Available online at www.sciencedirect.com
ScienceDirect
Research Policy 37 (2008) 888–899
research policy
www.elsevier.com/locate/respol

Across institutional boundaries? Research collaboration in German public sector nanoscience

Thomas Heinze[a,*], Stefan Kuhlmann[b]

[a] Faculty for Social and Economic Sciences, Department of Sociology, University of Bamberg, Lichtenhaidestraße 11, 96045 Bamberg, Germany
[b] School of Management and Governance, University of Twente, Capitool 15, AE Enschede 7500, The Netherlands

Received 25 January 2006; received in revised form 4 July 2007; accepted 30 January 2008
Available online 18 April 2008

Abstract

Research collaboration is a key mechanism for linking distributed knowledge and competencies into novel ideas and research venues. The need for effective inter-institutional knowledge flows is of particular importance in emerging domains of research, and also a challenge for public research systems with a high degree of institutional differentiation. Motivated by concerns about favorable institutional conditions for the conduct of scientific research, we analyze research collaboration in the emergent domain of nanoscience within the highly segmented German public research system. Drawing on multiple data sources, such as co-publications, macro research statistics, and in-depth interviews, we identify governance structures that support or hinder scientists' efforts to engage in collaborative work relations across institutional boundaries.

Keywords: Inter-institutional collaboration; Public research system; Governance; Nanotechnology; Knowledge flows

1. Introduction

It is widely acknowledged that research collaboration is a key mechanism for both knowledge production and diffusion in science and technology (Steensma, 1996; Ahuja, 2000; Hagedoorn et al., 2000; Powell et al., 2005). However, we know little about the institutional factors that influence the capability of public research systems to connect distributed knowledge and competencies across institutional and organizational boundaries. While the institutional interfaces between university and private sector research are comparatively well understood (Meyer-Krahmer and Schmoch, 1998; Owen-Smith et al., 2002; Calvert and Patel, 2003), there is a lack of systematic and comparative knowledge as to the institutional conditions that facilitate external work relations between public research organizations. A burgeoning literature addresses either the individual and network level of collaborative research (Landry and Amara, 1998; Melin, 2000; Newman, 2004; Lee and Bozeman, 2005), or the growth of international scientific collaboration (Georghiou, 1998; Glänzel, 2001; Jappe, 2007). Among the few studies that deal with the role of institutional structures in the formation of research collaboration in public research are Laudel and Gläser (1998) who examine the boundary-spanning role of collaborative research centers, and Corley et al.'s study of epistemic and organizational institutionalization in two large-scale, multi-discipline collaboration programs (Corley et al., 2006). Yet the question of how governance structures of public research organizations influence extramural collaborative research has rarely

* Corresponding author.
E-mail addresses: thomas.heinze@uni-bamberg.de (T. Heinze), s.kuhlmann@utwente.nl (S. Kuhlmann).

0048-7333/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.respol.2008.01.009

been addressed in recent sociology of science and public policy studies. The desire to know more about the factors that contribute to research collaboration is given further impetus by the substantial changes seen over the last three decades in the institutional and organizational conditions under which scientific research is conducted (Senker, 2006; Shapira and Kuhlmann, 2003; Gornitzka et al., 1998).

The need for effective inter-institutional knowledge flows is particularly critical in emerging research domains on the one hand, and institutionally differentiated research systems on the other hand. In emerging science and technology domains, a sizeable share of research is conducted at the intersection of established scientific disciplines and across fundamental and applied research, seeking for and building on cognitive and institutional complementarity. One such research domain is nanoscale science and technology, referred to as "nano S&T" in the following. Nano S&T embraces several disciplines and research areas, such as applied physics, materials science, physical chemistry, physics of condensed matter, biochemistry and engineering and polymer science, and potential application areas as diverse as drug delivery, environmental sensing, manufacturing, and quantum computing (Porter et al., 2008; Heinze, 2004; Heinze, 2006; Hullmann and Meyer, 2003).

The need for effective inter-institutional knowledge flows is also critical in public research systems with a high level of institutional differentiation. From an innovation policy point of view, such research systems need not only to allow knowledge diffusion across institutional boundaries via career paths, but also to institutionalize effective mechanisms to support day-to-day collaborations across organizations that scientists seek to establish and maintain. In this regard, the German research system (GRS) is an interesting example due to its high level of institutional fragmentation. In addition to the universities, the GRS embraces a large extra-university sector including institutes of the Helmholtz Research Centers (HGF), the Max-Planck Society (MPG), the Leibniz Association (WGL), and the Fraunhofer Society (FhG). These organisations have developed quasi-functional monopolies in particular research domains, such as fundamental research (MPG), applied contract research (FhG), and big-science research facility management (HGF). In consequence, they have traditionally not collaborated much with each other (Hohn and Schimank, 1990).

Therefore, studying the institutionally fragmented GRS in the emerging domain of nano S&T is an interesting case, because it touches upon the question how well the differentiated institutional structure of the GRS is aligned to the need for inter-institutional research in the emergent research domain of nano S&T. If institutional segmentation is viewed as an obstacle for effective knowledge exchange, then systems with such structures in their public research system are not expected to be among the top performers internationally. This, however, is not true for German nano S&T research. The GRS scores relatively high in what has been called the "global nanotechnology race". In absolute terms, Germany ranks fourth in publication output worldwide and third in patent applications at the European Patent Office (Hullmann, 2006). In relation to GDP measures, Germany ranks even higher (Heinze, 2004: Fig. 4).

Our analysis addresses three interrelated questions. First, how common is research collaboration across institutional boundaries empirically? Second, what are scientists' rationales to engage in collaborative research? Third, which governance structures are either conducive to inter-institutional research collaboration or interfere with scientists' efforts to engage in collaborative work? For answering these questions, we frame our analysis by dimensions of governance that reflect the ongoing debate on the coordination of autonomous, but interdependent actors (Hollingsworth and Boyer, 1997; Lütz, 2003). Furthermore, we draw on multiple data sources such as annual reports of German research institutions, internal reports and communications, co-publication analyses, and macro research statistics. Most importantly, we conducted 32 semi-structured interviews between 2004 and 2006 with representatives of all non-university research organizations, the German Ministry for Education and Research (BMBF), institute directors at universities and extra-university institutions, and senior researchers and junior group leaders in the field of nano S&T. More details on our data are presented in Appendix A.

