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Rydberg-atom electrical-field sensors – a case study of dual use of quantum sensors

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Abstract

Rydberg atoms in a room-temperature gas cell can be used for very sensitive detection of electrical fields in the megahertz to terahertz region. Sensors can be small, non-absorbing and are not destroyed by very strong fields with full-optical readout. Applications in communications, imaging and radar, and in metrology are foreseen. Military research is active, particularly in the USA, funding at first academic institutions, but increasingly development is contracted to commercial firms. There are similarities and differences between civilian and military applications, with interaction between both fields. Rydberg-atom electrical-field sensors are a general-purpose technology, and do not directly provide new offensive or threatening military options. No strong negative impacts on international security and peace are foreseen. Academic researchers have taken military funding readily.

Keywords: Rydberg atom; Electrical field; Radio frequency; Sensor; Dual use

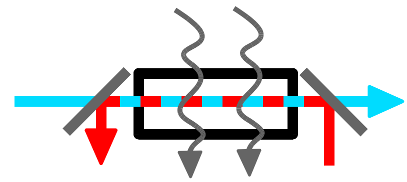
1 Introduction

Quantum technologies promise fundamental change in many areas of society – in private life, industry, government, and the military. Quantum computing could break many existing ciphers and help in the design of new materials. On the other hand, quantum communication could make information exchange secure. Quantum sensing could become much more sensitive and accurate. Armed forces could use these technologies in many areas of combat and its preparation [1]. To take advantage from them, quantum technologies have become a topic of high interest in military research and development in many countries. Military applications can bring dangers for international security and peace that should be investigated thoroughly; e.g., quantum sensing could endanger the second-strike capability of nuclear weapon states [2].

A special area of sensing concerns electromagnetic fields that could be used in communications, direction finding, imaging and electronic warfare. Here Rydberg atoms – once a field of fundamental physics research – have come to the fore in military research and development.

Rydberg atoms are atoms with at least one electron excited to a high principal quantum number n. They offer unique properties for applications in sensing and quantum technologies in general. Long radiative lifetimes, scaling with n^3, are beneficial for quantum

Figure 1 *Schematic view of a Rydberg vapour-based sensor.* Two lasers for the Rydberg excitation pass through a vapour cell filled with alkali atoms in a counter-propagating geometry while microwaves illuminate the cell from the side



computing as well as sensing. These atoms offer large dipole moments, scaling with n^2, for transition frequencies, scaling with n^{-3}, covering the MHz to THz range. Rydberg atoms are being investigated for several uses, e.g. in ultracold traps as qubits. Rydberg atoms can be used for sensing different modalities – electric field, magnetic field, temperature, pressure [3]. Here we focus on electrometry using normal-temperature alkali gases [4], apparently an application of high military interest and closest to actual use.

The article is structured as follows: Sect. 2 describes the working principle, Sect. 3 gives potential civilian and military uses. Military research and technology development are the subject of Sect. 4, with special emphasis on the USA. Development of concrete systems is covered in Sect. 5. Section 6 discusses civil-military connections. A military-technology assessment under viewpoints of international security and peace is given in Sect. 7. Section 8 discusses academic research and attitudes towards military work, and Sect. 9 gives a short conclusion.

2 Rydberg-atom electric-field sensors

The large dipole moments and long lifetimes make Rydberg atoms ideal candidates for sensing electric fields in the MHz to THz frequency region. While cold atoms usually are the system of choice for precision measurements and quantum computing, small sensors are desirable for real world applications, giving thermal vapours a significant advantage when it comes to SWaP-C (size, weight, power and cost) considerations for future devices. A few mm sized vapour cell filled with alkali atoms in combination with optics for two laser beams is already enough to build a microwave sensor based on Rydberg vapour, see Fig. 1. Alkali atoms (such as Rb, Cs) are typically used, at room temperature, with pressure around 10^{-3} mbar (0.1 Pa).

