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KIDSpec: An MKID-Based Medium-Resolution, Integral Field Spectrograph

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Abstract

KIDSpec, the Kinetic Inductance Detector Spectrograph, is a concept for a highly sensitive, medium-spectral-resolution optical through near-IR spectrograph. It uses the intrinsic-energy-resolving capability of an array of optical/IR-sensitive MKIDs to distinguish multiple orders from a low-resolution grating. By acting as an 'order resolver,' the MKID array replaces the cross-disperser in an echelle spectrograph. This greatly simplifies the optical layout of the spectrograph and enables longer slits than are possible with cross-dispersed instruments (to improve sky subtraction). KIDSpec would have similar capabilities to ESO's highly successful X-shooter instrument. It would provide an $R = 4000$–$10{,}000$ spectrum covering the optical and near-IR spectral range (0.4–1.5 μm). As well as a 'long-slit' mode, the IFU would provide a small (~ 50 spaxel) field of view for spatially resolved sources. In addition, the photon-counting operation of MKIDs and their photon-energy-resolving ability enable a read-noise-free spectrum with perfect cosmic ray removal. The spectral resolution would be sufficient to remove the bright night-sky lines without the additional pixel noise, making the instrument more sensitive than an equivalent semiconductor-based instrument. KIDSpec would enhance many existing high-profile science cases, including transient (GRB, SNe, etc.) follow-up, redshift determination of faint objects and transit spectroscopy of exoplanets. In addition, it will enable unique science cases, such as dynamical mass estimates of the compact objects in ultra-compact binaries.

Keywords MKID · Spectrometer · Astronomy

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1 Introduction

Microwave Kinetic Inductance Detectors (MKIDs) are a novel superconducting detector technology that promise to revolutionize many areas of astronomy. In the important ultraviolet/optical/infrared (UVOIR) regime, each pixel has the ability to deliver read-noise free, low-resolution spectroscopy. The advantage of MKIDs over similar superconducting detectors, such as superconducting tunnel junction devices (STJs) and transition edge sensors (TESs) is that they can be easily multiplexed into large arrays. Current MKIDs arrays contain ten thousand pixels, with the capability to increase to megapixel arrays. The current arrays are already more than an order of magnitude larger than the largest equivalent UVOIR TES [1] or STJ [2] arrays. These capabilities enable a broad range of unique science opportunities, including high-throughput integral field spectroscopy, hugely multiplexed ($>$ 100,000) low-spectral-resolution spectroscopic surveys (Giga-Z, [3]) and dark-speckle exoplanet direct imaging [4]. In this paper, we focus on another unique application, which is the use of the moderate native energy resolution of MKIDs to distinguish the orders of a dispersive element, such as a grating. This concept was initially presented by [5]) for the case of STJs, but here we present the application to MKIDs, showing the current possibilities and the range of possibilities for the near future.

2 KID Operating Principal

The operating principal of a Kinetic Inductance Detector is described in detail in [6]. In summary, in a KID each pixel is a resonant circuit containing a capacitor and an inductor. The inductor in a KID is made from a superconductor and has an additional impedance to an AC current in the surface of the superconductor. This current is carried by the Cooper pairs (loosely bound pairs of electrons) and energy is stored in the form of the kinetic energy of these pairs. When a photon is incident on the KID, it breaks Cooper pairs creating so-called quasi-particles in the superconductor. The addition of these quasi-particles changes the surface impedance of the material, and it is this change of impendence that can be measured as a change of resonant frequency and/or a change of dissipation of the resonator. The key factor is that this change in resonant frequency depends on the number of Cooper pairs broken (or equivalently the number of quasi-particles generated). As the energy required to break a Cooper pair is typically much lower than the photon energy, each UVOIR photon generates many thousands of quasi-particles.