Sections 2 and 3 provide key facts about the domain of nano S&T and the GRS. Sections 4 and 5 sketch current collaborative activities in nano S&T across research institutions in Germany and discuss rationales for cooperative research relationships across institutional boundaries. In Sections 6 and 7, we elaborate on institutional factors that either facilitate or hinder the transfer of knowledge and expertise between research organizations. Section 8 summarizes our findings and gives an outlook on research desiderata.

2. Nano S&T: research across established cognitive boundaries

Nano S&T is one of the most thriving research domains worldwide. Recent data show that the number of worldwide scientific publications in nano S&T has increased by a factor of six in the past ten years (Hullmann, 2006). Likewise, the annual number of patent applications in nano S&T at the European Patent Office more than doubled in the last decade (Scheu et al., 2006). Worldwide public funding has increased from €500 million in 1999 to €385.000 million in 2004 of which the United States, Japan, the European Commission and Germany together invested about 70% (European Commission, 2005).

One of the conspicuous characteristics of nano S&T research is its high level of research across established disciplinary and field boundaries, but also across the traditional distinction of basic and applied science. Although the cross-disciplinary character of nano S&T is sometimes questioned (e.g., Schummer, 2004), several studies have shown that this research domain shows a remarkable degree of research activities that cut across established cognitive boundaries. This means that a sizeable share of research is conducted at the intersection of established scientific disciplines and across fundamental and applied research. Among the earlier studies, Braun and Meyer (1998), based on bibliometric measures, identified nano S&T research as more cross-disciplinary than science in general. More recently, Heinze and Bauer (2007), based on a longitudinal multi-method research design, show that one key explanatory factor for research creativity in nano S&T is the ability of scientists to effectively communicate with their colleagues and their capability to address a broader than average work spectrum. Furthermore, Rafols and Meyer (2007), relying on both interview and bibliometric data, find a consistently high degree of cross-disciplinarity in the cognitive practises of scientists in the field of molecular motors. The authors argue that the need for a broad set of research instrumentalities, such as fluorescent microscopy or X-ray crystallography, is one of the main drivers of boundary crossing research in nano S&T. Their findings are in line with science history studies on the pivotal role of research instrumentalities as connectors between independent research specialties and disciplines (Shinn and Joerges, 2002).

Among the various nano S&T subfields, our analysis focuses on nano-electronics and nano-interfaces. *Nano-electronics* is an emerging subfield with topical areas, such as *carbon nanotubes* or *wafer bonding*. Carbon nanotubes have interesting electrical properties that are scientifically relevant for molecular electronics and biophysics; at the same time, however, carbon nanotubes have a high potential for future integrated circuits and thus for the computer industry. Wafer bonding is another nano-electronical area where epitaxy (method of thin-film deposition) methods are used to allow faster electron transmission within silicon structures, a development that is highly relevant to enhancing computer processor speed. *Nanoscale interfaces* is a second emerging field within nano S&T, spanning topical sub-areas such as *nano-capsules* or *nano-sensors*. Based on thin film colloidal chemistry methods, nano-capsules have considerable potential to be used as carriers for targeted medication. Similarly, the fundamental understanding of the reactivity of nano-surfaces allows the construction of biocompatible and portable nano-sensors.

3. The German research system: key facts and recent dynamics

Before examining collaboration in nano S&T within the GRS, we introduce some key facts on its institutional structure and recent dynamics. A striking feature of the GRS is the relatively large share of extra-university public sector research. Comparing input and output variables shows that the German university sector is larger than the extra-university sector in terms of personnel (Table 1, B), but has a much smaller research budget per researcher (Table 1, C). Nevertheless, university researchers are highly productive, as displayed by their share in all three output categories (Table 1, E–G).

Within the extra-university sector, the MPG has the strongest scientific profile. While MPG institutes recruit only 4% of German research personnel in the natural sciences (column B), they account for 10% of the German Science Citation Index (SCI) papers (column E) and 34% of all German *Science* and *Nature* articles (column F). In contrast, FhG institutes publish much less in the SCI but have the highest relative output of patent applications (column G). FhG institutes primarily conduct contract research for companies, but also for public agencies. Their core funding is substantially lower than that of all other research institutions (column D). In terms of research output, universities are located in between the distinct institutional profiles of MPG and FhG.

The HGF has traditionally had an institutional mission in big science research facilities and nuclear technology development and thus has stronger ties to the federal state. Although similar to the MPG in its high level of institutional funding (Table 1, D) and equipment level per researcher (Table 1, C), its relative productivity is substantially lower: 11% of German research personnel in the natural sciences (Table 1, B) publish 7% of the German SCI papers (Table 1, E) and 14% of all German *Science* and *Nature* articles (Table 1, F), and file 13% of all patent applications among the public sec-

Table 1
The German research system (GRS)—basic facts

	Budget in natural sciences and engineering 2001 (€ m) (A)	Research personnel in natural sciences and engineering 2001 (FTE) (B)	Ratio A/B (C)	Core funding 2003 (D)	Total SCI papers 2000–2002[3] (E)	Total *Science* & *Nature* papers 2000–2002[3] (F)	Total DPA and WPI patent applications 1999–2001 (G)
Universities	4,884[1] (49.0%)	57,060[1] (68.4%)	0.086	–[2]	165,183 (79.0%)	474 (51.4%)	6,394 (70.7%)
Extra-university public research	5,088 (51%)	26,375 (31.6%)	0.193	–	44,014 (21.0%)	449 (48.6%)	2,650 (29.3%)
Helmholtz Research Centers	2,075 (20.8%)	9,181 (11.0%)	0.226	78%	14,339 (7.0%)	125 (13.5%)	1,206 (13.3%)
Max-Planck Society	853 (8.6%)	3,235 (3.9%)	0.264	80%	19,390 (9.5%)	314 (34.0%)	245 (2.7%)
Leibniz Association	490 (4.9%)	2,728 (3.3%)	0.180	70%	8,270 (4.1%)	44 (4.8%)	188 (2.1%)
Fraunhofer Society	947 (9.5%)	5,581 (6.7%)	0.170	39%	2,015 (1.0%)	2 (0.2%)	1,011 (11.2%)
Others	723 (7.3%)	5,650 (6.8%)	0.128	–[2]	–[2]	–[2]	–[2]
Total	9,972 (100%)	83,435 (100%)	0.120	–[2]	209,197 (100%)	923 (100%)	9,044 (100%)

