi(R,\vartheta)\, e^{im\varphi} \exp(-iEt/\hbar); \qquad \text{for } n = 3$$

where $R = r/L$ is normalized with the characteristic length [20] $L = \hbar/\sqrt{(2Mb)}$. The equation for $\Theta = \chi\, e^{im\varphi}$,

$$\nabla^2\Theta + (\Omega + \ell n|\Theta|^2)\, \Theta = 0, \qquad (3)$$

is solved by the radially symmetric gaussons, $\Theta_0(R) = \exp(-R^2/2)$, which correspond to angular momentum quantum numbers $m = 0$ and $\ell = 0$ (the latter only for $n = 3$). The vortex-like solutions with non-vanishing angular momentum may be characterized by their behavior near the origin $R = 0$ where the centrifugal potential term dominates the logarithmic singularity. Therefore they should show the same behavior

$$\Theta \propto R^m\, e^{im\varphi}, \quad \text{for } n = 2; \text{ and } \quad \Theta \propto R^\ell\, P_\ell^m(\cos\vartheta)\, e^{im\varphi}, \quad \text{for } n = 3,$$

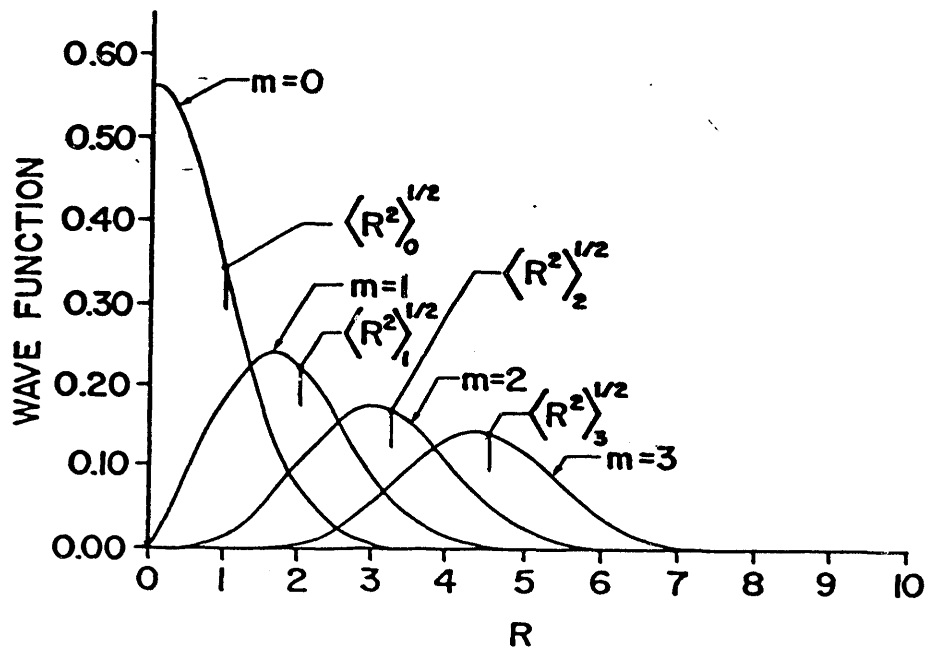
as the linear equation. ($P_\ell^m(\cos\vartheta)$ denotes the associated Legendre functions.) This property holds not only for the logarithmic non-linearity but would hold as well for any other "reasonable" form of non-linearity, and it is the reason why the vortex-like solutions may be characterized by the conventional quantum numbers m (for $n = 2$), or by ℓ and m (for $n = 3$).

In two space dimensions solutions to eq. (3) can be found by numerical integration starting from $R \ll 1$, where we know the asymptotic behavior $\chi(R) \to C_m R^m$, out to large R where a similar analysis shows that χ should decrease exponentially. This convergence is obtained only if a specific value had been chosen for the initial amplitude C_m. Fig. 1 shows a plot of solutions for $m = 0$ (the gaussons), and for $m = 1, 2, 3$. Due to the centrifugal potential the wave functions are concentrated at larger distances $R \approx \sqrt{\langle R^2 \rangle}$ from the origin as the angular momentum $m\hbar$ increases. It was proved in ref. [20] that the gausson (for $m = 0$) corresponds to the lowest possible energy E for a normalizable solution of the BBM equation in free space. If we shift the energy scale so that the lower energy bound E_0 is set equal to zero then the energies E_m of the vortex-solutions (at rest) are $E_1 = 1.23$ b, $E_2 = 1.84$ b, $E_3 = 2.23$ b, etc. As expected, their scale is determined by the strength, b, of the non-linear term giving rise to self-interaction of the wave.