These cells only consist of dielectric materials, especially no metal parts and no other conducting materials are used. This already reduces the interaction of the electric field with the cell a lot. The whole setup is almost transparent for the incoming field. Still, a lot of additional effort has been put into the reduction of radar scattering cross sections and minimizing the effects of the cell walls on the electric field even further.

The measurement technique is based on measuring a frequency splitting of an atomic level induced by the microwave electric field. To do so, a probe laser monitors the absorption on a ground state transition, for example the D2 line of Rb in Fig. 2 (red transition at 780 nm). The second laser (blue transition at about 480 nm) couples the excited state to a Rydberg state specific for the microwave frequency to be measured, covering the range from 1 GHz to several THz for n ranging from 20 to 90 [5]. This respective microwave then couples the Rydberg state to another Rydberg state of the same or different n. This coupling can be transformed into a level splitting of the |r> state in a dressed state picture, the so called Autler-Townes splitting. It is important to notice, that this splitting in frequency is always equal to the Rabi (angular) frequency induced by the microwave in

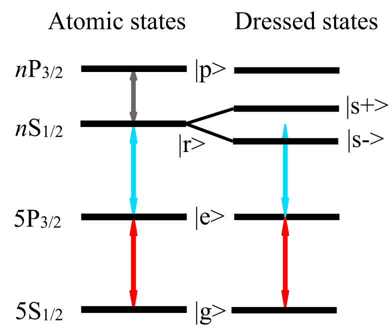


Figure 2 *Level scheme used for Rydberg based microwave sensing.* The probe laser couples the ground state |g> to the excited state |e>. The Rydberg laser then couples |e> to the first Rydberg state |r>. The microwave then couples |r> to another Rydberg state |p>

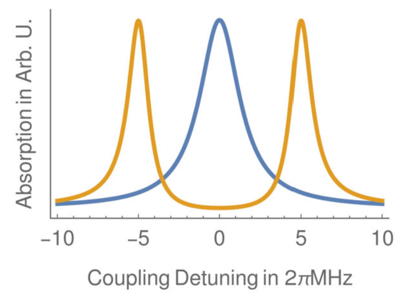


Figure 3 *Microwave induced splitting.* For a microwave Rabi frequency of $\Omega_{\mathrm{RF}} = 10 \times 2\pi$ MHz (yellow) two distinct transmission peaks can be identified, that are split symmetrically by Ω_{RF} around the original peak without microwave applied (blue)

the atomic states picture given by $\Omega = E\mu/\hbar$, were E denotes the microwave electric field strength and μ the transition dipole moment of the |r> to |p> transition, see Fig. 3.

While in the Autler-Townes regime the two absorption peaks are fully split and full electromagnetically induced transparency (EIT) on the original resonance is achieved, for lower Rabi frequencies these absorption peaks start to merge. For low enough Rabi frequencies, the only signal left is a change of absorption on resonance but no peaks can be identified anymore. This is the so-called amplitude regime. Nevertheless, even in this regime, the sensor operation is feasible and almost exact analytical formulas can be found in the weak probe regime [6].

While the main research focus is centered on sensitivity, in other words on the amplitude of the microwave field in the Autler-Townes-Regime as well as in the EIT-like amplitude regime [7] with a detailed summary in [4], extensions to more lasers can be used to reduce the effect of Doppler broadening [8]. All electric-field properties are nowadays accessible by all-optical Rydberg sensors. The polarization can be determined by making use of selection rules in the hyperfine manifold of Rydberg states [9], and recently phase detection was proposed in an all optical closed-loop system [10], not constrained by the limited carrier bandwidth that approaches with additional microwave (MW) fields suffer from. In combination with precise determination of arrival times [11], applications in radar and communication are possible.

One important aspect is the design of the vapour cells. On the one hand, the influence on the measured field can be minimized by choosing the right size and electromagnetic properties of the material [12]. On the other hand, having a small radar cross section avoids detection of the antenna itself and minimizes the influence on other vapour cell detectors nearby. In this way a denser packing of detectors can be achieved and smaller overall sizes of MW sensor heads possible.