A probe signal at the resonant frequency of the pixel can be used to sense this change as a change in the phase of the probe signal. The magnitude of this phase shift is then directly related to the number of quasi-particles and hence, the input energy of the photon. As the quasi-particles recombine with a characteristic time-scale, we see this as a fast-rise-exponential-decay profile. The accuracy to which we can determine the height of this pulse determines the accuracy to which we can determine the energy of the incident photon and hence the energy resolution of the detector. The energy resolution is determined by the magnitude of the pulse and the

associated noise. This noise is a combination of several factors, including statistical fluctuations and amplifier noise, as described by [7]. The accuracy to which we can determine the start time of the pulse determines the accuracy of the photon arrival time. The recombination timescale for the quasi-particles determines the maximum photon rate, as you need to distinguish the individual photon profiles.

The key advantage of MKIDs over other superconducting detector technologies is the fact that we can engineer the resonant frequency of the pixel. By careful microwave engineering ,we can have many pixels on a single microwave feedline and hence address many pixels at the same time. This frequency domain multiplexing allows us to build arrays of many thousands of pixels without complex cold electronics, requiring a single feedline and wide-band amplifier.

2.1 Status of the Technology

Much progress has been made since the initial operation concept was presented. There have been advances in resonator design, materials used, and perhaps most importantly for UVOIR astronomy in, the size of the arrays. In 2011 [8] went on sky with ARCONS, a 1024-pixel UVOIR MKID camera at the Palomar 200-inch telescope. This was the first UVOIR MKID instrument and has performed scientific observations in the field of pulsars and compact binaries, among others. Since that time, the Mazin Lab have fielded further instruments focused on the application to exoplanet direct imaging, with arrays of up to 20,000 pixels [4, 9]. These instruments contain UVOIR MKID arrays that use PtSi [10] as the superconductor. They have, however, been shown to have energy resolutions an order of magnitude or more below the maximum energy resolution for such a material. This aspect of the development of KIDs remains a very active area of research.

As this paper will focus on the application of MKID arrays rather than their development, we have chosen to use an energy resolution that we believe is achievable on a timescale of 5–10 years. This is similar to the development timescale of an astronomical instrument. We have chosen to adopt $R = 50$ at 400 nm throughout the study. For comparison, the current generation of arrays has $R \sim 10$ at 800 nm (equivalent to $R = 15$–20 at 400 nm) and the expected limit is $R \sim 100$ for $T_c \sim 1$ K.

3 KIDSpec

In this paper, the instrument concept we have investigated is based around the requirements for a wide-passband, medium-spectral-resolution spectrograph. The science cases for such an instrument range from dynamic observations of interacting binaries, supernovae, and gamma-ray bursts, to observations of the absorption lines in the spectra of high redshift quasars. This is much the same as the case for X-Shooter at the VLT, which has quickly become one of ESO's most over-subscribed instruments. In Fig. 1, we can see that the near-IR arm of X-Shooter is a cross-dispersed echelle spectrograph. In this type of spectrograph, there are two dispersive elements. The echelle grating is a relatively

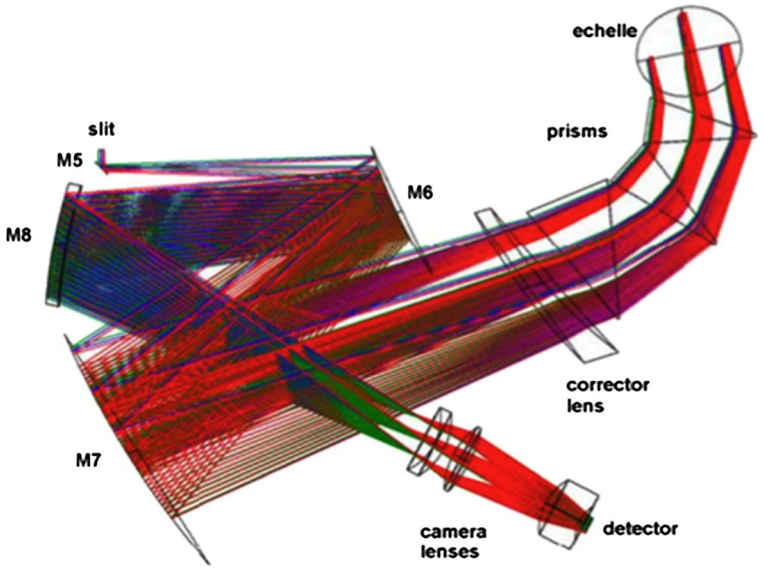

Fig. 1 Schematic showing the optical design of the near-IR arm of X-shooter, taken from the X-Shooter user manual. https://www.eso.org/sci/facilities/paranal/instruments/xshooter/doc.html (Color figure online)