In <u>three spatial dimensions</u> ($n = 3$) the analysis is complicated by the fact that the R and ϑ dependences of Θ can no longer be separated (in contrast to the linear case). In the cases investigated ($\ell, m = 1,0$; $1,1$; and $2,2$) a representation of Θ by the first three terms in the sum

$$\Theta(r,\vartheta,\varphi) = R^{\ell} e^{im\varphi} \sum_{\nu=0}^{\infty} d_{\nu}(R)\, P^{m}_{\ell+2\nu}(\cos\vartheta) \qquad (4)$$

was found to provide a satisfactory description of the wave field. The behavior of this Ansatz near the origin $R = 0$ can be studied by expanding the functions $d_{\nu}(R)$ in power series of the form



<u>Fig. 1</u> Normalized wave functions for vortex-like solutions to the BBM equation in two dimensions characterized by their orbital angular momentum $m\hbar$.

$$d_\nu(R) = \sum_{\rho=\nu}^{N} R^{2\rho} \sum_{\tau=0}^{\rho} C_{\nu\rho\tau} (\ell n\ R)^\tau ,$$

inserting into eq. (3) and equating coefficients. In this way we find that not only the coefficient C_{000} (the amplitude of the asymptotic solution $R^\ell\ P_\ell^m(\cos\vartheta)\ e^{im\varphi}$ determining the type of solution sought) is at our disposal for adjusting to boundary conditions at infinity but also all the coefficients $C_{\nu\nu 0}$ (for $0 < \nu \leq N$ where we have truncated the series in eq. (4) at $N = 2$).

The solutions constructed in this way for $\ell, m = 1,0;\ 1,1;$ and 2,2 show all the features outlined above as well as the topological properties of the respective spherical harmonics with respect to their zeroes. They are characterized by the following energies E (again referred to the lower bound), mean square angular momenta $\langle\hat{\ell}^2\rangle$, and mean-square radii $\langle R^2\rangle$:

<u>for $\ell = 1$ and $m = 0$</u>: $E = 0.71\ b$, $\langle\hat{\ell}^2\rangle = 5.4$, $\langle R^2\rangle = 7.2$;

<u>for $\ell = 1$ and $m = 1$</u>: $E = 1.23\ b$, $\langle\hat{\ell}^2\rangle = 2.6$, $\langle R^2\rangle = 4.7$;

<u>for $\ell = 2$ and $m = 2$</u>: $E = 1.85\ b$, $\langle\hat{\ell}^2\rangle = 8.2$, $\langle R^2\rangle = 10.5$.

[The wave functions can be normalized but within the framework of the BBM approach [20] the values given above do <u>not</u> depend on the normalization. All the operators are defined as in the linear theory but $\hat{\ell}^2$ is no longer a good quantum number while $\hat{\ell}_z = m$ and the Hamiltonian retain this quality. The $\langle\hat{\ell}^2\rangle$-values obtained are somewhat larger than the value $\ell(\ell+1)$ for the pure spherical harmonics, due to the admixture of wave components with larger angular momenta, in accordance with eq. (4).]

From the mathematical excursion presented above we draw the following conclusions:

(a) The introduction of non-linearities into quantum mechanics (motivated either by the search for hitherto unknown interactions or by the search for possibilities of "reasonable" fundamental modifications) gives rise to a (presumably) rich spectrum of novel rotational states of a free particle wave. They should exist both in two and in three spatial dimensions and are characterized by the ordinary integral quantum numbers (m and ℓ;m, respectively) for orbital angular momentum.

(b) The search for transitions between such states in high-resolution wave-optics experiments with cold or ultracold neutrons may provide a very sensitive handle on the study of these ideas, supplementing the previous approaches [22,23]. A feasible experiment could be based on a precise analysis of UCN beam profiles obtained under comparable conditions in mirror reflection and in diffraction on a reflection grating. A follow-up of the initial data reported in ref. [28] has so far shown no evidence for deviations of the line profiles.

