Study of Gamma-Gamma Coincidence using ^{22}Na

Gayatri P

3rd year, Integrated M.Sc. Physics

Roll No.: 2211185

(Dated: January 22, 2025)

In this experiment, we observed and recorded the coincidences of gamma rays produced during ^{22}Na nuclear decay. $\gamma - \gamma$ coincidence is the concurrent emission of gamma ray pairs produced in the positron-electron annihilation process. We have used scintillation detectors which use sodium iodide and specialised electronic modules. The coincidence rates are measured for four different configurations of the angular separation between the two detectors. Hence, we are able to find that the the coincidences are maximum when the detectors are placed 180° to each other.

I. THEORY

A. ^{22}Na Decay

^{22}Na radioactively deacys into an excited state of ^{22}Ne either by emission of a positron (with 90%) probability or by electron capture (10% probability). The excited ^{22}Ne nucleus decaus with a mean life of 3×10^{-12} s to the ground state with the emission of a 1.274 MeV gamma photon (Fig. 1).

Positrons are emitted with a range of kinetic energies upto about 0.5 MeV. They lose this energy within nanoseconds of release in the material sorrounding the source and when the reach atomic energies (eV), capture an electron to form positronium – a hydrogen like 'atom', which decays by the annihilation of the e^+ and e^- into two gamma photons. By energy conservation, the energy of these photons must equal the net rest energy of the positronium, hence they will each have an energy of 0.511 MeV (ignoring the binding energy $\sim$ a few eV). By momentum conservation, the net momentum of the two photons must equal the initial momentum of the positronium. Since in its rest frame there is no inital momentum, the two annihilation gamma photons must have equal and opposite momentum in that frame. This allows for simultaneous detection in two scintillation detectors placed on both sides of the sample, i.e. $\gamma - \gamma$ coincidence.

However it is to be noted that in a situation where the positronium is not at rest, depending on the direction of the initial positronium momentum relative to the gamma emission direction, the transformation to the lab frame may give gamma energies that are not 0.511 MeV and/or produce gammas that are not emitted exactly 180° apart.

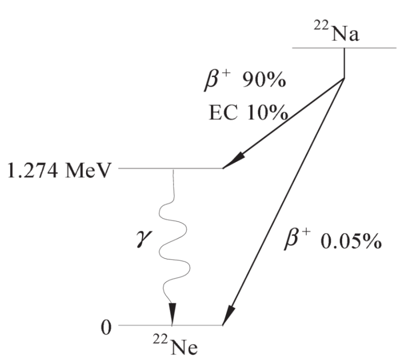


FIG. 1: ^{22}Na decay summarised

B. Coincidence Rate

The nuclear decay rate (number of nuclear decays per second) is $\Gamma_n = \alpha \cdot 3.7 \times 10^{10}$ decays/sec/curie, where α is the source activity in curies. 90% of the time, the nuclear decay proceeds by β^+ emission, and these always annihilate with an electron to produce two 0.511 MeV gammas. Thus the rate of emission of 0.511 MeV gammas is $0.9{\cdot}2{\cdot}\Gamma_n = 1.8\Gamma_n$. These gammas are emitted uniformly (in oppositely directed pairs) from the source.

Thus at a distance R from the source they are spread out over an area $4\pi R^2$ and the flux Φ (number per unit area per second) will be,

$$4\pi R^2 \Phi = 1.8\Gamma_n \tag{1}$$

The fraction of 0.511 MeV gammas which get through the lead shielding will is expected to be on the order of 20% and is expressed by the symbol κ. Hence, the rate Q of 0.511 MeV gammas striking the face of the scintillator can be calculated as,

$$Q = \Phi[A_a + \kappa(A_s - A_a)] \tag{2}$$

Here, $A_a = \pi r_a^2$ is the area of the aperture and $A_s = \pi r_s^2$ is the area of the scintillator.