low-line density grating that is designed to be used at a high angle of incidence, giving multiple, overlapping orders. These orders can be separated spatially by using a second, *orthogonal* dispersive element such as a grating or a prism (as is the case in X-Shooter). In X-Shooter, the light from the telescope passes through a slit before being collimated using 2 mirrors (M6 and M7 in Fig. 1) and a corrector lens. The light is then pre-dispersed using a series of prisms and forms a pupil on the echelle grating. Instead of the orders overlapping, the angle of reflection has a component orthogonal to the grating dispersion, enabling the order to be separated. The prisms are used in double pass to provide the cross-dispersion and minimize aberrations. Finally, the spectrum is imaged onto a 2D detector by a camera. This 2D geometry allows high spectral resolution with a single-order and wide spectral bandpass by measuring multiple spectral orders simultaneously. The cost of this is a complex optical design with, in the case of X-Shooter, 29 optical surfaces between the entrance slit and the detector.

In contrast, KIDSpec could be used in single pass, without the need for the prisms used for cross-dispersing, and the corrector lens used to compensate for the refractive prisms. This would remove the second reflections on M6–M8 as well as the 16 optical surfaces of the refractive elements that are used in the cross-dispersion. This simplification of the optical design would lead to higher throughput (approximately a factor 2 in the number of surfaces) and the associated simplification in the manufacturing and alignment. While the exact gains depend on a detailed optical design (including anti-reflection coatings) which is

outside the scope of this work, the optical design would more resemble that of a long-slit spectrograph, with a slit, collimator (3 surfaces), a grating (1 surface) and a camera (typically 8–10 surfaces). It is clear that the design would contain fewer elements.

3.1 KIDSpec Concept

In order to satisfy the requirements, we present the concept of a single and a dual-arm (Visible + Infrared) spectrograph. The instrument would us an echelle grating in low order (< 20) to achieve a spectral resolution of 5–10,000. The novel feature in comparison with echelle spectrographs such as X-shooter is that the use of cross-dispersing optics is replaced by the energy resolution of MKIDs. In contrast to a pixel of a semiconductor detector which can only measure the intensity of the incident radiation, an MKID pixel can generate a spectrum of the incident radiation. This means that a single MKID pixel measures light from all of the orders from an echelle grating and, if the MKID energy resolution is sufficient, it can distinguish which order the light belongs to. This is shown in Fig. 2 where light from one order of the grating can be seen with a peak at around 2.1 μm and the light from the next order can be seen at around 1.6 μm. The width of the peaks is determined by the energy resolution of the detector, as described later.

3.2 Required Instrument Characteristics

In order to demonstrate the power of KIDSpec, we have considered a number of requirements derived from the scientific goals of the instrument. KIDSPec should be

