

An Exploration of 2-D Coulomb Crystals in Quantum Computing

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In the nearly 20 years since Cirac and Zoller demonstrated that laser-cooled ions confined to a linear trap could be used to implement quantum gates, ion trapping has proven to be a suitable platform for practical quantum computation [1]. It didn't take long to show that each of the main DiVincenzo criteria (excluding those concerning flying qubits) can be satisfied by trapped ion systems, including single-qubit and multi-qubit gates [2]. Long trap lifetimes and internal-state coherence, along with strong interactions between ions, make it possible to achieve control and measurement with extremely high fidelity. At this point in time, the largest hurdle facing trapped ion quantum computing (and most other paradigms) is scalability, with some of the most advanced models being comprised of tens of qubits [3]. In this paper, I will explore the use of 2-D Coulomb crystals of trapped ions for increasing the scale of future quantum processors [4, 5].

Keywords: trapped ion, Coulomb crystals, quantum computing

I. THE SPECTRUM OF TRAPPED IONS

The foundation of any quantum computer is the qubits. Physical qubits can take many forms, from superconducting circuits made of Josephson junctions to topological qubits—an interesting new approach that utilizes quasi-particle excitations known as anyons. Regardless of form, our concern is with two-level quantum systems in which one state of the qubit can be readily distinguished from the other. When examining trapped ions as a candidate qubit, we have a choice on what atom and isotope we use, and the various interactions within those atoms will lead to different forms of energy level splitting in the internal electronic states [2].

There are four primary domains on the spectrum of energy level splitting. Zeeman qubits (which utilize an applied field for splitting magnetic sublevels) have energy splitting on the order of tens of megahertz. Hyperfine qubits, which depend on the hyperfine energy levels of atoms arising from nucleus-electron interactions, have states separated by gigahertz, and are known for having long coherence times [6]. Fine structure qubits, separated by tens of terahertz, display energy splitting due to the electron spin and relativistic effects. Finally, there are optical qubits whose energy levels are separated by up to hundreds of terahertz. These have properties which are advantageous to long distance entanglement mediated by photons [7].

We'll take a look at each of these categories in more detail to discuss the mechanisms which drive them, their respective strengths and weaknesses in general, and examine their potential applications within a 2-D Coulomb crystal framework.

A. Zeeman Qubits

At the lower end of the energy splitting spectrum are Zeeman qubits. The isotopes chosen for this type of

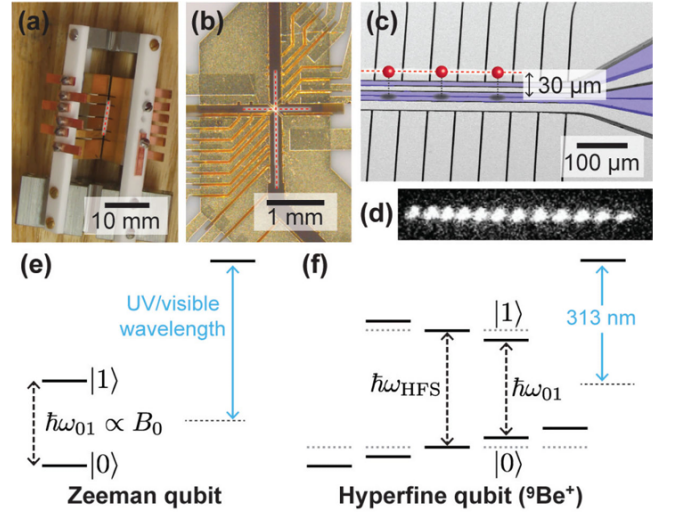


FIG. 1. (a, b) Two types of machined 3D traps. (c) Schematic of a surface-electrode trap. Shown in blue are integrated microwave antenna structures that allow for qubit control. The red spheres are ions, each in its own trapping potential well. (d) Real image of ions in a linear trap exhibiting fluorescence due to laser excitation. (e, f) Energy level diagrams comparing Zeeman qubit transitions to the closely related hyperfine qubit transitions. From *Microwaves in Quantum Computing* [8].