Sources: Columns A, B and C refer to data published by BMBF (2005: Tables 20, 21, 33, 34, 35,). Column D refers to figures from the research organizations' 2004 annual reports, which are available at www.helmholtz.de, www.mpg.de, www.wgl.de, www.fraunhofer.de. Columns E, F and G refer to publication data retrieved via Science Citation Index, and patent application data retrieved via PATDPA (German Patent Applications) and WPINDEX (World Patent Index). Both publication and patent application data were retrieved by the authors (online host: STN). Notes: [1]including teaching; [2]no data available; [3]non-fractional counts.

tor research institutions (Table 1, G). WGL institutes are also an important part of the German research landscape. Their overall relative research performance (4% of SCI publications) matches their relative size (3% of research personnel). However, the WGL has not developed a clear institutional profile on the upper organizational level thus far.

Fig. 1 maps the research profiles of German research institutions on two major output variables: publications and patent applications, both relative to 100 R&D staff between 1991 and 2002. These highly aggregated dimensions are useful to locate various profiles in the German public research system. Basic science (upper left area) and technology-driven research (lower right area) are positions occupied by the MPG and the FhG, respectively.

Two trends are discernible in Fig. 1. First, all institutions substantially increased their productivity between 1990 and 2002, as is visible by the movement both towards the right and upwards, indicating higher outputs per R&D staff. These shifts are a clear indication of the increasing pressure on the research system to demonstrate higher output efficiency. In the same period, public sector research funding decreased substantially: between 1990 and 2002, funding, particularly of the university sector, decreased by about 10% in real terms. In addition, the number of tenured university professors decreased from 25,000 to 23,000 between 1995 and 2005, while the scientific labor force in the public research sector stagnated (DHV Press Release 11/2005; BMBF, 2005: Tables 20, 21, 38). Despite this decrease in funding, scientists produced significantly more research papers and patent applications in 2002 than in 1990.

Second, while Fig. 1 does not indicate fundamental changes in the relative positions of German research institutions one should note, however, that current pressures on the research system have induced competition between formerly protected research domains. Shifts of research organizations in the direction of technological research (shift to the right in Fig. 1) tend to be more pronounced than movements in the direction of scientific output (upward movement in Fig. 1). Institutes that did not conduct technological research in the early 1990s apparently do so today. It also implies that institutes whose core competence has traditionally been in technology research have come under considerable pressure. Consequently, the FhG – financed largely through contract research with industry – today faces increasing resource competition from other research institutions.

In sum, the problem of institutional segmentation and dominance of organizational self-interests, as observed

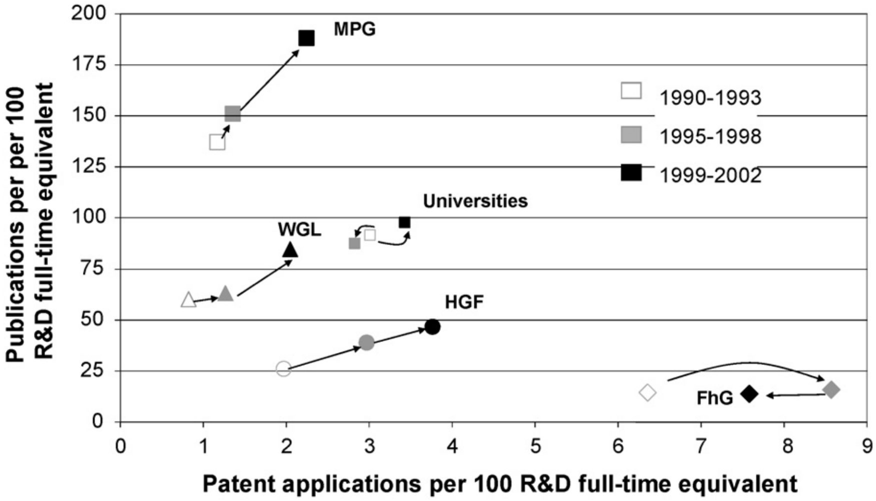

Fig. 1. Institutional dynamics in the German research system between1990 and 2002. Sources: publication data retrieved via Science Citation Index; patent application data retrieved via PATDPA and WPINDEX (online host: STN). Calculations by authors. Notes: Data do not include social sciences and humanities. Numbers are annual averages. For universities the scaling factor is 50 R&D FTE (instead of 100) because their institutional mission embraces both teaching and research. The Research Centre for Computational Sciences (GMD), which was transferred from Helmholtz to Fraunhofer in 2001, is not included in the data.

by a high-level evaluation committee (Brook et al., 1999), is still highly relevant. Budget cuts and pressure on output efficiency have increased competition for research funds, and might hamper synergies within the GRS.

4. Collaboration across institutional boundaries in Nano S&T

In this section, we address the first question: how common is inter-institutional research collaboration in the GRS in the field of nano S&T? In order to measure the level of inter-institutional collaboration, we systematically searched for collaborative research activities in the two subfields of nano-electronics and nano-interfaces. First of all, we identified nano-related publications and collaborative research projects by comprehensive search strategies. Further, we conducted interviews primarily with researchers who were experienced in extramural collaborations, but also with scientists who reported few external contacts only. This led to the identification of further types of collaborative activities.