3 Potential civilian and military uses

Rydberg-atom electric-field sensors provide several advantages: They can be more sensitive than traditional dipole antennas. The receiving area is very small, which is particularly relevant when wavelengths get in the millimetre range and below (frequencies of 30 GHz and above). The dielectric design makes them transparent and non-absorbing for the microwaves. Due to the high density of the Rydberg energy levels one sensor can cover a very broad bandwidth. Since the absolute field strength is directly linked to the transition frequencies, the former can be measured without the need for prior calibration. The atoms and the glass cell are insensitive to very strong fields, e.g. produced by high-power microwave weapons or the (nuclear) electromagnetic pulse; the control and readout can be fully optical via fibres, with the associated electronics in a fully shielded metal enclosure. Finally, the size, weight, power requirement and cost can be very low, allowing systems to be portable or integrated in small carriers, in particular if systems will be integrated with centimetre size.

Several civilian applications can be foreseen: receivers in microwave and general wireless communications, including for outer space (whether general use in cell phones [13] will turn out practical is unclear); receivers in imaging and radar systems where the receiving beam is formed by an array of sensing elements (the transmitters will still have to use traditional antennas with dishes). The measurement capacities can be used in metrology and in the design and optimisation of antennas, especially with near-field measurement capabilities. Research provides additional fields of use.

Military applications can be foreseen in many areas: Small receivers are less noticeable and better protected. Enemy communication and radar signals can be detected at all relevant frequencies, including fast frequency changes and scans. Imaging and radar receivers are relevant. All kinds of receivers will be central for electromagnetic warfare.

The relative size of the military and the civilian markets will depend on the respective scales of deployment which are difficult to assess at present.

4 Military research and technology development

Rydberg atoms have been a topic of academic, fundamental research for decades, including the idea of microwave detection. A decisive innovation came when the group at the 5th Institute of Physics (PI5), University of Stuttgart, in collaboration with the group at Oklahoma University went from cold atoms to room-temperature gas cells. The group – after a collaborator had moved back to the US – was supported by the US Defense Advanced Research Projects Agency (DARPA) early, at first rather on the sidelines (see 8). After the 2012 paper [14], sensing-focussed DARPA funding increased strongly, so that military research took up an increasing share of the activities.

Countries differ widely in what information on their military research and development (R&D) they make available. The USA is most transparent, in many cases programs, projects and budgets are published; academic groups with military funding generally publish their results at conferences and in scientific journals. Furthermore, a large portion of scientific funding in general is handled by military itself or organizations closely related. For these reasons and because the US activities seem the biggest, they are described below in some detail.

Table 1 *Teams selected for the DARPA SAVaNT programme* [21]. RyEl: Rydberg Electrometry, VcMg: Vector Magnetometry, vQED: Vapor Quantum Electrodynamics. Contract totals by search for Science of Atomic Vapors for New Technologies in [22], several contractors could not be found

Firm – location	Field	Contract total
ColdQuanta, Inc. - Boulder, Colorado	RyEl	-
Georgia Institute of Technology - Atlanta, Georgia	vQED	-
Quantum Valley Ideas Laboratories - Waterloo, Ontario, Canada	RyEl	$6.5 m
Rydberg Technologies - Ann Arbor, Michigan	RyEl	$4.0 m
Twinleaf LLC - Plainsboro, New Jersey	VcMg	$2.0 m
University of Colorado - Boulder, Colorado	VcMg	-
University of Maryland - College Park, Maryland	vQED	-
William & Mary - Williamsburg, Virginia	VcMg	-