trapped-ion qubit are characterized as not having a nuclear spin. In this scenario, the two-level quantized states of the qubit are realized by the spin states of the ground state valence electron subject to an external magnetic field. We can do a quick calculation of the qubit resonance frequency, ω_{01} , in proportion to an external magnetic field, B_0

$$\frac{\omega_{01}}{2\pi} = \frac{\gamma_e}{2\pi} |B_0| \quad (1)$$

where we've used $\gamma_e/2\pi \approx 28 \text{ GHz T}^{-1}$ as the electron gyromagnetic ratio. This tells us that Zeeman qubits,

with frequencies of ~ 10 MHz, can be operated in magnetic fields < 1 mT. As we'll see later, hyperfine qubits can also be operated in similarly small magnetic fields (but may require larger fields for higher-mass ions). Some ions which lend themselves to acting as Zeeman qubits are $^{174}\text{Yb}^+$ and $^{137}\text{Ba}^+$ [7, 9].

The low-frequency energy splitting, and subsequent weak magnetic field required to induce a transition, would seem to make Zeeman qubits sensitive to fluctuations in the magnetic field. That is indeed the case, and dephasing can occur for trapped ion qubits, and Zeeman qubits especially, due to deviations in the applied magnetic field. It can be shown that the first-order effects induce a shift in the frequency according to

$$\Delta\nu = \frac{g_s\mu_B}{\hbar}\Delta B \quad (2)$$

where $\Delta\nu$ and ΔB are the changes in frequency and magnetic field respectively, g_s is the Landé g-factor, μ_B is the Bohr magneton, and \hbar is the reduced Planck constant. As such, magnetic field noise is a significant source of dephasing in Zeeman qubits, and the main disadvantage for using Zeeman qubits in quantum computing applications [8, 9].

However, even with that downside, Zeeman qubits offer the advantage of being resistant to leakage errors. Leakage occurs when a system contains additional states which are not used for the qubit states. Hyperfine qubits, for example, may be insensitive to first order magnetic fields, but they suffer from spontaneous scattering resulting from stimulated Raman processes that can lead to leakage (See Fig. 2). When dealing with quantum error correction, it becomes important to account for leakage out of the qubit subspace. In situations where the magnetic field can be sufficiently stabilized, ≤ 10 μG , it has been shown that Zeeman qubits exhibit a lower logical error rate when compared to similar hyperfine qubits [9].

B. Hyperfine Qubits

Moving up the scale, we encounter hyperfine qubits, which are characterized by the interaction between their valence electron spin and nuclear spin that produces a splitting in otherwise degenerate energy levels. For example, in the $^2\text{S}_{1/2}$ ground state, hyperfine splitting will produce two distinct energy levels corresponding to the difference in total angular momentum quantum number F .

Hyperfine qubits offer greater resistance to magnetic fields but at the cost of leakage into additional unwanted states. Similar ions can be used for hyperfine qubits as for Zeeman qubits, Yb^+ being a common example, where the difference in qubit type results from the different nuclear spins amongst different isotopes. This difference in spin is due to the number of nucleons. An even number of nucleons, each with spin $1/2$, will pair off to give a total nuclear spin $I = 0$. However, in isotopes with an odd

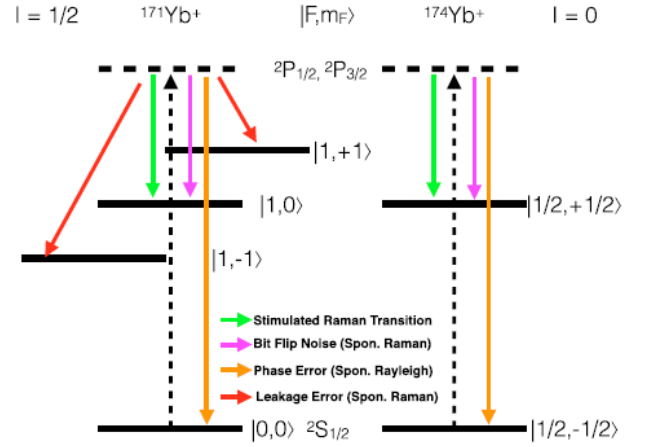


FIG. 2. Energy level diagram for $^{171}\text{Yb}^+$ and $^{174}\text{Yb}^+$ ions showing the potentials errors that can occur for each scattering event. These are assuming the ion always starts in a lower qubit state. From *Comparing Zeeman qubits to hyperfine qubits in the context of the surface code: $^{174}\text{Yb}^+$ and $^{171}\text{Yb}^+$* [9].

number of nucleons, the unpaired nucleon contributes a spin $1/2$ so that odd-mass-number nuclei will have half-integer nuclear spin. For example, $^{174}\text{Yb}^+$ (used for Zeeman qubits) has a nuclear spin of $I = 0$, while $^{171}\text{Yb}^+$ has a nuclear spin of $I = 1/2$, making it a candidate for hyperfine qubits [9].

