Summary of Research Center Project

* Compile in English withinA4 3 pages.

Center name: International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM^2)

Host institution: Hiroshima University (HU)

Head of host institution: Mitsuo Ochi, President and Professor, Hiroshima University

Prospective Center director: Ivan Smalyukh, Professor, Univ. Colorado Boulder & Hiroshima Univ.

Prospective Administrative director: Manabu Abe, Exec. Vice President & Professor, Hiroshima Univ.

(1) Overall Framework of the Center Project

The proposed WPI introduces the paradigm of "***knotted chiral meta matter* (*KCM^2*)**". Everything we see around us, ourselves included, is ordinary matter. Antimatter can exist too, but no macroscopic amounts of antimatter have ever been observed, albeit antiparticles are generated at accelerators and in processes like cosmic ray collisions. Our ***KCM^2*** will have its own analogs of fundamental particles/antiparticles and physical principles for designing new materials based on them; it will offer profoundly deep insights ranging from the inner workings of the World to the origins of life, as well as fundamental breakthroughs capable of enabling green technologies needed to sustain it. Aiming to create entirely new embodiments of everything, from fundamental (anti)particles to quasi-atoms and quasi-molecules to both liquid & solid crystals of knots and to materials with highly unusual properties, our WPI's ***KCM^2*** paradigm will deepen fundamental understanding of natural phenomena through creating their pre-designed analogs, as well as will solve the knotty Global problems of growing energy demand & climate change by designing matter with highly desirable material properties.

(2) World-Leading Scientific Excellence and Recognition

1) Research content

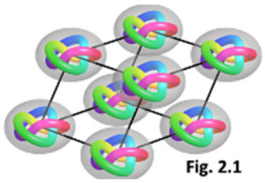

Fig. 2.1

Einstein proved the existence of atoms while explaining Brownian motion & introducing the notion of so-called "colloidal atoms". This later led to using colloids to gain insights into the behavior of atomic crystals and glasses, and recently to the large variety of optical, mechanical and other types of metamaterials made from pre-designed, artificial "quasi-atom" building blocks. However, the meta-matter-like behavior of known metamaterials made from such man-made building blocks is limited to only certain types of properties, like the refractive index or mechanical behavior. We envisage creation of the "***knotted chiral meta matter***", the ***KCM^2*** paradigm that builds on particle-like quasi-atom properties of topological knot solitons, knotted vortices and knots in colloidal or (bio)polymer molecular strands. Our ***KCM^2*** is anticipated to share and explain many properties of ordinary matter and antimatter, but also overcome their fundamental limitations. For example, Fig. 2.1 shows a knot crystal that Smalyukh developed through the self-assembly of topological solitons in the order parameter field [*Science* 2019]. Such knot crystals of quasi-atoms show ~50% anisotropic electro-strictive strain [*Science* 2019], more than two orders of magnitude larger than that known for crystals in conventional matter. While knotted solitons can have chiral nature, the key role played by chirality is in enabling the energetic stability of such particle-like objects. A different ***KCM^2*** example is a crystal made of interlocked molecular rings (Fig. 2.2) developed by our PI Sato & colleagues [*Nature* 2021], where topological linking leads to interesting physical properties that may potentially enable carbon dioxide capture and transparent thermal superinsulation often needed for boosting energy efficiency. Like in these examples, the World of ***KCM^2*** that we design and create will help to overcome the perceived limits of the World around us. In implementing this vision, we will take advantage of the recent developments in topology in both physical and momentum spaces, and in a large variety of order parameter spaces ranging from chiral liquid crystals to colloids, magnets, (bio)polymers, gels & other condensed matter & biological systems. Within the ***KCM^2*** paradigm, we will gain insights into the nature of fundamental building blocks of (anti)matter & origins of life & will create foundations to address global problems of growing energy demand, climate change & human health vulnerability.

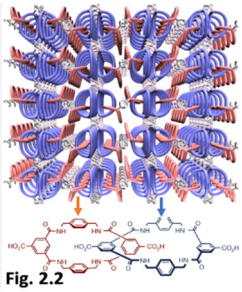

Fig. 2.2

2) Interdisciplinary research

The proposed International Institute for Sustainability with Knotted Chiral Meta Matter (***SKCM^2***) will interknit mathematics, physics, chemistry, material science, biology, cosmology & planetary science to create entirely new research fields & to enable a sustainable future. While ***KCM^2*** intrinsically requires collaborations between researchers with different preparation backgrounds, we will assure that the WPI shared laboratories are set up to facilitate interdisciplinary collaborations of researchers recruited globally. One way to promote collaborations