4.1 Military research and technology development in the USA

In the *USA*, the most systematic military research and technology development is organised by the DARPA. Its general mission is "[t]o create technological surprise for U.S. national security." [15] DARPA has supported work in quantum science and technology since the 1990s; in the 2000s atomic clocks became a focus [16]. In the sensing field the programme Quantum-Assisted Sensing and Readout (QuASAR) was active from 2010 to 2018 [17] to develop a suite of measurement tools and atom- and atom-like sensors [18]. Based on the results, after some break, in 2020 the programme Science of Atomic Vapors for New Technologies (SAVaNT) was started, geared towards technology development; the goal is to use atomic vapours at room temperature [19]. In September 2021 eight teams were selected [20] with contract sums of several $ million each (Table 1). Phase 1 is to demonstrate the physics while phase 2 aims toward an integrated benchtop package, in three technical areas: Rydberg electrometry, vector magnetometry and vapour quantum electrodynamics. Warm vapours of alkali atoms are central in all three. High sensitivity and low size, weight and power are important goals.

A second programme was started more or less in parallel: Quantum Apertures (QA). It aims at a portable radio-frequency receiver operating over the frequency range from 10 megahertz to 40 gigahertz or more, with the sensor element in a one cubic centimetre package [23]; the selected teams are led by Honeywell, Northrop Grumman, ColdQuanta, and SRI International.

Based on first results from the SAVaNT programme, in 2024 DARPA has started the parallel programme Enhancing Quantum Sensor Technologies with Rydberg Atoms (EQSTRA) for rapid progress to Rydberg sensors [24]. Other programmes are devoted to robust functioning in real-world conditions with e.g. vibrations or electromagnetic interference [25] and to quantum testbeds [26].

Among the research branches of the armed services, the US Army is most active, in particular by its own Army Research Laboratory, theoretically and experimentally, e.g. [27, 28].

4.2 Military research and technology development in other countries

In other countries with interest in high technology for their armed forces, the picture differs. In order to find instances of military research, we searched in Web of Science for "Rydberg (sensor* OR RF OR "radio frequency")"; the 498 articles found were refined to the Countries/Regions, yielding authors from 41 countries. For the 22 countries (excluding the USA) with 4 or more entries, we further refined to Affiliations and to Funding Agencies, looking for military institutions or military funding. A coarse view served to select the articles treating room-temperature RF sensing. In case of authors from several countries or institutions, the article was assigned according to the place where (most of) the work had been done. This procedure accepts a few possible misclassifications, but should suffice for a first overview.

For China this yielded 29 articles of which 26 came from the National University of Defense Technology, starting in 2022, e.g. [29, 30]. But there also articles with an author from the PLA (People's Liberation Army) Strategic Support Force Information Engineering University or the Air Force Engineering University [31, 32]. This can be a consequence of the high priority that China has given quantum technologies on the highest level, including for the military [33]. One can presume that development of technology and of concrete systems is underway.

Concerning *Russia*, we did not find military research, but some civilian, academic research is going on, e.g. [34]. The Russian Quantum Center [35] does not seem to work in this area, rather focusing on quantum computing. Given the extensive US efforts it is reasonable to assume that some military work is being done in Russia without publications.

For *Canada*, we found 15 articles, with US and Canadian defence funding. In *France*, there was one [36], the same with *Australia* [37]. US support was found in *Poland* [38]. No military funding or work at military institutions was found in: Austria, Denmark, England, Germany, India, Japan, Scotland, Singapore and Switzerland.

Of course, a lack of scientific publications does not mean that military research is not undertaken. It is probable that countries with high-technology armed forces do such research in secrecy. Wider-ranging internet search could bring additional information. E.g., in the *European Union* the European Defence Fund (EDF) has a major quantum project underway, but in the RF sensing part Rydberg atoms seem not to play a major role [39, 40].

5 System development

Development of actual military systems seems still some time off. Civilian devices are beginning to be offered commercially. One firm advertises "the world's first atomic RF sensor", the "Rydberg Field Measurement System" for atomic spectroscopy, spanning a frequency range of "over 6 orders of magnitude"; it consists of an "RF field probe (RFP) connected to a mainframe control unit with a ruggedized fiber-optic patch cord"; also offered are vapour cells [41].