In general, the energy level splitting for hyperfine qubits will be in the low GHz range. For our example of $^{171}\text{Yb}^+$ the hyperfine splitting is 12.6 GHz. The magnetic fields used to manipulate ions in this regime are still considered relatively low with $B_0 \lesssim 50$ mT. Other odd isotopes that could be used for hyperfine qubits include $^{137}\text{Ba}^+$, which also benefits from long-lived metastable states and the longest visible-wavelength cooling transition of any potential ionic qubit [7]. In particular, there exist clock states $|F = 0, m_F = 0\rangle$ and $|F = 1, m_F = 0\rangle$ which are resistant to first-order magnetic fields. They only exhibit dependence on second-order magnetic fields, which can be derived from the Breit-Rabi formula

$$\Delta\nu = \frac{(g_J - g_I)^2 \mu_B^2}{2\hbar\omega} [2B_0\Delta B + (\Delta B)^2] \quad (3)$$

where g_J and g_I are the electronic and nuclear Landé g-factors respectively, and ω is the angular frequency of the hyperfine splitting. It turns out, this second-order effect is negligibly small, so hyperfine qubits are not susceptible to magnetic field noise [2, 9].

The benefits that hyperfine qubits possess don't come without their share of drawbacks. The most prominent source of errors in hyperfine qubits is population leakage outside the qubit subspace. Our idealized qubit operates as a two-level system, however, there exist additional levels in the physical system beyond the two qubit states. If the ion leaks into one of these undesirable states, that

introduces errors. These types of errors are particularly harmful since standard error correction methods are not effective for treating them. There is research from Hayes *et al.* that shows leakage can be suppressed by pumping from the leakage state back into the qubit state by utilizing the quadrupole transition (see Fig. 3) [10].

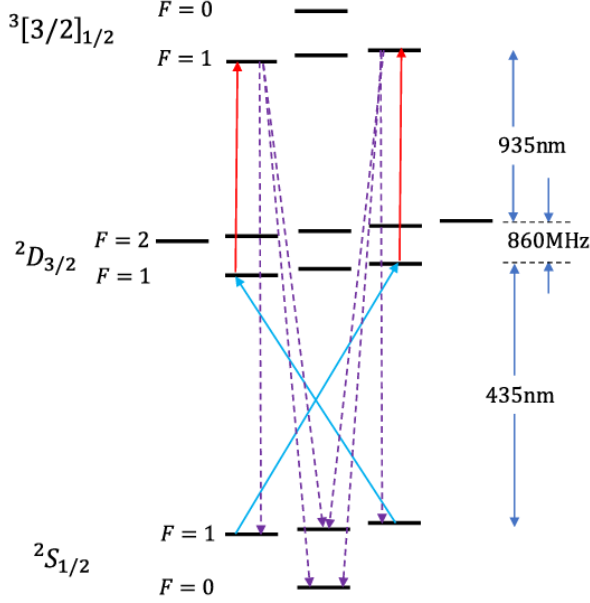


FIG. 3. Energy level diagram for $^{171}\text{Yb}^+$. In this repump scheme, leaked population is first driven to the $^2D_{3/2}$ by the 435nm quadrupole transition. In the next step, the population is driven to $^3[3/2]_{1/2}$ by the 935nm dipole transition. Completing the cycle, the $^3[3/2]_{1/2}$ states decay to $^2S_{1/2}$ with high probability. From *Eliminating Leakage Errors in Hyperfine Qubits* [10].

C. Fine Structure Qubits

Continuing through our spectrum of trapped ion qubits, we reach fine structure qubits, which operate in the range of $\lesssim 10$ THz. Similar to the hyperfine qubits we just discussed, fine structure qubits also suffer from leakage, and as a result, their lifetimes tend to be ~ 1 s. However, unlike hyperfine qubits, fine structure qubits fall into the category of zero nuclear spin qubits (along with Zeeman and optical qubits). As such, they typically come in the form of even mass number isotopes [2]. An example is $^{40}\text{Ca}^+$ which can transition between the metastable fine structure states $D_{3/2}$ and $D_{5/2}$ that are separated by 1.82 THz [11].