Using co-publications as a bibliometric indicator (Melin and Persson, 1996; Bordons and Gómez, 2000; Glänzel and Schubert, 2004; Newman, 2004), we find that - at the level of research organizations - the majority of research collaborations are observed between universities and the extra-university research sector, while co-authorship relationships between organizations of the extra-university sector are tenuous. The MPG collaborates most frequently with universities, followed by the HGF and the FhG, but there are few co-publications between MPG, FhG or HGF (Table 2). These results confirm the conclusions of the Brooks report which criticized the low level of collaboration within the extra-university public research sector (Brook et al., 1999).

At the level of institutes within universities and extra-university research organizations, we identified *formal project collaborations* by a systematic screening of research projects funded either by the German

Table 2
Co-publications between German research institutions in nano S&T, 1999–2003

	Universities	Helmholtz Research Centers	Max-Planck Society	Fraunhofer Society
Universities		375 (81%)	568 (86%)	107 (78%)
Helmholtz Research Centers	375 (36%)		74 (11%)	12 (9%)
Max-Planck Society	568 (54%)	74 (16%)		18 (13%)
Fraunhofer Society	107 (10%)	12 (3%)	18 (3%)	

Source: Co-publication data retrieved via Science Citation Index by the authors (online host: STN). Leibniz Association (WGL) is not included; for a recent study of WGL institutes see Arnold and Groß, 2005.

Research Foundation (DFG) or the Federal Ministry for Education and Research (BMBF). The DFG has been funding basic research projects in the areas of *nano-colloids and -polymers*, *nano-materials and optical nano-technologies*. These programmes have been extended in size and scope over the last decade and thus provided ample opportunities for collaborative activities to develop. In the applied research funding of BMBF, we found collaborations in the fields of *nano-polymers*, *semiconductors*, *nano-materials and laser*. Some of these projects are part of the two broad subfields mentioned in the above, and several scientists from such projects were selected for interview.

Interviews helped identify other types of formal collaborations. There are, for instance, *cooperation contracts* between research institutes specifying use of research instrumentation and interchange of personnel. We identified *junior research groups* at the intersection of institutes that were located at one institution, but personnel and instrumentation costs were shared among two or more institutions. Furthermore, *education of junior researchers* is an institutional vehicle for collaborations, not only between universities (where junior staff receive their doctoral degrees) and the extra-university sector (where they carry out their projects), but also within the extra-university sector. In addition, various forms of *informal collaborations* exist, including meetings of the heads of institutes whose function is information sharing and preparation of collaborative research proposals; also, doctoral students who travel between sites and carry out experiments are shared. In sum, the interview data suggests a more nuanced picture of collaborative relations, particularly within the extra-university research sector. Our interview data confirm the conclusion of earlier literature that co-publications are only a partial measure of collaborative activities (Katz and Martin, 1997; Laudel, 2002).

5. Rationales for research collaboration

Understanding research collaboration in a highly differentiated research system requires consideration of scientists' rationales for engaging in collaborative activities. Generic motives for research collaboration include curiosity, knowledge advancement, sharing the excitement of a research area with other scientists, or intellectual companionship (Katz and Martin, 1997; Beaver, 2001). These motives are anchored in what Luhmann (1975) describes as a "cognitive style of expectation". However, these motives do not specify why particular scientists would collaborate at a given time. For the field of nano S&T, we empirically validated the following additional collaboration rationales.

The first set of rationales is *expansion of research capacity*, which embraces (a) the need for complementary knowledge and expertise; (b) access to equipment and instrumentation; and (c) the ability to build consortia that compete for funding. An example for (a) is an ongoing collaboration between two groups, one of which specializes in the electrical measurement of nanowire characteristics, while the other is highly knowledgeable in respective optical measuring techniques. Both knowledge domains have been fruitfully combined over time, leading to many co-authored publications. Combining complementary knowledge and expertise expanded both groups' capacities to address new questions and to enter new thematic areas. An example for (b) is one group interested in solving a particular research question on metallic nanoparticles and two instrumentation groups (synchrotron and molecular beam lithography) that are interested in learning more about the various possibilities of their complex machinery. There were many examples for (c). Because expanding research capacity requires additional funding and many research questions (due to their complexity) cannot be addressed by single groups alone, researchers have an incentive to build project consortia that compete collectively for third-party funds.

A second set of collaboration rationales is anchored in strategies to *improve current research capabilities*. It includes (d) keeping own research activities focused and (e) learning new skills or techniques. Examples for (d) and (e) are three chemistry groups that are embedded in institutes with strong physics capacities. Such embedding has several benefits: the most important are access to new research questions generated outside a given specialty and opportunities to become acquainted with new methods and instrumentation, but also important is continuous scrutiny from the physicists with regard to interpretation of experimental results.

Third, *realisation of institutional complementarities* is an important collaboration rationale: Universities seek cooperative relations with extra-university institutes to obtain access to facilities, instrumentation, and research topics, while extra-university institutes depend on access to students and junior researchers. Institutional complementarities also exist between groups specialized either in basic or applied research. FhG institutes usually provide considerable expertise in testing and development of reliable technical processes, while university or MPG groups have access to the latest knowledge at research frontiers. In the areas of nano-electronics and nano-interfaces, such institutional profiles have been found to be complementary for both sides. On the one hand, there are novel scientific approaches in wafer bonding and nano-polymers that require considerable engineering before their industrial application becomes feasible. On the other hand, problem solving on the engineering side has generated new research questions that are valuable for a fundamental science perspective.

Fourth, research institutions seek collaborations to *enhance their visibility for scientists and companies in the field*. We identified cases in which collaborators related to each other because of their different research profiles that in turn are anchored in different organizational missions. There are MPG institutes (not the majority, however) that use their FhG collaborations to signal to industrial companies their openness to applied technological research questions (which traditionally lie outside their core competency). Contacts with larger companies can be beneficial for MPG institutes in terms of additional funding, but they also have value with regard to future job opportunities for doctoral students and post-docs. Conversely, a number of FhG institutes (not the majority, however) employ contacts with MPG institutes to signal scientific prestige to academic researchers in university departments and other basic science facilities. Furthermore, because the FhG funding regime allows only little exploratory research, such contacts signal access to research frontiers, which, in combination with engineering and reliability testing capacities, might be an incentive for companies to fund contract research in FhG institutes. The difference between the MPG and FhG institutes is that the former use signalling primarily to attract industrial recognition, while the latter attempt to draw either academic or industrial attention to their research activities.

