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A SUPERCONDUCTING STORAGE RING FOR VERY SLOW NEUTRONS

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Summary

It was shown experimentally that neutrons can be confined in a magnetic storage ring by means of their magnetic moments. Due to the small dipole moment the energy of the neutron is limited to a few 10^{-6} eV in spite of the high field in the superconducting magnet of 1 m diameter. In many respects the beam dynamics are similar to a storage ring for charged particles. The basic field configuration is a sextupole field superimposed of a strong decapole term in order to overcome imperfaction resonances by a non harmonic potential. As only neutrons in one spin state are confined, care has to be taken to avoid spin flips. The neutrons are injected by a totally reflecting mirror system which can be removed out of the confinement region. Neutrons were detected up to a storage time of 45 min. Their number decreases according to their lifetime ($\tau_{1/2}$=10·6 min) due to radioactive decay.

1. Introduction

A superconducting magnetic storage ring for very slow neutrons came into operation at the ultracold neutron beam of the ILL Grenoble. We followed an old idea of guiding and focusing particles having a magnetic moment by means of a magnetic sextupole field which was successfull in atomic beam physics (1) and proposed also for neutron beams (2). In such a field, bent to a torus with a radius R, neutrons can be guided on circular orbits. Similar proposals were made by Heer (3) and a Russian group (4).

2. Principle

The potential energy of a particle with a magnetic moment μ and a spin 1/2 in a magnetic field is $\phi=-\vec{\mu}\cdot\vec{B}$ and the corresponding force: $\vec{F}=\pm\mu\,\mathrm{grad}B$, the sign + for parallel and - for antiparallel position of μ to B. In a linear sextupole with a field as indicated in fig. 1a the induced field is given by

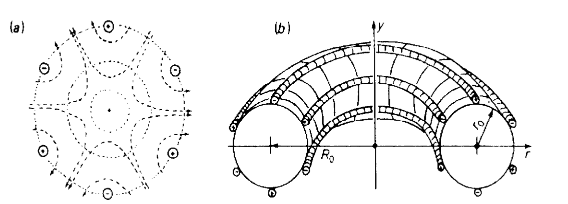

Fig. 1. (a) Field lines and field induction B of a linear sextupole and (b) a sextupole torus.

$B=(B_0/r_0^2)r^2$, thus the restoring force is $\sim r$. For μ parallel to B the particles oscillate harmonically around the central axis r=0, if i) the kinetic energy of the motion perpendicular to the axis is less than $E_{kin\perp}\lesssim\mu B_0$. With $\mu_n=-6.02\cdot10^{-8}$ eV/T and B_0=3.5 T one gets $E_{kin\perp}\lesssim 2.1\cdot10^{-7}$ eV corresponding to $v_\perp\lesssim 6.4$ m/s. ii) $\vec{\mu}$ remains parallel to $\vec{B}$. This condition is held, if the larmor frequency ω_L is large compared with the angular frequency of rotation of $\vec{B}$: $\omega_L=-\mu B/h \gg |\dot{\vec{B}}|/B$, which is satisfied everywhere except in the central zone $r\lesssim 0.5$ mm, where B is very small.

In case of a toroidal sextupole field with mean diameter $2R_0$ as shown schematically in fig. 1b the particles will oscillate harmonically (in first order approximation) around circular orbits, with $R>R_0$ given by the equivalence of centrifugal and magnetic force: $mv_\theta^2/R=\mu\delta B/\delta rR$. Thus the central zone $R\approx R_0$ where spin flip may occur is excluded. The betatron frequencies are given by $\nu_x^2=3+R\cdot(\delta^2B/\delta r^2)/(\delta B/\delta r)$ in the radial and by $\nu_y^2=R(\delta^2B/\delta y^2)/(\delta B/\delta r)$ in the axial direction for small amplitudes.