Stimulating these transitions for fine structure qubits is not much different from the previous qubits that we've discussed, except there are challenges that arise in generating narrow-linewidth laser beams at terahertz frequencies. One way around that is to utilize two phase-

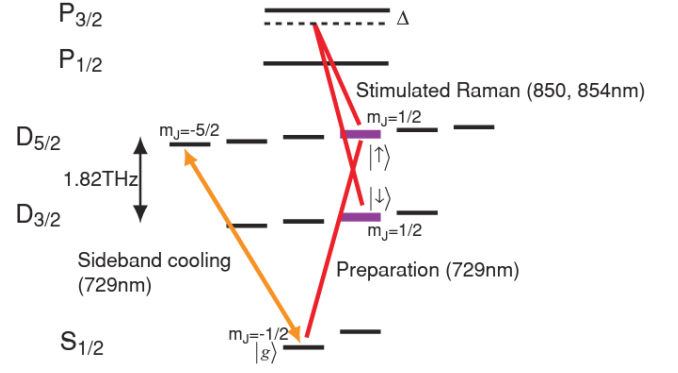


FIG. 4. Energy level diagram for $^{40}\text{Ca}^+$. The quadrupole transition between $S_{1/2}$ and $D_{5/2}$ is used to apply a conditional phase shift while the stimulated Raman transition is used to switch between qubit states $D_{5/2}$ and $D_{3/2}$, thereby implementing a CZ gate. From *Quantum gate using qubit states separated by terahertz* [11].

locked lasers in order to excite a stimulated Raman transition. For the $^{40}\text{Ca}^+$ ion, Toyoda *et al.* demonstrated that phase-locked Ti:sapphire lasers at 850 nm and 854 nm could be used to implement a CZ gate between the qubit states $|\uparrow\rangle \equiv |D_{5/2}(m_J = 1/2)\rangle$ and $|\downarrow\rangle \equiv |D_{3/2}(m_J = 1/2)\rangle$ in such a way (see Fig. 4) [11]. In this scheme, coherence times are potentially limited by the relative phase stability between the phase-locked laser. Nonetheless, the ease of scalability of IR lasers in integrated photonics offers a potential advantage over the blue and UV lasers required for Raman transitions in Zeeman and hyperfine qubits [2].

D. Optical Qubits

Finally, we reach our last stop on the energy splitting spectrum of trapped ions: optical qubits. Until now, all the previous qubit types have employed pairs of qubit states within the same orbitals. On the other hand, optical qubits generally make use of the ground-state S level and the metastable D level for the two qubit states. Typical energy level splitting is in the range of hundreds up to a thousand THz.

Being optically separated allows for extremely high efficiency detection of the qubit state based on resonant fluorescence. This works by utilizing an auxiliary level which rapidly decays to the ground state. First, a laser that is resonant with the transition between the S level ground state and the P level auxiliary state is applied to the qubit. If the qubit is in the ground state at that time, it will be excited to the P level, where, upon decay, it will emit a photon that can be detected. On the other hand, if the qubit is already in its D level upper state, then it will not be in resonance with the applied laser and the ion remains dark [2].

Optical qubits are generally similar to Zeeman and fine structure qubits when it comes to choice of isotope. It's possible to base an optical qubit on odd mass number isotopes (non-zero nuclear spin) but that can lead to unwanted shifts due to hyperfine splitting in the D state. Consequently, optical qubits will commonly make use of even mass number isotopes (zero-nuclear-spin). One such ion, $^{88}\text{Sr}^+$, has been shown to be a viable candidate for optical qubits capable of implementing a universal set of gates with high fidelity. As depicted in Fig. 5, the quantum information is encoded in states $|S_{1/2, m=+1/2}\rangle$ and $|D_{5/2, m=+3/2}\rangle$ [12].