Another developer of Rydberg-atom RF sensor systems describes the properties to be expected from commercial devices by mentioning "self-calibrated", "MHz, GHz, THz range", "can be made in practically any size and geometry", "novel photonic crystals (PC) that amplify the RF fields with which the atoms interact"; a "commercial-ready prototype is being transitioned to Ideas Lab's first startup" [42]. This firm is "commercializing quantum sensors" with caesium-filled vapour cells, but a commercial device is not yet offered [43].

6 Civil-military connections

6.1 Similarities and differences

There are similarities and differences between civilian and military applications of Rydberg-atom RF sensors. These have to be deduced from the present state, still mostly research and development.

Similarities concern the fundamental principles and the basic technology. From the different requirements in both realms follow several differences.

Size, Weight, Power:

For many civilian applications there is no need to mount them on a mobile platform, and they need not be very small; weight and power will not present limits in such cases. A small probe head may be useful for many applications, but transmitting the laser frequencies through optical fibres can allow flexible connection to a bigger control unit. Whether the idea of having Rydberg-atom RF sensors integrated in mobile phones [44] can materialise remains to be seen, there can be significant hurdles with size, complexity and cost. Even if laboratory experiments have demonstrated reception of standard modulated radio emissions (analogue with amplitude or frequency modulation, digital with phase-shift keying) [45], it is unclear if Rydberg-atom sensors can become a cost-effective alternative to the established antennas and electronic circuits.

In several military applications size would not present a problem either, e.g. when the receiving antenna of a radar system would be replaced by an array of Rydberg-atom sensors – it would need the same overall size to achieve the same beam angle – and the emission antenna of similar size would remain the same anyway. Here weight and power would not create problems as well.

But smaller size, weight and power can become decisive if the receiving system is to be placed on small (uncrewed) vehicles/platforms.

Electromagnetic hardening:

Very strong electromagnetic waves impinging on sensitive electronic components and circuits can induce electric currents that can produce damage by overheating or by electrical discharge. Waves of such strengths can be produced in a large area by a nuclear explosion outside of the atmosphere [46]. For achieving similar effects over much shorter distances (tens to hundreds of metres) special EMP weapons have been constructed, some of them use high-power microwaves (HPM) [47].

In a civilian context both types of EMP need not be taken into account, the same holds for protection against HPM weapons. The normal measures for electromagnetic compatibility will suffice.

On the other hand, military applications, in particular those to be used close to enemy systems or under conditions of nuclear war, need to be protected. Whereas the Rydberg-atom sensing element itself and the optical fibres carrying the laser frequencies to and from it are not affected, the control electronics needs to be hardened, leading to higher cost than for civilian systems. But this would not be qualitatively different from the measures that are being taken routinely for traditional military electronics.

Temperature, Acceleration, Vibration:

While many civilian applications will work in static conditions and in normal temperatures (exception are possible for research in arctic climates, at high altitudes, using drones), many military devices will be mounted on mobile platforms and need to work in very different climates and weathers. Thus, special measures will be needed to ensure functioning in a wide temperature range and in the presence of accelerations and vibration. Military specifications for Rydberg-atom sensors will be much stricter than civilian ones.

Cost:

In a civilian context, cost of development as well as cost to the customer are central criteria. While enterprises or research institutions can tolerate high prices for specific measuring equipment, systems for use by general consumers need to be affordable for the latter. At least here the extent of sophistication is limited usually, unless cheap methods of series production have been developed.

Military technology, on the other hand, is motivated by the highest national interest, up to national survival. Thus cost is a secondary thought, and the motive to gain or keep the upper hand in armed conflict usually takes precedence. This justifies not only special efforts for hardening or reducing the size, but also for using cutting-edge technologies.

Other aspects:

Military systems should work in environments with nuclear radiation, chemical or biological agents, thus some protection is built in often. Military systems should be resilient under attack, continuing to function even if parts have been destroyed.

Thus, while basic research can support both kinds of application, the paths separate when it comes to technology development and, all the more, to systems development. But mutual support is still possible. One example would be a new production technology for atom cells, at first established with military funding and then transferred to the civilian side. In the other direction, somewhat fictitiously, mass-produced goods could find uses in military systems, as in other cases of commercial off-the-shelf equipment.