3. Beam dynamics

It is rather instructive to compare this storage ring for neutrons with those for charged particles. For a charged particle, dipole fields provide the compensation of the centrifugal force, quadrupole terms for the focusing forces, sextu- and octupoles are used for corrections of the optical system. In the neutron case using the magnetic moment one has to use one order higher of multipole expansion of the magnetic field: here the quadrupole term compensates the centrifugal force, sextupole terms provide focusing, and we use higher (decapole) terms to introduce nonlinearities in order to keep the amplitudes of the betatron oscillations limited (see below).

However, there are strong differences between the concepts. In the neutron case we have rather strong focusing ($n\approx25$) in axial and radial directions at the same time and (neglecting field imperfactions) no azimuthal field dependence. This leads to equations of motion for the deviations x (and y) of the cicular orbits of the form:

$$x''+a_1x+a_2x^2+a_3x^3+\ldots=0 \qquad (1)$$

with the primes denoting $d^2/d\theta^2$ and a_i independent of θ (with a_1 as leading term). In the ideal case of an azimuthally symmetric field the solutions are s t a b l e unharmonic oscillations with frequencies $\nu\approx\sqrt{a_1}$ and amplitudes depending mainly on the cubic term a_3.

As the real magnetic field has small perturbations (of the order of 0.5%) the equations (1) have to be modified mainly by adding terms of the form $\varepsilon_k\cdot\cos(k\theta+\beta_k)$ on the right hand side with k integer and ε_k small compared with a_1. If there were no nonlinear terms a_i with $i>1$ these perturbation terms would cause forced oscillations with amplitudes proportional to $\varepsilon_k/|k^2-\nu^2|$, thus leading to infinitely increasing amplitudes in the resonance case. On the other hand in the presence of nonlinear terms a_i with $i\geq3$ the maximum amplitude x_{max} is limited, because the resonance curves are bent due to the amplitude dependence of the betatron frequency $\nu(x_{max})$, which gives the characteristically triangular shaped amplitude/frequency curves. As an example fig. 2

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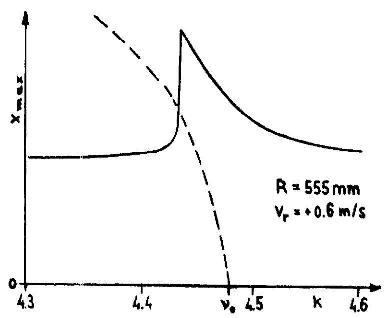

Fig. 2. Resonance curve for radial oscillations at orbit radius R = 55.5 cm (NESTOR).

shows a curve which results from computer calculations of neutron paths in the ideal field of NESTOR perturbed by typical imperfections of different frequencies k per turn (5). These calculations together with theoretical considerations showed that (due to the smallness of the perturbation term ε_k) this effect is strong enough to allow storage of neutrons without losses in a momentum band as large as $\Delta p/p \approx 0.35$ corresponding to azimuthal velocities v_θ = 12 ... 17 m/s, if the orbits of the neutrons are limited to the central part of the storage region. This is provided by beam scrapers at the inner and outer radius of the storage region, each of which covers about one third of the total cross section and is removed a few seconds after the beginning of storage, thus allowing the remaining beam to blow up. Because of the low incoming flux of very slow neutrons it is important, that a large momentum band corresponding to an extended working region is acceptable.

In case of storage rings for charged particles the equations of motion for the ideal field without perturbations and nonlinearities are of the form $x'' + (1-n)\,x = 0$ and $y'' + ny = 0$ with n strongly depending on θ (for strong focusing and weak focusing with straight sections). Here, in contrast to the neutron ring, the well known regions of instability resulting from first and higher order resonances occur already in the ideal field case. From this it follows that only particles in a very small momentum band of typically $\Delta p/p \lesssim 10^{-3}$ remain in a stable motion, and the corresponding working region in the working diagram has to be pointlike and is not even allowed to move near stop bands. Therefore, perturbations by imperfections of the field will influence the particle motions much more than in the neutron case and have to be corrected.