6. Factors conducive to inter-institutional research collaboration

Rationales for research collaboration across institutional boundaries lead us to the third question: which governance structures are conducive to inter-institutional research collaboration? Recent publications on the GRS investigate primarily interdisciplinary cooperation (Röbbecke et al., 2004; Lengwiler, 2006), and only a few studies deal in more detail with the institutional framework of the GRS, but they discuss data from the 1980s and early 1990s and do not cover more recent institutional developments (Hohn and Schimank, 1990; Hohn, 1998; Laudel and Gläser, 1998).

In order to examine the governance of inter-institutional research collaboration in more detail, we refer to a *governance cube* as a heuristic tool (Fig. 2).

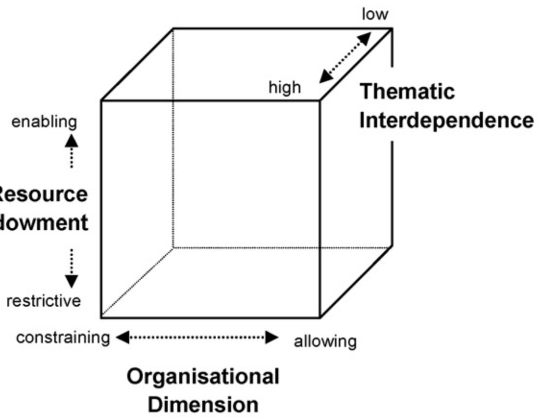

Fig. 2. Governance dimensions of research collaboration. (I) Thematic interdependence: (1) interdependency of research activities (e.g., extensive division of labor); and (2) integration of research results (e.g., methodological, disciplinary, by subject). The degree of intellectual interdependence can vary between high and low, both between research units (e.g., institutes, research groups) and on the level of research fields (Whitley, 2000). (II) Organizational dimension: (1) degree of centralization and formalization of decisions and decision processes (e.g., regarding reward structures, personnel policy, young researchers, career pattern); (2) relationship between organizational micro, meso, and macro levels (e.g., deep or flat hierarchies, leverage, and permeability across levels); and (3) cultural integration (e.g., self-images, taken-for-granted rules, missions). The organizational dimension varies between constraining and allowing. (III) Resource endowment: (1) financial structure (e.g., level of institutional and third-party funding, allocation mechanism); (2) infrastructure (e.g., buildings, apparatus, instruments, computing capabilities); and (3) human resources (e.g., qualified personnel, job mobility). The resource endowment can be conceived of as either restraining or enabling (Hohn and Schimank, 1990).

Generally speaking, governance refers to analytically distinguishable forms of institutional coordination of autonomous, but interdependent actors. Hierarchy, competition, network, association, and community are ideal types of governance capturing the *rules of a game* at a highly generalized level (Hollingsworth and Boyer, 1997; Lütz, 2003). In reality, these governance forms are often interconnected, thus forming *governance regimes*. Benz (2007) argues, for instance, that actors have to find out how to cooperate with competitors or to compete with partners in networks, to negotiate an agreement under tight organizational constraints, or to find approval for the outcome in external arenas in their own organization or group. The governance cube takes up notions of both governance forms and governance regimes but is specifically tailored to the research question of inter-institutional research collaboration.

The dimension of *thematic interdependence* captures the extent to which research activities build on each other and how the cognitive structure of research fields impinges upon the work organization of research. The *organizational dimension* depicts the governance regimes of both the university and the extra-university sector including HGF, MPG, and FhG. On the level of single research units (institutes, groups), the organizational dimension embraces variables such as internal differentiation, permeability of communication across levels of hierarchy, career incentives, or research missions. *Resource endowment* includes the quantity and the quality of staff and equipment as well as the funding structure of research units (Fig. 2).

By applying dimensions of the governance cube, we identified a number of institutional factors that are important in facilitating inter-institutional research cooperation in the GRS. As far as the intellectual dimension is concerned, *specific thematic profiles* of research groups (and research institutes) are of paramount importance because they support search processes and decision-making (ex ante), and increase mutual benefits from collaborative activities (ex post). Many of the interviewed groups tend to be highly interdependent both in terms of the interdisciplinary character of work and also with regard to the need for complex instrumentation and materials. This point is in accordance with the finding that one of their major rationales for collaborative activities is the need for complementary knowledge and expertise. It also fits our finding that researchers prefer collaborators with a reputation for a certain expertise that proves valuable in research consortia competition for additional research grants (see Section 4). Specific profiles are also important with respect to the organizational dimension, but here they pertain to the "research mission" of groups or institutes. Such *specific research profiles* include basic versus technology-driven research, the capability to conduct highly reliable routine research or the capacity to conduct research at scientific frontiers. Organizational and intellectual profiles need not overlap.

Further along the organizational dimension, *recruiting qualified research personnel with a record of job mobility* endow the employing organizations with a better understanding of different institutional perspectives. This organizational capacity seems valuable in a functionally differentiated research system, as is the case in Germany. Researchers with inter-organizational career tracks or with a record of visiting fellowships enable informal contacts to other research institutions that help in building consortia at certain times and for particular purposes.

In addition, *research leadership* facilitates collaborative activities across institutional borders. Research leadership means conceiving and implementing mid-term research goals which enable external coalition building. It also means proactive strategies to access external funding and the ability to shift the initial research goals in the direction the research is moving. Research leadership is in accordance with the rationales of expansion of research capacity and improvement of current research.

Finally, *effective administration* at the organizational level supports research collaboration, for instance, by making decisions promptly, by not consuming resources above a certain threshold ("overhead"), or by allowing flexible interchange of resources, including mobility of personnel.