6.2 Dual use, civil-military interaction

Civilian academic research funding has shown the principal possibilities of RF sensing by Rydberg atoms. The next step, technology development, was made possible by military funding. It is unclear if corporate money would be invested for development of the technology and then of actual products, since there is an established antenna-receiver technology with good properties, and the market for new kinds of RF sensors in the civilian sector is small. Public funding would be needed, at least the 50% sharing of development cost often used in funding by the European Union and the German Federal Ministry of Research, Technology and Space (BMFTR).

Without such civilian funding it is questionable if Rydberg-atom RF sensor systems would arrive if there were no military funding. But it is noteworthy that there is systematic co-ordination between defence ministries and those for civilian research (for Germany see e.g. [48]), so that the latter may decide to not invest additional money and rather wait for what will come out of the military funding.

In any case the firms that have taken military funding will try to develop products for both sectors, with modifications according to the respective requirement. It is to be expected that in further development, improvements in one sector will be transferred to the other, e.g. by exchanges between the respective teams within firms.

As with traditional antenna-receiver combinations, the technology of Rydberg-atom RF sensors is general purpose, thus separation of civilian and military uses at the technology level is not really possible. Dual use may not be applicable, however, to finished products which reflect the respective application needs. Such characteristics are typical of general-purpose technologies, with a wide span of the degree of generality – from steel or the transistor on one end to explosives or turbine materials on the other.

7 Military-technology assessment

For an assessment of the potential effects of Rydberg-atom RF sensors on international security and peace, one can use the criteria of preventive arms control that have been used for many other new military technologies [49, 50]. Sensors are in a different category than weapons, thus the considerations differ qualitatively.

In the field of *arms control, disarmament and international law*, direct *dangers to existing or intended treaties* are not visible.

A positive contribution would be possible theoretically if the sensors would provide for better verification of compliance, but electromagnetic signals are normally not part of the regulations. There is one field where signal detection is included, namely with respect to telemetry from ballistic-missile tests for which the New Strategic Arms Reduction Treaty (New START) of 2010 stipulates exchanges of recordings for certain missile launches, without the signals being part of compliance verification [51]. The Treaty has expired in February 2026, and Russia had "suspended" its implementation in 2023 [52]. If similar telemetry rules were contained in a potential follow-up treaty, the existing antennas and receivers suffice for the task, so Rydberg-atom sensors would not bring qualitative change.

Concerning verification from satellite by radar, it is conceivable that Rydberg-atom sensors would allow shorter wavelengths with better spatial resolution, but optical imaging with around 10 cm resolution is easier and suffices for relevant military objects and installations.

On intended treaties, one can speculate that more sensitive RF reception could find indications for the presence of military systems in off-limits areas from satellites better than existing receivers and could thus help in verifying compliance with new nuclear-weapon free zones e.g. on the oceans. But again optical detection of surface ships is a well-established method; submarines pose a general problem because electromagnetic waves are strongly absorbed by seawater.

Concerning indirect effects on treaties, no clear picture comes to mind.

With respect to the *existing norms of international humanitarian law* (the laws of warfare), new types of RF sensors do not pose problems, neither directly nor indirectly.

Concerning the question of *utility for weapons of mass destruction*, there is no direct connection. Indirectly more sensitive RF sensors could bring some improvement to the use of nuclear weapons. (While the prohibition of biological and chemical weapons is widely accepted, the Treaty on the Prohibition of Nuclear Weapons is rejected by the nuclear-weapon states and those who have foreign nuclear weapons on their territory.)

Principally, there could be a positive function for the nuclear-weapon ban if verification could be linked to specific RF emissions, but this is speculative at present.