is through co-mentoring of young researchers, the doctoral students and postdocs, where these researchers will have primary, secondary and international co-mentors with whom they will jointly publish while supported by the WPI grant. Having collaborative publications will be an important aspect of performance evaluations. Establishing the primary function of the WPI under one roof of a new building will promote discussions and scientific exchanges between researchers from different fields. Moreover, we intend to organize various tutorials and short courses for teaching key concepts from the fields different from one's primary training. Besides the formal seminars, the WPI will have an informal discussion forum of early outcomes of research, to which all WPI members will be invited. While engaging our international PIs and their teams, we will take full advantage of online meetings, short- and long-term stays of overseas PIs and young researchers in Japan and vice versa.

(3) Global Research Environment and System Reform

1) International research environment

The ***SKCM²*** network of PIs will involve the very top global centers, including MIT, Cambridge U., Max Planck Inst., CU-Boulder, etc. We will strive to increase the time foreign PIs spend at HU beyon 2-3 months through sabbatical, cross-appointment, consulting & other agreements. Shared laboratory space & equipment from the WPI funding will be provided to foreign PIs as the top priority at the very beginning of the project. Foreign PIs will be the primary advisors for postdocs hired at HU, who will spend 50% time abroad in labs of these PIs & 50% at HU. In addition to HU-based mentors, all WPI-supported PhD candidates will have foreign PI co-mentors, spending ~50% time abroad. Joining research groups is like becoming a family member, so that the foreign & HU PIs will be all inter-knotted with family-like links via their young researcher group members.

2) Center management and system reform

Our institute will have a level of autonomy envisaged by the MEXT for WPI centers. The director will make all key decisions related to personnel, hiring, budget, etc. His leadership team will assist with the implementation of vision and goals of the proposed project. The current group of PIs at HU and other nodes of the WPI involves a majority of research leaders in the emerging ***KCM²*** field & will be strengthened further through new hires of top young researchers via open international searches, where 5-10 new PIs will join within the 10-year implementation period, including potential new joint hires with RIKEN & AIST. To help implement ambitious WPI-enabled reforms within the entire HU, Abe will initially combine his current role of HU's Executive Vice President with the role of WPI's Administrative Director. Afterwards, Abe will devote himself to the role of the WPI's Administrative Director as soon as possible. Out of three Deputy Directors, two are women: Yabuta will be a Deputy Director for Science, Kotorii for Outreach & Dissemination & Inoue for Education. Women will be in majority on the Executive Board. Moreover, Yabuta & Kotorii will form a strategic planning group and, together with Abe, will help the Director oversee daily operations of the WPI. The overall administration of the center will achieve a balance of gender representation, experience, young energy & the need of both using the WPI to seed reforms and maintain its administrative autonomy, per the vision of MEXT. Kotorii, Senyuk, Yabuta & Inoue, will lead the four research thrust areas of the WPI. Director & PIs will plan and implement education and system reforms at WPI as a seed to reform HU, with strong support from President Ochi. Director will meet with the President on a monthly basis. Once the WPI is launched, research and educational activities will be evaluated within the concept of "meritocracy" introduced under the leadership of Director. To stimulate ground-breaking research with corresponding publications in top-ranked international journals, a cumulative annual impact factor of publications of PIs will be systematically monitored as a summation of impact factors of journals in which individual articles are published, serving as a guide for Director in distributing resources & salary bonuses (this strategy will account for field-specific differences, e.g. between materials science and pure math); additional external grants, international awards, outstanding service to WPI missions & other major successes will be similarly rewarded too. This concept does not exist at HU; once this new system is validated by the WPI, it will be implemented throughout HU as an improvement to the existing system. In addition, by adopting the best practices of administrative procedures learned by the WPI's foreign researchers at their respective institutions, we will pursue reforms, which will lead to the improvement of the administrative system at HU.

(4) Values for the Future

1) Generating and disseminating the societal value of basic research

Through high-impact publications & outreach, we will convey to both scientific communities & the general public how our fundamental research helps address many knotty problems that Japan & the entire World face, like the growing energy demand & its impact on climate change. For example, buildings consume 40% of all generated energy for cooling and heating; 20% out of it lost through windows, the least efficient part of the building envelope. Could one maintain the desired environment within a building interior without energy consumption, like in a thermos? Sato & Smalyukh will collaborate to develop such transparent super-insulating materials by