With regard to the resource endowment, our analyses suggest that research collaboration is facilitated when partners have *sufficient core funding* at the group or organizational level. Such funding is obviously a prerequisite for developing *specific research profiles*, which support search processes and increase mutual benefits from research collaboration. Findings from our interviews also suggest that sufficient core funding is a prerequisite for engaging in research venues that are intrinsically risky, a finding that pertains in particular to research creativity. However, *third-party funding also stimulates cooperative behaviour*; external collaboration is requested in many funding programmes. One of the major benefits of third-party funding is that it helps research groups keep their research focused and coordinate various research agendas. Institutes with a high level of core funds compete for third-party funding only if the research leadership decides to do so. MPG and HGF departments, for instance, which traditionally enjoy very high levels of core funding (Table 1), tend to be less involved in extramural collaborative research projects if their research leaders do not actively seek third-party funding. Neither core funding nor third-party funding alone induce collaborative activities in the field of nano S&T. Instead, a balance between the two seems advantageous.

Furthermore, *resource flexibility* appears to be important in facilitating extramural research collaborations. *Flexible allocation and interchange of resources between institutes* supports collaborative activities because this flexibility helps to conduct research effectively. One example is scientists who, while changing jobs from one institution to another, take their research projects with them. Another example is the shifting of project funding from a MPG institute to a university institute because a collaborating doctoral student has access to special equipment at the university and thus can carry out the work more effectively. A third example is collaboration contracts between extra-university institutes arranging mutual support in instrumentation or library services.

7. Barriers to inter-institutional research collaboration

With regard to the organizational dimension, *stereotypes and prejudices* tend to impede cooperation between various research organizations. Examples of stereotypes that we validated in our interviews are as follows: HGF researchers have a reputation for being slower and less productive than average, while MPG scientists are viewed as those with lavish laboratories and sometimes arrogant attitudes towards researchers from other research organisations. In contrast, FhG researchers are often equated with industry because they primarily focus on money instead of scientific quality. Furthermore, university researchers are often regarded as conducting research projects in a chaotic and even unprofessional way. These examples are not based on experience, but rather on hearsay, because both low overall job mobility and a low degree of formal and informal inter-institutional collaborations have provided only limited opportunities for genuine experiences with other research organizations.

Second, and in contrast to the first factor, inter-institutional collaboration can be hampered by *incompatible working routines* anchored in divergent organizational missions. Interviewees from FhG institutes and MPG institutes agreed in their assessment that straightforward interaction between what they called the "engineering attitude" of FhG researchers (i.e. to produce a project result within a finite time frame and with a finite sum of money) and the "playing attitude" of MPG researchers (i.e. searching without restrictions or "picking flowers") can be bothersome if there is no facilitator or translator. Combining divergent working routines in a synergetic fashion requires mobility record and/or active research leadership at the level of institute directors.

Third, *lack of interface management* seems a common problem for researchers who do not dispose of means or resources to organise follow-up activities in cases when they have results that might be relevant for other research institutions. It was only very recently that the headquarters of the MPG and the FhG started a dialogue on pooling expertise and know-how in various research areas, among them nano S&T (Gruss, 2002: pp. 19–20).

Regarding the *resource endowment dimension* in the governance cube (Fig. 2), our analysis suggests that *sustained budget cuts over the last decade*, particularly in the university system, have negatively affected the ability of research groups to engage in inter-institutional collaboration. This situation has been counterbalanced only partly by the comparatively good funding situation in the field of nano S&T. *Immediate effects* of funding restrictions are the discontinuation of ongoing cooperation or the loss of future options for collaboration. These impacts pertain especially to the university system, where *research collaboration covered by core funding* has become difficult over time. We have argued above that combinations of core and third-party funding together provide incentives to build up specific research profiles and seek extramural collaboration. Such a mix seems advantageous, compared to either mere core or project funding. However, if core funding falls below a certain threshold, capacities for building and sustaining research profiles will decline significantly which, in turn, inhibits the search for collaboration partners and the opportunity to gain from collaborative activities. These results are corroborated by Laudel (2006).

Mid-term effects of funding cuts include the emergence of *status hierarchies* between the university and the extra-university sector. Table 1 shows that MPG institutes have a budget/research personnel ratio of 0.264, while this ratio for the universities is merely 0.086. Thus, according to this coefficient, MPG researchers are about three times better equipped than their university colleagues. This finding is consistent with our interview results showing that university researchers increasingly experience problems in catching up with the instrumentation and research equipment of MPG institutes; thus, they are not well-positioned as research partners.

However, apart from budget restrictions, accompanying regulatory structures also have adverse effects. First, research careers have become increasingly unattractive: not only have real income opportunities for younger researchers been levelled downward, but also current changes in labor law have, in fact, erected new barriers to job mobility because researchers face real income (or pension scheme) losses when moving from one type of institution to another. Second, budget cuts have been accompanied by New Public Management (NPM) reforms that substitute hierarchical for academic control (Boer et al., 2007). In his analysis of such NPM reforms in the United Kingdom, Georghiou (2001: p. 294) argues that public research sector institutions have been converging in their research activities and profiles, thus narrowing the capabilities of the research system as a whole.

8. Discussion and conclusion

Our analysis started with the observation that the need for effective inter-institutional knowledge flows is critical in the emerging domain of nano S&T, where a sizeable share of research is conducted at the intersection of established scientific disciplines and across domains of fundamental and applied research. In addition, organizing effective knowledge flows is a particular challenge in institutionally segmented research systems, such as the GRS with a broad and differentiated extra-university research landscape. However, since little is known about the factors that influence the capability of public research systems to connect distributed knowledge and competencies across institutional and organizational boundaries, we investigated inter-institutional knowledge flows within the GRS in the domain of nano S&T.

First, we find that the majority of domestic research collaborations are observed between universities and the extra-university research sector, while co-authorship ties within the extra-university sector are tenuous. Our qualitative data suggests a more nuanced picture of collaborative relations including cooperation contracts between research institutes, joint junior research groups, or informal meetings of institute directors, particularly within the extra-university research sector. Second, we find that scientists collaborate primarily to expand and improve their research capacity, to benefit from institutional complementarities, and to enhance their visibility within the research field. Our findings add to collaboration motives identified by previous literature including curiosity, knowledge advancement, sharing the excitement of a research area with other scientists, or intellectual companionship (Katz and Martin, 1997; Beaver, 2001).