II. EXPERIMENTAL SETUP

Apparatus

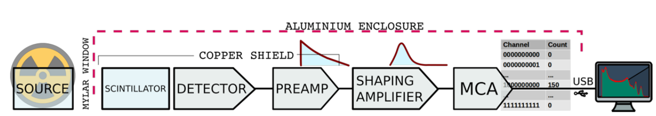


FIG. 2: A flow diagram of the experimental setup

1. ^{22}Na source
2. Two scintillation detectors
3. Gamma ray spectroscopy setup, with Multiple Channel Analyser (MCA)
4. Software (`CNSPEC`) and computer for analysis

The experimental setup is that of a gamma ray spectroscope with multiple channel analyser with two scintillation detectors (Fig. 2, 3). The detector is made of an 8mm diameter entrance window coated in aluminium to block visible light. Inside, a PN junction coupled in reverse bias mode is mated to a scintillator that measures 10mm × 10mm × 8mm. The scintillator is made of NaI with Thorium doping that emits photns with the same energy as the gamma ray's descent. The scintillation photons are transformed into an equivant amount of electron-hole pairs in the depeletion area of the PN junction. An event in the photopeak area transforms into a charge pulse in the PN junction. The preamplifier converts it into a matching output voltage (of the range 0 to 3.3V) and the shaping amplifier then generates a pulse with a Gaussian form. The signal enters the MCA and a spectrum is produced with 10 bit resolution. `CNSPEC` software is then used for data analysis [1].

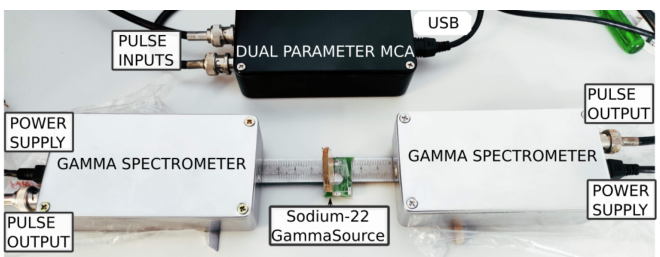
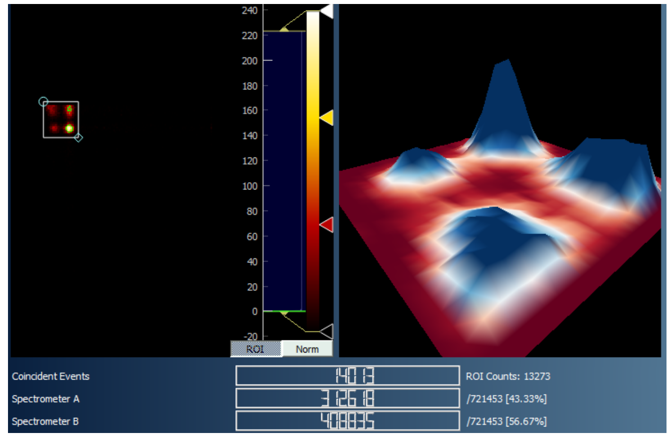


FIG. 3: The experimental setup, composed of two gamma spectrometers placed with a ^{22}Na source in the middle. Data acquisition is carried out by the Multiple Channel Analyser

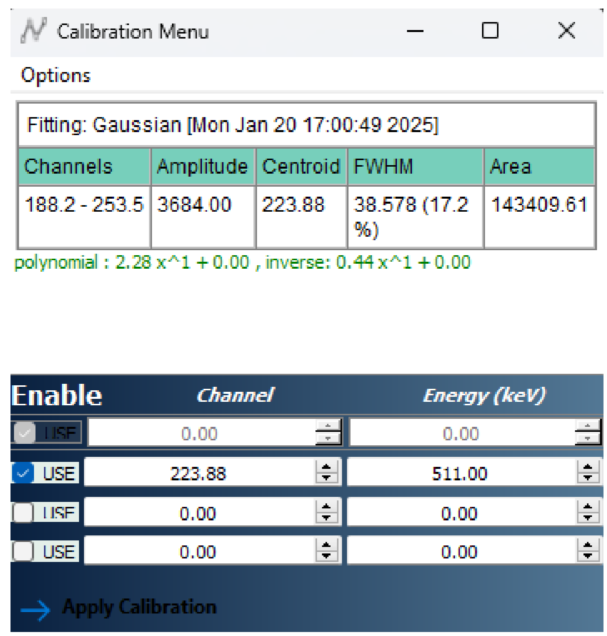
III. OBSERVATION AND CALCULATIONS

We placed the two scintillation detectors are four different angles and took data for 3000s (15 mins.) each. The observations are summarised below. Figs. 4, 5, 6, 7 show the `CNSPEC` screenshots of the observational data. Part (a) of all the figures show the 3D heatmap of the peak counts against the channel numbers of both detectors on the x-y plane.

