# Effects of mechanical rotation on spin currents

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In 1915, Albert Einstein, Wander Johannes de Haas and Samuel Jackson Barnet discovered the coupling of magnetism and rotational motion [1,2]. They measured the gyromagnetic ratio and the anomalous g factor of electrons well before the dawn of modern quantum physics. Recent developments in nanoprocessing technologies have led to the detection of the effects of mechanical rotation on nanostructured magnetic systems [3, 4].

Spin-dependent transport phenomena in magnetic nanostructures are of great interest in the field of spintronics, i.e. the study of "spin current" or flow of spins. One of the more intense research areas concerns the coupling of the magnetization and spin current leading to such phenomena as spin transfer torque [5,6], spin pumping [7], and spin motive force [8].

Comparing to the well-established coupling of mechanical rotations and magnetization, and that of magnetization and spin currents, the direct coupling of mechanical rotations and spin currents has not been demonstrated so far. Our purpose is to link the mechanical rotation with spin currents (Fig. 1).

We derived the fundamental Hamiltonian with a direct coupling of spin currents and mechanical rotations from the general relativistic Dirac equation [9]. The introduction of mechanical rotations involves extending our physical system from an inertial to noninertial frame. The dynamics of spin currents is closely related to the spin-orbit interaction (SOI), which results from taking the low energy limit of the Dirac equation. We obtained the SOI in a uniformly rotating frame:

$$H_{SOI} = \frac{e\lambda}{\hbar}\boldsymbol{\sigma}\cdot(\mathbf{p}+e\mathbf{A})\times\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)$$

where Ω is rotation frequency, **E** and **B** are applied electric and magnetic fields, **A** is a vector potential, $\sigma$ is the spin operator of electron and $\lambda$ is the spin-orbit coupling. This new term responsible for the spin current generation arising from mechanical rotation.

To clarify physical meanings of the SOI, we investigate the semiclassical equation of motion for electron. Choosing **E**=0, **B**=(0,0,$B$), and Ω=(0,0,Ω), we have the spin-dependent velocity of electron:

$$\mathbf{v} = \dot{\mathbf{r}} + \mathbf{v}_\sigma, \quad \mathbf{v}_\sigma = (e\lambda/\hbar)\boldsymbol{\sigma}\times B\Omega\mathbf{r}.$$

The first term is conventional velocity of electron. The second term, $v_\sigma$ is so-called anomalous velocity, i.e., the spin-dependent velocity. The $z$-polarized spin current $J_s$ can be estimated by

$$J_s = ne\mathrm{Tr}\sigma_z\mathbf{v} = (2ne\lambda B\Omega r/\hbar)\mathbf{e}_\phi,$$

where $n$ is the density of electron and $\mathbf{e}_\phi$ is the azimuthal unit vector. The magnitude of the spin current is linearly proportional to the angular velocity of the mechanical rotation, a magnetic field, and the spin-orbit coupling strength. The formula above reveals a mechanism for the quantum mechanical transfer of angular momentum between a rigid rotation and a spin current. The $z$-polarized spin current is created in the azimuthal direction by the mechanical rotation (Fig. 2). In the case of $B$=1 T, Ω=1 kHz, $r$=$10^{-1}$ m, $\lambda = 0.6\times10^{20}$ m$^{-2}$ [10], the spin current becomes $J_s$~$10^8$ A/m$^2$. This can be investigated using spin detection methods such as nonlocal spin valves [11], the inverse spin Hall effect [12] and the real-time imaging method [13].

It should be noted that starting from the general relativistic Dirac equation is essential when treating spintronic phenomena in accelerating frames. The present formalism [9] offers a route to ''spin mechatronics'', viz., a strong coupling of mechanical motion with spin and charge transport in nanostructures. Our findings will be experimentally examined by R.G. for Mechanical control of materials and spin systems.

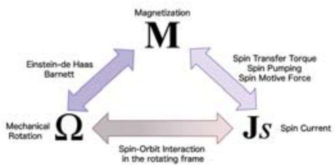


Fig. 1 Angular momentum transfers between interacting systems.

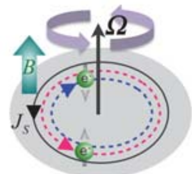


Fig. 2 Schematic illustration of electrons' trajectories under mechanical rotation Ω and a magnetic field **B**. The circular spin current is generated in the uniformly rotating body.