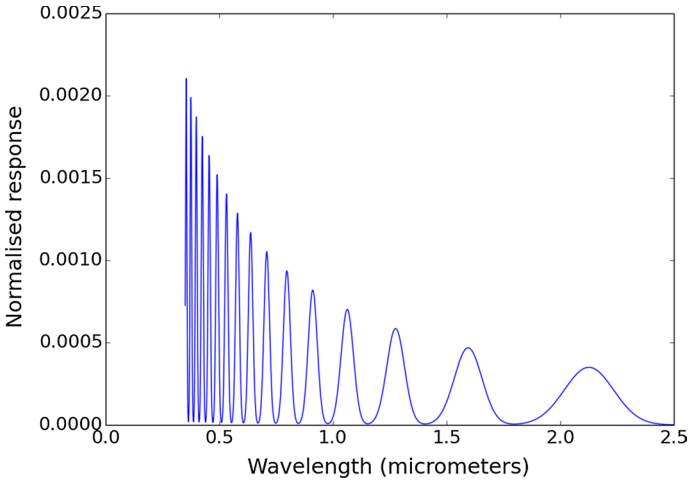

Fig. 2 The spectrum of a uniform source as seen in a single pixel of an MKID array. The wavelength is in micrometers and matches the increasing separation of the orders as the energy resolution decreases (Color figure online)

a single-object instrument as the faint or time variable objects are sufficiently sparsely distributed on the sky to not be able to take advantage of multi-object spectroscopy. KIDSpec should deliver a medium-spectral-resolution ($R > 3000$) to distinguish velocity components in the emission lines of interacting binary systems, as well as many other applications. It should have a wide passband (ideally 0.35–2.4 μm) to simultaneously capture as much of the Spectral Energy Distribution of the object as possible, thus avoiding the need for multiple observations with different central wavelength settings, which is highly inefficient for observatories. In order to sample characteristic timescales (frequencies of variability, light-travel times, orbital periods) in interacting binaries, the instrument should have a time resolution to sample the fastest timescales that are expected to be observed. While this can be as fast as 0.001 s in the case of material close to a Neutron Star or Black Hole, more typical variability is on the timescale of ~ 0.1 s [11]. In addition to this, low- (or ideally zero-)noise on each measurement is required to avoid the penalty of combining multiple measurements, as is the case with readout noise from most semiconductor detectors. An instrument with these characteristics will optimize the collecting power of large telescopes, such as the VLT, ELT and TMT.

3.3 KIDSpec Spectral Format

In order to show the potential of MKIDs for such an instrument, we have investigated a number of potential grating parameters that would satisfy the requirements for KIDSpec. We have also considered what is possible now and what increase in capabilities is required to realize the full KIDSpec instrument. These are summarized in the following sections.

3.3.1 Single MKID Array

In this concept, we have chosen to use a single MKID array to show what would be possible in the simplest configuration. The MKID has an energy resolution ($\lambda/\Delta\lambda$) of 50 at 400 nm and is a linear array of 8000 pixels. We have used a grating with 100 grooves/mm in Littrow configuration with an incidence angle of 18.6°. The results are shown in Fig. 3. The spectrum from 0.35–2.4 μm can be recreated by extracting the flux in each order for a given pixel and then summing this over many pixels (which all have a slightly different wavelength.

3.3.2 Dual-arm MKID Array

As can be seen in Fig. 3, by using low orders, many of the pixels have light from only a single order, which is not an optimum use of the MKID array.

In order to improve the final spectral resolution of the instrument, or equivalently to reduce the number of MKID pixels required for a given spectral resolution, it is possible to use a dual-arm spectrograph. In this scenario, the light is split into a VIS and an IR spectrograph. This would enable the fabrication of each MKID device to maximize the signal-to-noise of the pulses and hence the energy resolution of the array at two

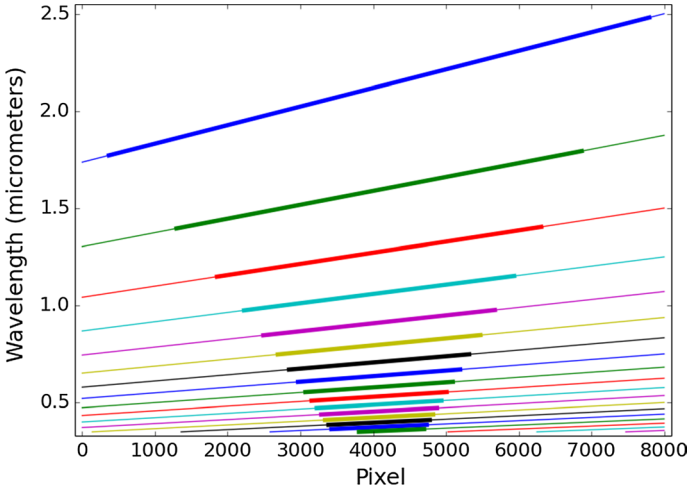

Fig. 3 The spectral orders used in the 8000 pixel "single MKID array" KIDSpec concept. The colored lines are orders from the echelle grating. For each order, the total range is shown together with the free spectral range of a given order (highlighted in bold)