cost-effective fabrication of novel aerogels via knotting/linking molecules. Jointly with Vignolini, they will also develop materials for the building envelope inspired by gold and silver beetles that use porous chiral structures for thermal regulation (silver/gold reflections play a role like silver coatings in a thermos, though instead noble metals beetles use the emergent power of chiral self-assembly of chitin fibers). Learning from nature, we will develop low-cost energy-efficient materials from nanocellulose. From yet another perspective, further developments of electronics require miniaturization, which is limited by quantum effects at small scales. These limits can be overcome by our chiral magnetic spin systems and topological insulators. For example, the racetrack memories can utilize topologically protected multi-dimensional solitons like hopfions as information carriers to design entirely new principles of future electronic devices, where topological objects like knots in fields can serve as information carriers. From the standpoint of biomedical applications, changes of chirality & knotting in proteins can cause protein metamorphosis diseases, such as Alzheimer's disease, so the ability of detecting and controlling these processes may aid in developing biomedical treatments. Knots are also found in the viral RNA genome of coronavirus whereas the spike protein coat that changes with mutations of coronavirus may be responsible for vaccine inefficiency, as studied by our PI Hsu. These examples show how our research may help to address pressing problems that the World faces, also achieving missions of Japan's Society 5.0. We will pursue a vast variety of outreach activities designed to elevate public awareness of our sustainability enabling ***KCM²*** research & to attract talented young people to science careers, led by Kotorii, Deputy director for outreach & dissemination. WPI's summer/winter schools & conferences will have public lectures & outreach designed to interest the public in Japan in science for sustainability. Mimicking US NSF's guidance for dissemination of research outcomes to the public, PIs will develop their own unique outreach components of the WPI-related activity to broadly share the excitement about the research we do. Public lectures by Peace Nobel Laureates will complement the science programs at WPI schools, as a reminder of the important roles that need to be played by scientists to sustain global peace. The WPI will seed reforms & boost global reputation, making HU like the Harvard of Japan, educating a new generation of researchers with a global perspective, enabling energy demand reduction, climate change mitigation, Japan's society 5.0 missions & economic growth.

2) Fostering next-generation human resources linked with higher education

Over 50% of the WPI grant funds will be dedicated to supporting young scientists, including PhD students. To promote highly interdisciplinary research, we will introduce a system of co-mentoring young talented researchers, doctoral students and postdocs, who each will have three or more co-advisors with different backgrounds. For example, a doctoral student in Physics at HU might be co-advised by HU PIs in chemistry or math & by a PI from an international node. Specialized graduate coursework will be co-designed and taught by the WPI PIs. Our strategy will take advantage of the top international research centers in this research area, allowing students and postdocs from HU, TokyoTech and RIKEN to spend extended periods of time at the other WPI nodes, such as MIT, Cambridge & CU-Boulder. Conversely, Japanese institutions will host young researchers & PIs from the international nodes of the WPI, all co-mentored by foreign & domestic PIs. These arrangements will allow doctoral students to take specialized courses at the partner institutions. Furthermore, to help reform graduate education, we will introduce cross-disciplinary coursework, along with international research exchange, schools, conferences & forums to bring the broader interdisciplinary community together. The WPI will pay PhD students' salary, like in USA graduate programs, as well as will sponsor student/postdoc exchanges between Japanese & international nodes. Using matching funds, 5-10 new young PIs will be hired within the implementation period, striving to attract the most talented young researchers & achieve gender balance & diversity. Our WPI will seed reforms of education & research at HU, in other institutions of the large Chugoku-Shikoku geographic area and throughout Japan. Our Center will promote internationalization and gender balance in academia, will mobilize and reinforce the global research efforts for a sustainable, peaceful future. The WPI will strive to hire women PIs, young researchers & administrators. Out of 5-10 faculty hires, we will recruit 50:50 male-female, Japanese-International, achieving gender balance & a stimulating cross-disciplinary & multi-cultural environment. Young researchers will connect HU with top global centers & will erase disciplinary boundaries between the fields by working with co-mentors having different backgrounds.

3) Self-sufficient and sustainable center development

In addition to the WPI grant, PIs will pursue multiple individual grant applications in Japan, in countries of participating PIs & globally. Our ability to attract such funding will be enhanced further by the international network of collaborations & visibility of research outcomes of the ***SKCM²***. Besides these conventional funding sources, we will pay attention to private foundations (like the Simons, Templeton & Moore foundations in the USA) & will establish Endowed Chair positions & student/postdoc fellowships jointly with philanthropists and industry in Hiroshima/Japan/globally, as well as local governments of Hiroshima prefecture/city. While HU's support will be sustained past 10 years, the external funding will grow with each success, making the ***SKCM²*** an independent permanent center of research excellence at HU, self-sustained after the implementation period.