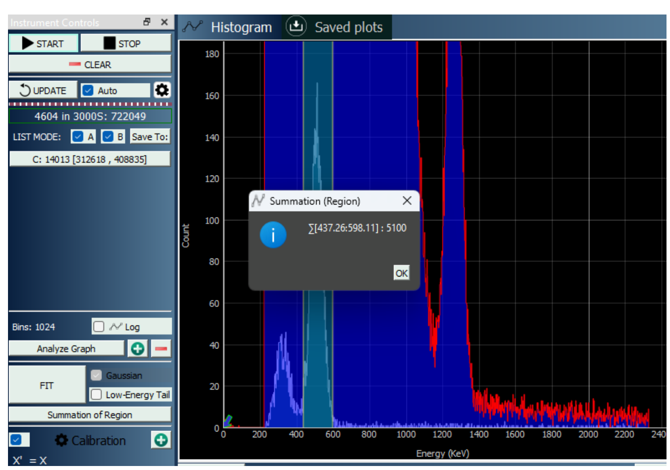
A. 180°



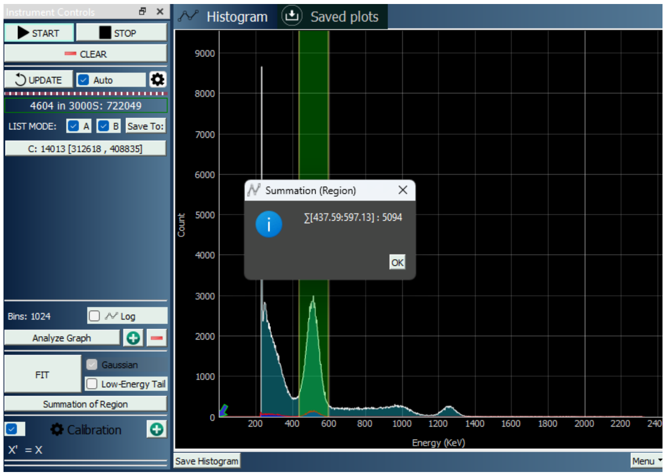
(a) Coincidence plots: Heat map and 3D surface view



(b) Calibration of the 0.511 MeV photopeak



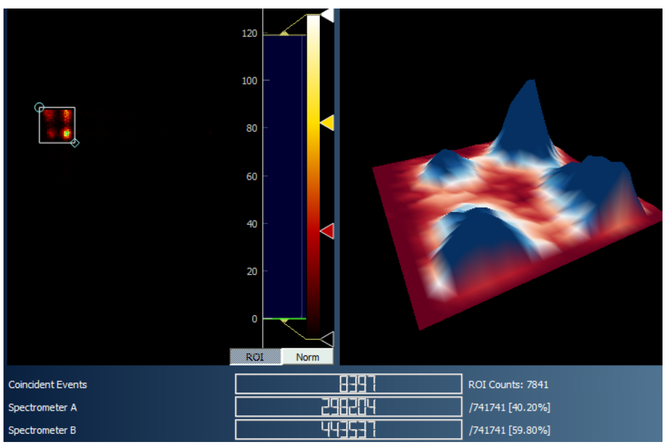
(c) Coincidence count of the red channel w.r.t. the blue channel = 5100



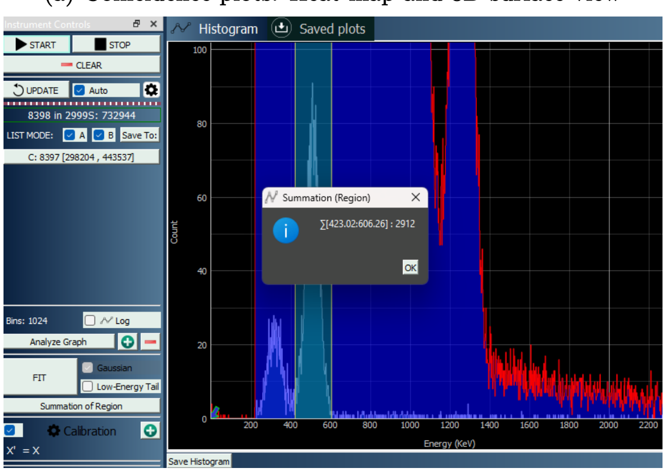
(d) Coincidence count of the blue channel w.r.t. the red channel = 5094

FIG. 4: CNSPEC screenshots for $\gamma - \gamma$ coincidence with the detectors placed 180° to each other