separate fiducial wavelengths. This mitigates the drop in energy resolution when the pulses drop to close to the noise floor, for instance from the amplifier.

3.4 2-D MKID Arrays

In the previous concepts, we have only considered 1-D (linear) arrays of MKIDs. However, the multiplexing scheme of MKIDs is not limited to linear arrays. The second dimension in these arrays can be thought of as spatial pixels in much the same manner as a long-slit spectrograph, or the small slit length of X-Shooter. However, unlike cross-dispersed spectrographs, there is no intrinsic limit to the length slit due to the need to avoid overlapping the projection of the top of the slit in one order with the bottom of the slit in the adjacent order. This means that the number of spatial pixels is in theory only limited by the size of arrays that you can produce. Thus a megapixel array in the dual-arm KIDSpec concept would allow 200 spatial pixels (spaxels). These could either form a long-slit spectrograph, or be used with an image slicer or lenslet array in an integral field spectrograph.

3.5 Effect of Improved/Reduced Energy MKID Energy Resolution

If the MKID energy resolution is higher than we have used in this study, then this would enable the echelle grating to be used in higher orders. This is shown in Fig. 2 where the individual peaks would be narrower, enabling them to be placed more closely together while remaining resolvable. Working in higher order will enable you to stack more orders on the MKID array, which in turn increases the final spectral resolution. Alternatively, the same final spectral resolution could be achieved with fewer MKID pixels.

Conversely, a lower MKID energy resolution will have the opposite effect and limit the final spectral resolution. Ultimately, you would reach the limit where only a few orders could be resolved and your final spectral resolution would be insufficient to merit using an MKID array. For comparison, an MKID array with 2000 pixels and a $R = 15$ would achieve a final spectral resolution of ~ 1400 which is sufficient to resolve (and hence remove) sky lines, but is not sufficient for dynamical studies.

4 Science Cases

4.1 Dynamical Masses of Black Hole X-ray Binaries

The dynamical masses of the compact objects in Black Hole and Neutron Star binaries can be determined using radial velocity measurements of components of the binary. This in turn can be used to constrain the masses. Most X-ray binaries are only optically bright during outbursts, which limits our ability to observe lines characteristic of the donor star. However, Steeghs et al. [12] used the Bowen-blend fluorescence lines to track the velocity of the secondary star. This enables the mass function to be constrained while the system is in an optically bright state. This method enabled us to determine masses for around 10 Neutron Star and Black Hole binaries, including the first dynamical mass for the Black Hole in GX339-4 [13]. The high throughput and exquisite time resolution of KIDSpec would enable us to study many more systems, including those at shorter orbital periods, such as the ultra-compact sources, which are candidates for the progenitors of gravitational wave sources.

4.2 Faint Source Spectroscopy

While the gains made by KIDSpec in the field of time domain astronomy are obvious, it would also importantly enable the observation of some of the faintest sources, such as high redshift galaxies. There is a significant increase in signal-to-noise for faint objects, driven by the lack of read-noise when compared to semiconductor detectors, especially those operating in the infrared. In addition to this, there are a number of other benefits. KIDSpec would have excellent cosmic ray removal due to the intrinsic time resolution. Cosmic rays will only affect the few microseconds it takes for the array to return to its unperturbed state. In contrast, CCDs and CMOS detectors sum the flux over many minutes, rendering large parts of the data useless. There is the potential for improved sky subtraction. Due to the lack of read-noise, spectra can be obtained at high spectral resolution, the sky lines removed and then the final spectrum rebinned without any noise penalty. This will be especially important in observing between the bright sky lines in the infrared region of the spectrum. Finally, MKIDs enable dynamic exposures, where the maximum exposure time of a sub-exposure is not limited by saturating the brightest lines to avoid bleeding, but it can be determined after the exposure. This allows to avoid multiple short sub-exposures, which will limit the ultimate signal-to-noise of the combined exposure.