In the field of *military stability*, Rydberg-atom RF sensors would not directly lead to destabilisation. This is markedly different from quantum-technology sensors that would allow detection and localisation of strategic submarines, e.g. by magnetic- or gravity-field disturbance. Indirectly, better RF receivers could be used in intelligence, e.g. for finding and localising RF emitters. This could allow more effective attack; this possibility could increase threats. The advantage of striking first could appear more attractive, with the corresponding fear that the adversary would use it and the pressure to pre-empt in a hard crisis. On the other hand, a better view of the adversary could give assurance that an attack is not imminent with potentially less fear and pressure of pre-emption.

With respect to dangers from a *technological arms race*, in some sense it has begun already, but still mostly at the stages of research and development. As first countries will deploy Rydberg-atom RF sensors in their armed forces, the mutual competition will likely intensify. Indirectly the prospect of better target finding can instigate work for new kinds of weapons that use the additional information. In particular a race in tools for electronic warfare is possible, where the armed forces strive for on the one hand better detection of enemy emitters, but on the other hand for better protection of one‘s systems.

Concerning *horizontal or vertical proliferation or diffusion* of Rydberg-atom RF sensors, it will likely occur, because of the military interest in better information. It will be alleviated by dual use so that export controls will have only limited effects.

With respect to *humans, environment and society* in peace time, no direct negative effects come to mind – the used substances are not more toxic or otherwise dangerous than many used e.g. in semiconductor production. Indirectly one can think of second- and third-order effects of better RF receivers, but this is very speculative.

In sum, the addition of Rydberg-atom RF sensors to armed forces would be part of their usual technological advance. Big dangers specifically tied to them are not seen, thus there are no strong reasons for introducing preventive-arms-control measures for them, and considerations of special methods or means of verification of compliance are not needed. Problems are rather created by new offensive technologies, use of artificial intelligence and the acceleration of battle tempo, so limitations should be directed at these [53].

Generalising this thought: Military threats arise mostly from offensive weapons, and these have been the subject of the arms-control treaties since the 1960s. In the field of sensing, it seems obvious that passive listening/observing generally will be perceived as less intrusive and less threatening than the use of active systems that illuminate the scene. (There may be exceptions, e.g. passive sonar used for the localisation of submarines on stealthy platforms that would not betray their presence by active emission; they might make attack easier.)

Does it make sense at all to co-operatively limit sensor capabilities? Probably only in rare cases, in particular if such limits are connected to limits on weapon systems. There is one important example in the Anti-Ballistic Missile (ABM) Treaty (1972-2002) – here defence capabilities were limited in relation to offence ones. ABM radars and early-warning radars were limited in number and location. As a measure of the "potential" of a radar its power-aperture product, i.e., the mean power times the antenna area, was defined. This is a rough measure of the signal strength at a distance, depending on the emitted power and the beam opening angle (which has to do with the wavelength divided by the antenna diameter, a bigger antenna produces a narrower emitted beam). This definition uses the characteristic of the emitting antenna which consists of an array of many individual emitting elements. It would still apply if the traditional, electric antenna elements in the receiving array were replaced by Rydberg-atom sensors. The potentially much smaller individual sensors would not significantly change the properties of the receiver antenna array, the size of which is roughly similar to the one of the emitting array, needed for achieving a receiving beam that is narrow, too.

But these limitations are an exception, tied to the offence-defence relationship with (nuclear) ballistic missiles, and the ABM Treaty was abrogated 2001/2002 anyway. It is difficult to conceive of agreed limitations on other military radars, deployed on the ground, on ships, on aircraft or on satellites.

8 Academic research and attitudes towards military work

As stated, the idea of using Rydberg atoms in room-temperature gas cells for RF sensing can be traced back to the PI5 and Oklahoma groups and their early application to the US DARPA QuASAR programme that had had rather different goals. The motive had been to secure funding for continuing the co-operation with a PI5 guest researcher who had moved to the University of Oklahoma; a European funding had not seemed promising at the time. This collaboration is continuing to work on this topic at Quantum Valley Ideas Laboratories in Canada. Following the article of 2012 co-authored by one of us [7], military interest from the DARPA increased soon (see 4.1). In the next decade, university groups in the US and several other countries applied for support in the various DARPA programmes that followed each other, and in corresponding programmes of the research institutions of the US Army, Navy and Air Force. In academic publications, such support is usually mentioned in the acknowledgements, sometimes with the respective contract numbers (see 4.1, 4.2).