This brings with it challenges related to the narrow line-widths required for the lasers used to control the optical transitions. Because fluctuations in the phase of the laser can lead to decoherence in the qubit, the lasers themselves can often become the limiting factor in coherence times [2]. In their scheme involving the $^{88}\text{Sr}^+$ qubit, Akerman *et al.* implemented stabilized diode lasers in a controller-follower configuration capable of producing a narrow linewidth. These diode lasers offer another advantage in that they tend to be affordable and compact compared with other light sources while still remaining capable of the precise frequencies necessary to facilitate quantum gate operations [12].

Optical qubits are being studied beyond just gate operations as well. The future of fault-tolerant quantum computation is likely to rely on quantum error correction (QEC) as devices increase in scale. QEC relies on being able to detect and correct errors during computation while keeping the encoded quantum information intact and unaltered. There are various platforms, including those making use of superconducting circuits and topological features, that have been presented as possible paths to achieve this. In their 2017 paper, Bermudez *et al.* examine how QEC could be implemented for trapped ions and chose to use $^{40}\text{Ca}^+$ ions due to the high-fidelity state detection that is offered by optical qubits (although their work shows the need for additional improvements before a truly beneficial QEC protocol can be achieved) [13].

II. TRAPPING CONFIGURATIONS

Now that we have a better understanding of the types of ions used in trapped ion quantum computing, as well as some of the advantages and disadvantages they each have, we can turn our attention to the trapping configurations.

When considering the possible geometries that an ion trap can have, we're essentially given two choices: one-dimensional (1D), also known as linear arrays; or two-dimensional (2D), sometimes called planar arrays, which is the basis for the 2D Coulomb crystals we're building up to.

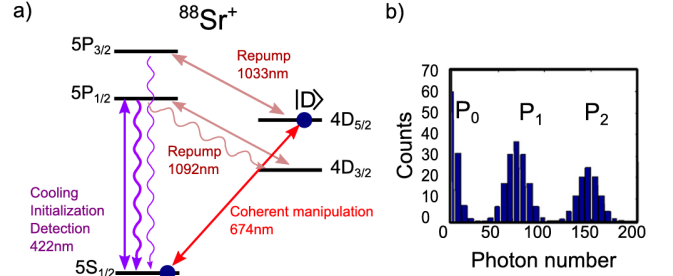


FIG. 5. (a) Energy level diagram for $^{88}\text{Sr}^+$. The transitions depicted with straight lines are driven by lasers, while the wavy lines indicate transitions due to spontaneous emission. The thick wavy line between the $5P_{1/2} \rightarrow 5S_{1/2}$ transition represents the fluorescence used for detection. (b) Measurements of two-qubit fluorescence. From *Universal gate-set for trapped-ion qubits using a narrow linewidth diode laser* [12].

A. Linear Arrays

It may come as no surprise that the first quantum computers to be described using trapped ions made use of linear traps. Despite the simplistic geometry, all the necessary features of a quantum computer can be realized with linear ion traps. It's even possible to implement quantum gates between any set of ions in this scheme, not necessarily neighboring ions, for gates involving pairs, triplets, or any arbitrary number of ions. However, in practice, increasing the number of effective qubits is not an arbitrary task. Decoherence due to the environment interacting with the quantum system remains a significant challenge [1].

Nevertheless, advances have been made that show how quantum computers based on linear arrays could provide solutions to difficult problems in materials design and molecular modeling through quantum simulation. In one example from 2017, Zhang *et al.* successfully performed a quantum simulation of a dynamical phase transition (DPT) using up to 53 qubits in a linear ion trap. In this system, the qubits are coupled at long-range through their collective quantized motion due to Coulomb interactions. Each individual qubit is measured by a global long-range Ising interaction which has an efficiency of almost 99%. This high efficiency makes it possible to measure many-body correlations between qubits in one shot, thereby allowing the DPT to be probed directly [14].

The method employed by Zhang *et al.* for confinement of long ion chains relied on a three-layer linear Paul trap with $^{171}\text{Yb}^+$ ions. Across the chain, ion spacing is anisotropic, ranging from $1.5\ \mu\text{m}$ at the center to $3.5\ \mu\text{m}$ towards the ends. As one might expect, the average lifetime of the chain scales inversely with the number of ions. At the maximum, 53 ions, an average lifetime of about 5 minutes was observed (which was sufficient for this experiment). The greatest factor in limiting the effective lifetime of the ion chain was Langevin collisions with

residual background gas. When looking to scale up a system of this type, it will be crucial to implement cryogenic trap systems to reduce the pressure and collision energies [14].