5 Summary

MKIDs are a disruptive technology that has the potential to transform many areas of UVOIR astronomy. They offer zero read-noise, low dark current, broad passband, photon-counting observations with the ability to detect the energy (to a few percent) and the arrival time (to a microsecond) of the arriving photon with good quantum efficiency. This unique combination of capabilities is enhanced by the ability to fabricate the detectors in large arrays due to their natural frequency domain multiplex scheme. In this paper, we have investigated the characteristics of a novel second-generation MKID instrument that uses the intrinsic energy resolution of the detectors to separate the orders of an echelle spectrograph, thus removing the need for cross-dispersing optics and many of the optical surfaces in a more traditional cross-dispersed spectrograph like X-Shooter. KIDSpec is planned to be a demonstrator of this new approach in the use of UVOIR MKIDs. In the era of the ELT, KIDSpec could be used on its own, or in conjunction with ELT-MOS to provide a high S/N spectrum of any object (or objects if combined with an IFU) in the science field of view. Such an instrument would take maximum advantage of the large collecting area of the ELT for both faint sources as well as time domain astronomy.

References

1. R.W. Romani, A.J. Miller, B. Cabrera, E. Figueroa-Feliciano, S.W. Nam, Astrophys. J. **521**, L153 (1999)
2. M.A.C. Perryman, C.L. Foden, Peacock, Nucl. Instrum. Methods Phys. Res. Sect. A **325**, 319 (1993)
3. D.W. Marsden, B.A. Mazin, K. O'Brien, C. Hirata, Astrophys. J. Suppl. Ser. **208**, 8 (2013)
4. S.R. Meeker, B.A. Mazin, A.B. Walter, P. Strader, N. Fruitwala, C. Bockstiegel, P. Szypryt, Publ. Astron. Soc. Pac. **130**, 988 (2018)
5. M. Cropper, M. Barlow, M.A.C. Perryman, K. Horne, R. Bingham, M. Page, Mon Not R Astron Soc **344**, 33 (2003)
6. P.K. Day, H.G. LeDuc, B.A. Mazin, A. Vayonakis, J. Zmuidzinas, Nature **425**, 817 (2003)
7. N. Zobrist, B.H. Eom, P. Day et al., Appl. Phys. Lett. **115**, 042601 (2019)
8. B. Mazin, S. Meeker, M. Strader, P. Szypryt, D. Marsden, J. van Eyken, G. Duggan, A. Walter, G. Ulbricht, M. Johnson, B. Bumble, K. O'Brien, C. Stoughton, Publ. Astron. Soc. Pac. **125**, 1348 (2013)
9. J. Lozi, G. Olivier, N. Jovanovic, S. Goebel, P. Pathak, N. Skaf, A. Sahoo, *Adaptive Optics Systems VI. SPIE*, p. 270, (2018)
10. P. Szypryt, S.R. Meeker, G. Coiffard et al., Opt. Express **25**, 25894 (2017)

11. B.A. Mazin, G.D. Becker, G. Cancelo, K. France, W.C. Fraser, T. Jones, S.R. Meeker, K. O'Brien, J.X. Prochaska, S. Tendulkar, G. Vasisht, in *Proceedings of SPIE 10702, Ground-based and Airborne Instrumentation for Astronomy VII*, p. 107020H (2018)
12. D. Steeghs, Casares, Astrophys. J. **568**, 273 (2002)
13. R.I. Hynes, D.J. Steeghs, J. Casares, P.A. Charles, K. O'Brien, Astrophys. J. Lett. **583**, L95 (2003)