Following the development and use of nuclear weapons, after 1945 in physics worldwide there was a feeling of responsibility and a considerable movement for nuclear disarmament. Connected to this was some restraint towards work for nuclear weapons, with exceptions mainly in nuclear-weapon states. This carried over to other natural sciences and more general military work, in particular in non-nuclear-weapon states. Hesitation derived also from the academic ideal of transparency and free international exchange. In Germany many universities concluded civil clauses, increasingly after the end of the Cold War [54][1], but not all.[2]

It seems that Rydberg-atom researchers in academia took military funding readily, maybe viewing it as just one more source of funding for their research, including salaries of doctoral students and post-doctoral scientists. Particularly in the USA one factor may be the tradition of such support. Among the considerations may have been that such work is not directed at weapons, that Rydberg-atom sensors would be just another kind of antenna, and that publication of results was not impeded. The latter usually is an important precondition for participation for most of the groups in academia.

As US military funding is increasingly directed towards system integration and miniaturisation, that is, moving from research to technology development, the tasks are growing beyond the capabilities of academic research groups, and big armament firms are taking over increasingly. Correspondingly, the contract sums are no longer in the hundreds of thousands, but amount to many millions of dollars. Academic research may then direct its interest to other aspects of Rydberg atoms, e.g. cold atoms for quantum computing, Rydberg-Rydberg interactions and optical nonlinearities in vapour cells.

9 Conclusion

Rydberg-atom radio electric-field sensors are an example where curiosity-driven, fundamental research found something that is then realised as having potential military uses. Such research is scanned most systematically in the US, predominantly by the DARPA, other countries follow. As a next step, military funding often goes to academic institutions, motivating and enabling deeper research, in many cases already with a view towards applications. When the expectations are fulfilled, then the military turns to technology development and, given further positive results, to development and testing. The latter usually are no longer done under research agencies, but are contracted by the armed services.

[1] Recently there is a counter-movement in the context of the "Zeitenwende".

[2] E.g. the University of Stuttgart does not have a civil clause whereas the TU Dortmund University does.

Within quantum technologies, Rydberg-atom RF sensors are a small subfield, but with considerable funding. They have much fewer applications and less far-reaching implications than other fundamental-research results, such as the laser [55], not to speak of the discovery of nuclear fission. Nevertheless, this case sheds light on the interaction between fundamental research and military applications and on the process of converting insight of the former to the latter.

Since fundamental research is open by definition, it can happen, and principally cannot be avoided, that fundamental researchers find something with potential military applications. But transforming principal knowledge into actual military systems requires many additional steps and significant resources. How far academic researchers engage in the latter steps depends on funding and on their motivation, including ethical considerations.

Abbreviations
ABM, Anti-Ballistic Missile; ANR, National Research Agency (France); Cs, caesium; DARPA, Defense Advanced Research Projects Agency (USA); EDF, European Defence Fund; EIT, electromagnetically induced transparency; EMP, electromagnetic pulse; EQSTRA, Enhancing Quantum Sensor Technologies with Rydberg Atoms; HPM, high-power microwave; MW, microwave; New START, New Strategic Arms Reduction Treaty; PC, photonic crystal; PI5, 5th Institute of Physics (University of Stuttgart); PLA, People's Liberation Army; QA, Quantum Apertures; QuASAR, Quantum-Assisted Sensing and Readout; R&D, research and development; Rb, rubidium; RF, radio frequency; RFP, RF field probe; SAVaNT, Science of Atomic Vapors for New Technologies; SWaP-C, size, weight, power and cost.

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JA wrote most of the text, HK wrote a part of the introduction and Sect. 2. Both edited the full text.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

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