More recently, a flexible scheme for maintaining efficient entanglement between ions in a long chain as the size scales up has been introduced by Leung and Brown. By utilizing both amplitude and frequency modulation, they were able to apply high-fidelity pulse sequences to drive transverse motional modes, which can suppress gate errors. However, this comes at the cost of gate power for improved robustness against errors [15].

B. Planar Arrays

This is a test of the github branch.

Unidentified vessel travelling at sub warp speed, bearing 235.7. Fluctuations in energy readings from it, Captain. All transporters off. A strange set-up, but I'd say the graviton generator is depolarized. The dark colourings of the scrapes are the leavings of natural rubber, a type of non-conductive sole used by researchers experimenting with electricity. The molecules must have been partly de-phased by the anyon beam.

Run a manual sweep of anomalous airborne or electromagnetic readings. Radiation levels in our atmosphere have increased by 3,000 percent. Electromagnetic and subspace wave fronts approaching synchronization. What is the strength of the ship's deflector shields at maximum output? The wormhole's size and short period would make this a local phenomenon. Do you have sufficient data to compile a holographic simulation?

I have reset the sensors to scan for frequencies outside the usual range. By emitting harmonic vibrations to shatter the lattices. We will monitor and adjust the frequency of the resonators. He has this ability of instantly interpreting and extrapolating any verbal communication he hears. It may be due to the envelope over the structure, causing hydrogen-carbon helix patterns throughout. I'm comparing the molecular integrity of that bubble against our phasers.

We're acquainted with the wormhole phenomenon, but this... Is a remarkable piece of bio-electronic engineering by which I see much of the EM spectrum ranging from heat and infrared through radio waves, et cetera, and forgive me if I've said and listened to this a thousand times. This planet's interior heat provides an abundance of geothermal energy. We need to neutralize the homing signal.

Communication is not possible. The shuttle has no power. Using the gravitational pull of a star to slingshot back in time? We are going to Starbase Montgomery for Engineering consultations prompted by minor read-out anomalies. Probes have recorded unusual levels of geological activity in all five planetary systems. Assemble a team. Look at records of the Drema quadrant. Would

these scans detect artificial transmissions as well as natural signals?

Exceeding reaction chamber thermal limit. We have begun power-supply calibration. Force fields have been established on all turbo lifts and crawlways. Computer, run a level-two diagnostic on warp-drive systems. Anti-matter containment positive. Warp drive within normal parameters. I read an ion trail characteristic of a freighter escape pod. The bomb had a molecular-decay detonator. Detecting some unusual fluctuations in subspace frequencies.

Resistance is futile.

III. COULOMB CRYSTALS

These are the voyages of the Starship Enterprise. Its continuing mission, to explore strange new worlds, to seek out new life and new civilizations, to boldly go where no one has gone before. We need to neutralize the homing signal. Each unit has total environmental control, gravity, temperature, atmosphere, light, in a protective field. Sensors show energy readings in your area. We had a forced chamber explosion in the resonator coil. Field strength has increased by 3,000 percent.

Unidentified vessel travelling at sub warp speed, bearing 235.7. Fluctuations in energy readings from it, Captain. All transporters off. A strange set-up, but I'd say the graviton generator is depolarized. The dark colourings of the scrapes are the leavings of natural rubber, a type of non-conductive sole used by researchers experimenting with electricity. The molecules must have been partly de-phased by the anyon beam.

A. Coulomb Interaction

Run a manual sweep of anomalous airborne or electromagnetic readings. Radiation levels in our atmosphere have increased by 3,000 percent. Electromagnetic and subspace wave fronts approaching synchronization. What is the strength of the ship's deflector shields at maximum output? The wormhole's size and short period would make this a local phenomenon. Do you have sufficient data to compile a holographic simulation?

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Communication is not possible. The shuttle has no power. Using the gravitational pull of a star to slingshot back in time? We are going to Starbase Montgomery for Engineering consultations prompted by minor read-out anomalies. Probes have recorded unusual levels of geological activity in all five planetary systems. Assemble a team. Look at records of the Drema quadrant. Would these scans detect artificial transmissions as well as natural signals?