4. Experimental setup

The superconducting magnet with a diameter of 1.2 m has a maximum usable field of B_o= 3.5 T and a gradient dB/dr = 1.2 T/cm (6). The confinement region has a cross section of 5 x 10 cm^2. Fig. 3 shows the coil configuration. The field is open inside (coils 1 - 4 generate the outer part of the sextupole field, the coils 5 and 6 provide the decapole term). The equipotential lines (dotted) are closed by adding the centrifugal potential. The velocity acceptance in the azimuthal direction is 8-20 m/s, in the perpendicular direction $\pm$ 4 m/s corresponding to a

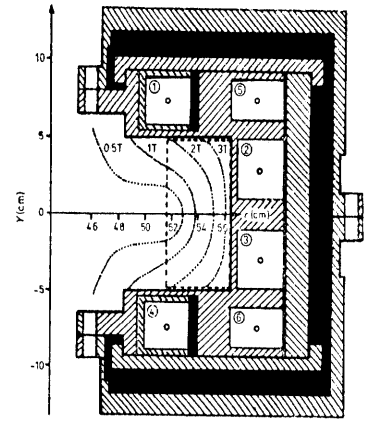

Fig. 3. The coil configuration and field induction B (dotted). The confinement region is indicated by the broken lines. Hatching denotes copper alloy, the solid area liquid He.

total kinetic energy up to $2\cdot10^{-6}$ eV.

Neutrons are injected from inside in the ring by a totally reflecting mirror system (glass nickel coated) in both directions. It can be removed from the confinement region by a pneumatic system in a time small compared to the time for one revolution. The injection time is ≈ 0.2 sec corresponding to one revolution.

Since the vacuum between the He-cooled coil support is better than 10^{-11} N/m^2 the beam-gas collisions are no problem.

The stored neutrons are detected by a ^3He proportional counter moved into the ring after a preset time.

5. Measurements

Some measurements concerning the storage time of the confined neutrons in the ring for different positions of the beam scrapers are shown in fig. 4. Each point is the average of several injection cycles. The dotted areas indicate the respective position of the injection system limited by the beam scrapers during the first 6.2 s (curve (b) and (c) only).

The upper most curve (a) was made without beam scrapers. It shows that, after some losses in the first minutes due to improper injection parameters, the number of neutrons remaining in the ring decreases according to the lifetime of the radioactive decay: the straight line represents this decay with a mean lifetime of τ = 918 s, it is adjusted to the value occurring at 600 s. The measurement (b) was made with beam scrapers reducing the confinement region only slightly. We detected neutrons up to three lifetimes. The losses during the first minutes are reduced.

The third measurement (c) was made with beam scrapers leaving≈40% of the confinement region (in the radial direction) for the injected neutrons. The observed decrease is purely exponential and corresponds to a storage time of τ = 907 $\pm$ 70 sec, which can be taken as a lower limit of the neutron lifetime.

Future measurements will be done to study the properties of the storage ring in more

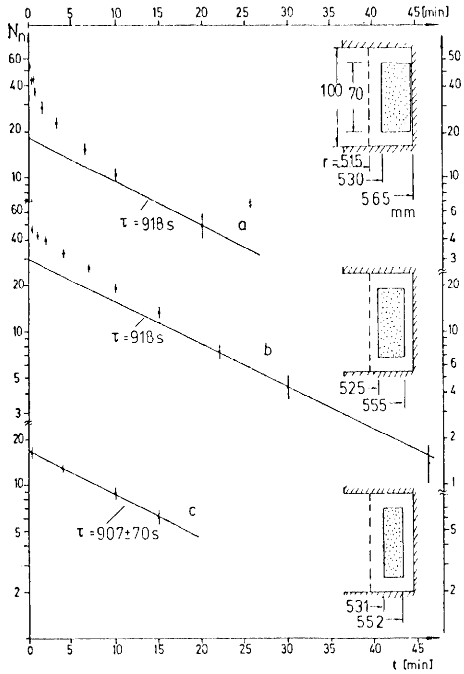

Fig. 4. The number of stored neutrons against storage time for different injection conditions.

detail and to compare with theory. A more precise measurement of the neutron lifetime seems feasible.

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