Third, we identify specific thematic profiles, recruitment of research staff, support for job mobility, research leadership, balanced core and third-party funding, and flexible mechanisms for funding allocation as institutional conditions that are conducive to inter-institutional research collaboration. In contrast, organizational stereotypes and prejudices, incompatible working routines anchored in diverse organizational missions, lack of interface management, and sustained budget cuts particularly in the university system, have had negative impacts on scientists' opportunities to engage in collaborative work relations outside their home institution.

Our empirical evidence suggests that the institutional structure of the GRS is permeable enough to allow sufficient knowledge flows in the emergent research domain of nano S&T between universities and the extra-university research sector. In fact, this seems one key explanation why Germany is among the top players in the global nanotechnology race. In recent years, the Max-Planck-Society and the Helmholtz-Association have taken several measures to improve collaborative relationships with universities, for instance via the establishment of new joint junior research groups, or contracts with universities that allow mutual access to instrumentation and library services, and the establishment of new research schools.

Sufficient knowledge flows cannot be observed, however, between organizations of the extra-university public research sector. Here many of the adverse effects of the segmented institutional structure, described in Section 6, are salient. The high level of segmentation becomes especially obstructive when, like in the case of the GRS, research systems operate both under output pressure and resource stagnation. Recent efforts to establish stronger collaborative relationships between the MPG and the FhG are exceptional and are not indicative of a paradigm shift within the public non-university research sector.

The strong position of German research in global nano S&T has also to do with the many collaborative ties to research labs abroad. Several of the studied research teams are active collaborators of groups in Europe, the United States and Russia. One key condition of these collaborations could be the gradual emergence of the "European Research Area" (Kuhlmann, 2001), but still only little is known about the institutional conditions (organizational cultures, funding systems, intellectual property rights regulations, career paths, or promotion criteria) for effective knowledge transfer in the public research sector (in nano S&T) across inherited national research systems—a field for future research.

Acknowledgement

This paper is based on research sponsored by the Deutsche Forschungsgemeinschaft (FOR 517). The authors gratefully acknowledge helpful comments on earlier versions of this paper from Dorothea Jansen, Uwe Schimank, Harry de Boer, Jürgen Enders, and one anonymous reviewer. Research assistance was provided by Martin Übelhör, Christian Pangert und Rebecca Rangnow.

Appendix A. Interview data

We conducted, in total, 32 semi-structured interviews between 2004 and 2006 with representatives of all non-university research organizations (except for WGL), the German Ministry for Education and Research (BMBF), institute directors at universities and extra-university institutions, and senior researchers and junior group leaders in the field of nano S&T. We conducted interviews primarily with researchers who were experienced in extramural collaborations, as displayed in their number of external project collaborations. Interviewees with few external contacts were also included. The average length of interviews is ca. 1.5 h. Interviews were fully transcribed and coded into dimensions and factors.

References

Ahuja, G., 2000. Collaboration networks, structural holes, and innovation: a longitudinal study. Administrative Science Quarterly 45 (3), 425–455.

Arnold, N., Groß, T., 2005. Die Entscheidungsstrukturen der Leibniz-Gemeinschaft - Ein Beitrag zur Governancediskussion im Forschungsbereich. Wissenschaftsrecht 38, 238–263.

Beaver, D.d., 2001. Reflections on scientific collaboration, (and its study). past, present, and future. Scientometrics 52 (3), 365–377.

Benz, A., 2007. Governance in connected arenas—political science analysis of coordination and control in complex rule systems. In: Jansen, D. (Ed.), New Forms of Governance in Research Organizations—From Disciplinary Theories Towards Interfaces and Integration. Kluwer, Dordrecht, pp. 3–22.

BMBF (Ed.), 2005. Bundesbericht Forschung 2004. Bundesministerium für Bildung und Forschung, Bonn.

Boer, H.d., Enders, J., Schimank, U., 2007. Orchestrating creative minds. The governance of higher education and research in four countries compared. In: Jansen, D. (Ed.), New Forms of Governance in Research Organisations. From Disciplinary Theories towards Interfaces and Integration. Kluwer, Dordrecht, pp. 130–146.

Bordons, M., Gómez, I., 2000. Collaboration networks in science. In: Cronin, B., Atkins, H.B. (Eds.), The Web of Knowledge. ASIS, New Jersey, pp. 197–213.

Brook, R., et al. (Eds.), 1999. Forschungsförderung in Deutschland. Bericht der internationalen Kommission zur Systemevaluation der Deutschen Forschungsgemeinschaft und der Max-Planck-Gesellschaft. Volkswagen-Stiftung, Hannover.

Calvert, J., Patel, P., 2003. University—industry research collaborations in the UK: bibliometric trends. Science and Public Policy 30 (2), 85–95.

Corley, E., Boardman, P.C., Bozeman, B., 2006. Design and the management of multi-institutional research collaborations: Theoretical implications from two case studies. Research Policy 35, 975–993.

European Commission, 2005. Some Figures about Nanotechnology R&D in Europe and Beyond. www.cordis.europa.eu/nanotechnology.

Georghiou, L., 1998. Global co-operation in research. Research Policy 27, 611–626.

Georghiou, L., 2001. The United Kingdom National System of Research, Technology and Innovation. In: Larédo, P., Mustar, P. (Eds.), Research and Innovation Policies in the New Global Economy. An International Comparative Analysis. Edward Elgar, Cheltenham, pp. 253–296.

Glänzel, W., 2001. National characteristics in international scientific co-authorship relations. Scientometrics 51 (1), 69–115.

Glänzel, W., Schubert, A., 2004. Analyzing scientific networks through co-authorship. In: Moed, H.F., Glänzel, W., Schmoch, U. (Eds.), Handbook of Quantitative Science and Technology Studies. Kluwer, Dordrecht, pp. 257–276.

Gornitzka, A., Kyvik, S., Marheim Larsen, I., 1998. Bureaucratisation of Universities. Minerva 36, 21–47.

Gruss, P., 2002. Grundlagenforschung als Basis für Innovation. In: MPG (Ed.), Jahrbuch 2002. Generalverwaltung der MPG, München, pp. 9–21.