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References

1 D.N. Schramm and L. Kawano, in Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons, Grenoble, NIMRD9 A284(1) (1989) 84.

2 W. Mampe, P. Ageron, C. Bates, J.M. Pendlebury and A. Steyerl, Phys. Rev. Lett. 63 (1989) 593.

3 W. Paul, F. Anton, L. Paul, S. Paul and W. Mampe, Z. Physik C 45 (1989) 25.

4 A.G. Kharitonov, V.V. Nezvizhevsky, A.P. Serebrov, R.R. Taldaev, V.E. Varlamov, A.V. Vasilyev, V.P. Alfimenko, V.I. Lushchikov, V.N. Shvetsov and A.V. Strelkov, in Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons, Grenoble, NIMRD9 A284(1) (1989) 98.

5 Yu.Yu. Kosvintsev, V.I. Morozov and G.I. Terekhov, JETP Lett. 44 (1986) 571; Yu.Yu. Kosvintsev, Yu.A. Kushnir, V.I. Morozov and G.I. Terekhov, JETP Lett. 31 (1980) 236.

6 J.C. Bates, Nucl. Instr. and Meth. 216 (1983) 535.

7 V.K. Ignatovich, *Fizika ultrakholodnikh neitronov* (Physics of ultracold neutrons), Nauka, Moscow, 1986 (in Russian).

8 H. Scheckenhofer and A. Steyerl, Phys. Rev. Lett. 39 (1977) 1310.

9 D. Dubbers, W. Mampe and J. Döhner, Europhys. Lett. 11 (1990) 195.

10 J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. 13 (1964) 138.

11 R. Casella, Phys. Rev. Lett. 22 (1969) 554.

12 E.M. Purcell and N.F. Ramsey, Phys. Rev. 78 (1950) 807.

13 N.F. Ramsey, Phys. Rev. 109 (1958) 225.

14 J.H. Smith, E.M. Purcell and N.F. Ramsey, Phys. Rev. 108 1957) 120.

15 S.K. Lamoreaux, in Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons, Grenoble, NIMRD9 A284(1) (1989) 43.

16 K.F. Smith, N. Crampin, J.M. Pendlebury, D.J. Richardson, D. Shiers, K. Green, A.I. Kilvington, J. Moir, H.B. Prosper, D. Thomas, N.F. Ramsey, B.R. Heckel, S.K. Lamoreaux, P. Ageron, W. Mampe and A. Steyerl, Phys. Lett. B 234 (1990) 191.

17 L.S. Altarev, Yu.V. Borisov, N.V. Borovikova, A.B. Brandin, A.I. Egorov, S.N. Ivanov, E.A. Kolomenskii, M.S. Lasakov, V.M. Lobashov, A.N. Pirozhkov, A.P. Serebrov, Yu.V. Sobolev, R.R. Tal'daev and B.V. Shul'gina, JETP Lett. 44 (1986) 460.

18 D. Thompson, in Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons, Grenoble, NIMRD9 A284(1) (1989) 40.

19 L. de Broglie: *Non-Linear Wave Mechanics*, Elsevier, Amsterdam, London, 1960.

20 I. Bialynicki-Birula and J. Mycielski, Ann. of Phys. 100 (1976) 62.

21 S. Weinberg, Ann. of Phys. 194 (1989) 336.

22 C.G. Shull, D.K. Atwood, J. Arthur and M.A. Horne, Phys. Rev. Lett. 44 (1980) 765.

23 R. Gähler, A.G. Klein and A. Zeilinger, Phys. Rev. A 23 (1981) 1611.

24 J.J. Bollinger, D.J. Heinzen, W.M. Itano, S.L. Gilbert and D.J. Wineland, Phys. Rev. Lett. 63 (1989) 1031.

25 R.L. Walsworth, I.F. Silvera, E.M. Mattison and R.F.C. Vessot, Phys. Rev. Lett. 64 (1990) 2599.

26 R. Jackiw and So-Young Pi, Phys. Rev. Lett. 64 (1990) 2969.

27 A. Steyerl, to be published.

28 A. Steyerl, Internat. Conf. on Neutron Scattering (ICNS), Grenoble, 1988; in *Neutron Scattering*, ed. W. Gläser, J. Rossat-Mignod, J. Schweizer and C. Vettier, Physica B 156 & 157 (1989) 528.

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