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# New type of asymmetric fission in proton-rich nucleus $^{180}$Hg

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From the discovery of nuclear fission [1], extensive measurements have been done to understand this dramatic phenomenon in nucleus. An essential feature of the liquid-drop model [2] is that nucleus has a saddle point which is formed by the interplay between the attractive surface force and the repulsive Coulomb force. Fission proceeds when the excitation energy of a compound nucleus is higher than the saddle point. The classical model, however, cannot explain the important features of fission, such as mass asymmetric fission as observed in neutron-induced fission of $^{235}$U. This necessitates the microscopic model (effects associated with shell structure) in fission. The effects of the doubly closed shells at $^{132}$Sn play a role in the rupture process in the last stage of fission in such a way that the fragment in the vicinity of $^{132}$Sn is preferentially formed.

The fission of a proton-rich nucleus like $^{180}$Hg is free from the shells of $^{132}$Sn due to largely different proton to neutron ratio of $Z/N$ = 0.800 ($^{180}$Hg) from 0.610 ($^{132}$Sn). Instead, the fission would be influenced by the semi-magic nucleus $^{90}$Zn ($Z/N$ = 0.800), and thus the symmetric fission would be expected when we simply apply the current understanding in fission.

A $\beta^+$-decay delayed fission ($\beta$DF) gives an opportunity to observe fission for such a proton-rich nucleus. The excited daughter nucleus is formed by the $\beta^+$ decay with the maximum excitation energy corresponding to the $Q$ value of the $\beta^+$ decay, $Q_\beta$. The fission takes place when the fission barrier height $B_f$ is lower or nearly equal to $Q_\beta$. The first observation of $\beta$DF in proton-rich nucleus $^{180}$Tl was reported in [3] where the $\beta$DF fragment is recorded as a track on a plastic plate. Instead, by using silicon detectors we observed large amplitude of pulse signals from both $\beta$DF fragments of $^{180}$Hg (daughter of $^{180}$Tl) in coincidence. Furthermore, we registered $K$ X-ray of Hg in coincidence with fission fragments. They give a definite evidence for $\beta$DF. Using the pulse height (energy) of each fragment, we determined the mass division in the fission of $^{180}$Hg.

The experiment was carried out at the ISOLDE mass separator at CERN. The $^{180}$Tl was produced by using a 1.4 GeV proton beam impinging on a stack of UC$_x$ targets. A laser ionization and mass separation are used to extract a pure $^{180}$Tl ion beam. The $^{180}$Tl$^+$ ions with 30 kV were implanted onto a thin carbon foil to detect $\beta$DF fragments.

Totally 346 events of coincided fragments were registered. The results are shown in Fig. 1, where the number of events is plotted as functions of mass and total kinetic energy (TKE) [4]. The spectrum clearly shows an asymmetric mass distribution with the most probable masses of $A_H$ = 100(1) and $A_L$ = 80(1) for heavy and light fragments, respectively. By assuming the $Z/N$ ratio of the fragments to be equal to $^{180}$Hg, the most probable isotopes become $^{100}$Ru and $^{80}$Kr. The average TKE of both fragments is determined to be 134.6(7) MeV.

The observed asymmetric fission in $^{180}$Hg apparently contradicts the expected feature in fission built from the actinide fissions. The shells of fragments ($^{90}$Zr) do not play a role.

To understand this feature, we calculated a potential energy surface of $^{180}$Hg as shown in Fig. 2 using a macroscopic-microscopic model where the effects of the shells are taken into account. It is found that the saddle point is located at the mass asymmetry of $A_H/A_L$ = 108/72 with a fission barrier height $B_f$ = 9.8 MeV. Considering $Q_\beta$ = 10.4 MeV [5], fission proceeds only through the asymmetric saddle point. The result also shows a deep symmetric valley on the elongated nuclear shape, which linked to the shells of $^{90}$Zr. The experiment reveals that the mass asymmetry in the fission of $^{180}$Hg is fixed at the saddle point, and rearrangement of mass asymmetry does not occur in descending from the saddle to scission.

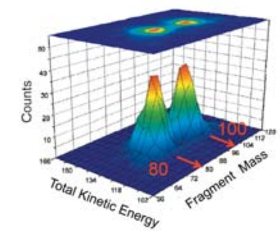


Fig. 1 Number of fission events plotted as functions of mass and total kinetic energy.

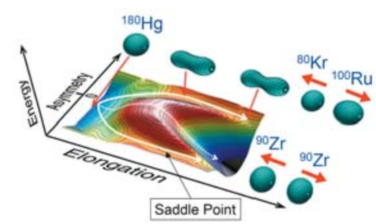


Fig. 2 Potential energy surface of $^{180}$Hg. Saddle point is indicated.

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