Hagedoorn, J., Link, A.N., Vonortas, N., 2000. Research partnerships. Research Policy 29, 567–586.

Heinze, T., 2004. Nanoscience and nanotechnology in Europe: analysis of publications and patent applications including comparisons with the United States. Nanotechnology Law & Business 1 (4), 427–447.

Heinze, T., 2006. Die Kopplung von Wissenschaft und Wirtschaft. Das Beispiel der Nanotechnologie, Campus, Frankfurt a. M.

Heinze, T., Bauer, G., 2007. Characterizing creative scientists in nano S&T: productivity, multidisciplinarity, and network brokerage in a longitudinal perspective. Scientometrics 70, 811–830.

Hohn, H.-W., 1998. Kognitive Strukturen und Steuerungsprobleme der Forschung. Kernphysik und Informatik im Vergleich, Campus, Frankfurt a. M.

Hohn, H.-W., Schimank, U., 1990. Konflikte und Gleichgewichte im Forschungssystem: Akteurkonstellationen und Entwicklungspfade in der staatlich finanzierten außeruniversitären Forschung, Campus, Frankfurt a. M. und N.Y.

Hollingsworth, J.R., Boyer, R., 1997. Coordination of economic actors and social systems of production. In: Hollingsworth, J.R., Boyer, R. (Eds.), Contemporary Capitalism. Cambridge University Press, Cambridge, UK, pp. 1–47.

Hullmann, A., 2006. Who is winning the global nanorace? Nature Nanotechnology 1 (1), 81–83.

Hullmann, A., Meyer, M., 2003. Publications and patents in nanotechnology. An overview of previous studies and the state of the art. Scientometrics 58 (3), 507–527.

Jappe, A., 2007. Explaining international collaboration in global environmental change research. Scientometrics 71, 367–390.

Katz, S.J., Martin, B.R., 1997. What is research collaboration? Research Policy 26, 1–18.

Kuhlmann, S., 2001. Future governance of innovation policy in Europe—three scenarios. Research Policy 30, 953–976.

Landry, R., Amara, N., 1998. The impact of transaction costs on the institutional structuration of collaborative academic research. Research Policy 27, 901–913.

Laudel, G., 2002. What do we measure by co-authorships? Research Evaluation 11 (1), 3–15.

Laudel, G., 2006. The art of getting funded: how scientists adapt to their funding conditions. Science and Public Policy 33, 489–504.

Laudel, G., Gläser, J., 1998. What are institutional boundaries and how can they be overcome? Germany's Collaborative Research Centres as Boundary-Spanning Networks. Wissenschaftszentrum Berlin für Sozialforschung, Berlin.

Lee, S., Bozeman, B., 2005. The impact of research collaboration on scientific productivity. Social Studies of Science 35 (5), 673–702.

Lengwiler, M., 2006. Between charisma and heuristics: four styles of interdisciplinarity. Science and Public Policy 33, 423–434.

Luhmann, N., 1975. Die Weltgesellschaft. In: Luhmann, N. (Ed.), Soziologische Aufklärung 2. Westdeutscher Verlag, Opladen, pp. 51–71.

Lütz, S., 2003. Governance in der politischen Ökonomie. Politische Vierteljahresschrift 44, 231–243.

Melin, G., 2000. Pragmatism and self-organization: research collaboration on the individual level. Research Policy 29, 31–40.
Melin, G., Persson, O., 1996. Studying research collaboration using co-authorships. Scientometrics 36, 363–377.
Meyer-Krahmer, F., Schmoch, U., 1998. Science-based technologies: university-industry interaction in four fields. Research Policy 27, 835–851.
Newman, M.E.J., 2004. Who is the best connected scientist? A study of scientific coauthorship networks. In: Ben-Naim, E., Frauenfelder, H., Toroczkai, Z. (Eds.), Complex Networks. Springer, Berlin, pp. 337–370.
Owen-Smith, J., Riccaboni, M., Pammolli, F., Powell, W.W., 2002. A comparison of U.S. and European university–industry relations in the life sciences. Management Science 48 (1), 24–43.
Porter, A.L., Youtie, J., Shapira, P., Schoeneck, D.J., 2008. Refining search terms for nanotechnology. Journal of Nanoparticle Research, doi:10.1007/s11051-007-9266-y.
Powell, W.W., White, D.R., Koput, K.W., Owen-Smith, J., 2005. Network dynamics and field evolution: the growth of interorganizational collaboration in the life sciences. American Journal of Sociology 110 (4), 1132–1205.
Rafols, I., Meyer, M., 2007. How cross-disciplinary is bionanotechnology? Explorations in the specialty of molecular motors. Scientometrics 70, 633–650.
Röbbecke, M., Simon, D., Lengwiler, M., Kraetsch, C., 2004. Inter-Disziplinieren. Erfolgsbedingungen von Forschungskooperationen. Sigma, Berlin.
Schummer, J., 2004. Interdisciplinary issues of nanoscale research. In: Baird, D., Nordmann, A., Schummer, J. (Eds.), Discovering the Nanoscale. IOS Press, Amsterdam, pp.9–20.
Scheu, M., Veefkind, V., Verbandt, Y., Molina Galan, M., Absalom, R., Förster, W., 2006. Mapping nanotechnology patents: the EPO approach. World Patent Information 28, 204–211.
Senker, J., 2006. Reflections on the transformation of European public sector research. The European Journal of Social Sciences 19, 67–77.
Shapira, P., Kuhlmann, S. (Eds.), 2003. Learning from Science and Technology Policy Evaluation. Edvard Elgar, Cheltenham, UK.
Shinn, T., Joerges, B., 2002. The transverse science and technology culture:dynamics and roles of research-technologies. Social Science Information 41 (2), 207–251.
Steensma, H.K., 1996. Acquiring technological competencies through inter-organizational collaboration: An organizational learning perspective. Journal of Engineering and Technology Management 12 (4), 267–286.
Whitley, R., 2000. The Intellectual and Social Organization of the Sciences. Oxford University Press, Oxford.