B. Experimental Methods

Now what are the possibilities of warp drive? Cmdr Riker's nervous system has been invaded by an unknown microorganism. The organisms fuse to the nerve, intertwining at the molecular level. That's why the transporter's biofilters couldn't extract it. The vertex waves show a K-complex corresponding to an REM state. The engineering section's critical. Destruction is imminent. Their robes contain ultritium, highly explosive, virtually undetectable by your transporter.

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1. Laser Cooling

Exceeding reaction chamber thermal limit. We have begun power-supply calibration. Force fields have been established on all turbo lifts and crawlways. Computer, run a level-two diagnostic on warp-drive systems. Anti-matter containment positive. Warp drive within normal parameters. I read an ion trail characteristic of a freighter escape pod. The bomb had a molecular-decay detonator. Detecting some unusual fluctuations in subspace frequencies.

Sensors indicate no shuttle or other ships in this sector. According to coordinates, we have travelled 7,000 light years and are located near the system J-25. Tractor beam released, sir. Force field maintaining our hull integrity. Damage report? Sections 27, 28 and 29 on decks four, five and six destroyed. Without our shields, at this range it is probable a photon detonation could destroy the Enterprise.

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It indicates a synchronic distortion in the areas emanating triolic waves. The cerebellum, the cerebral cortex, the brain stem, the entire nervous system has been depleted of electrochemical energy. Any device like that would produce high levels of triolic waves. These walls have undergone some kind of selective molecular polarization. I haven't determined if our phaser energy can generate a stable field. We could alter the photons with phase discriminators.

2. Radio-Frequency

Communication is not possible. The shuttle has no power. Using the gravitational pull of a star to slingshot back in time? We are going to Starbase Montgomery for Engineering consultations prompted by minor read-out anomalies. Probes have recorded unusual levels of geological activity in all five planetary systems. Assemble a team. Look at records of the Drema quadrant. Would these scans detect artificial transmissions as well as natural signals?

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C. Ongoing Challenges

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1. Micromotion

Exceeding reaction chamber thermal limit. We have begun power-supply calibration. Force fields have been established on all turbo lifts and crawlways. Computer, run a level-two diagnostic on warp-drive systems. Anti-matter containment positive. Warp drive within normal parameters. I read an ion trail characteristic of a freighter escape pod. The bomb had a molecular-decay detonator. Detecting some unusual fluctuations in subspace frequencies.

Sensors indicate human life forms 30 meters below the planet's surface. Stellar flares are increasing in magnitude and frequency. Set course for Rhomboid Dronegar 006, warp seven. There's no evidence of an advanced communication network. Total guidance system failure, with less than 24 hours' reserve power. Shield effectiveness has been reduced 12 percent. We have covered the area in a spherical pattern which a ship without warp drive could cross in the given time.

Shields up. I recommend we transfer power to phasers and arm the photon torpedoes. Something strange on the detector circuit. The weapons must have disrupted our communicators. You saw something as tasty as meat, but inorganically materialized out of patterns used by our transporters. Captain, the most elementary and valuable statement in science, the beginning of wisdom, is 'I do not know.' All transporters off.

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2. Something Else

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Deflector power at maximum. Energy discharge in six seconds. Warp reactor core primary coolant failure. Fluctuate phaser resonance frequencies. Resistance is futile. Recommend we adjust shield harmonics to the upper EM band when proceeding. These appear to be some kind of power-wave-guide conduits which allow them to work collectively as they perform ship functions. Increase deflector modulation to upper frequency band.

Run a manual sweep of anomalous airborne or electromagnetic readings. Radiation levels in our atmosphere have increased by 3,000 percent. Electromagnetic and subspace wave fronts approaching synchronization. What is the strength of the ship's deflector shields at maximum output? The wormhole's size and short period would make this a local phenomenon. Do you have sufficient data to compile a holographic simulation?

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IV. CONCLUSION

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Sensors indicate human life forms 30 meters below the planet's surface. Stellar flares are increasing in magnitude and frequency. Set course for Rhomboid Dronegar 006, warp seven. There's no evidence of an advanced communication network. Total guidance system failure, with less than 24 hours' reserve power. Shield effectiveness has been reduced 12 percent. We have covered the area in a spherical pattern which a ship without warp drive could cross in the given time.

Resistance is futile.

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