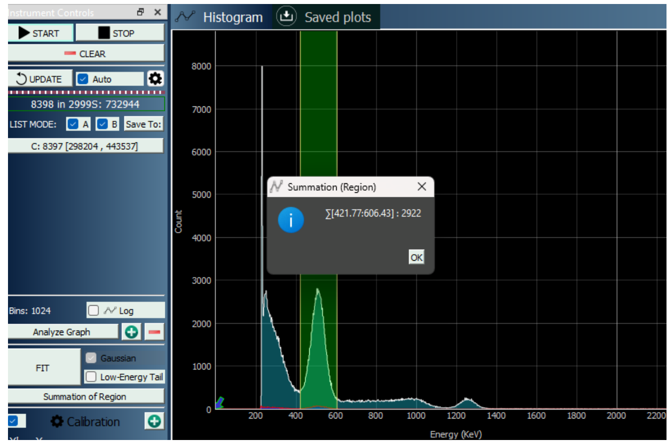
B. 170°



(a) Coincidence plots: Heat map and 3D surface view



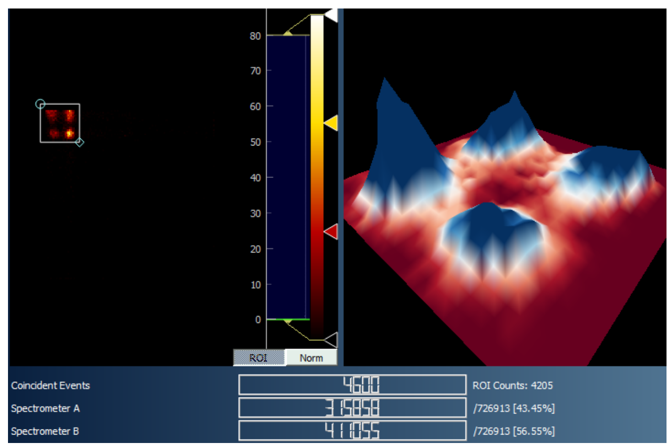
(b) Coincidence count of the red channel w.r.t. the blue channel = 2912



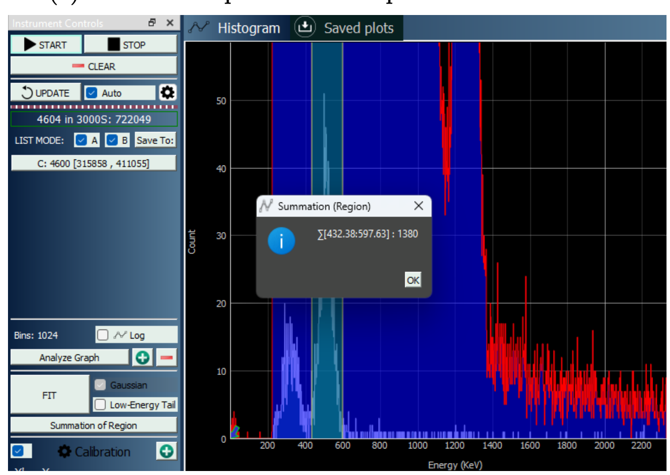
(c) Coincidence count of the blue channel w.r.t. the red channel = 2922

FIG. 5: CNSPEC screenshots for $\gamma - \gamma$ coincidence with the detectors placed 170° to each other

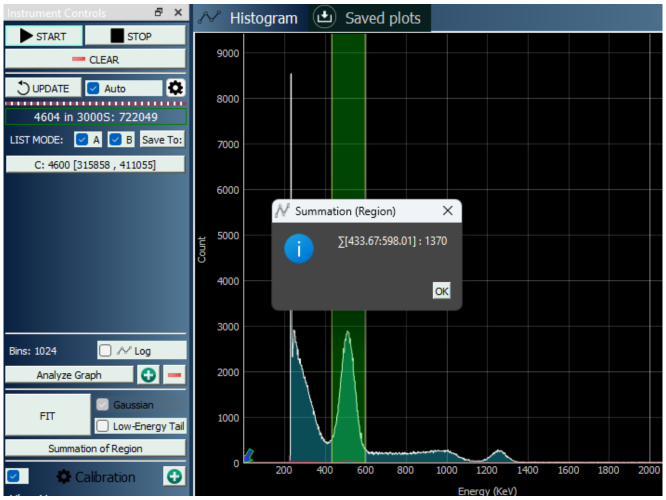
C. 190°



(a) Coincidence plots: Heat map and 3D surface view



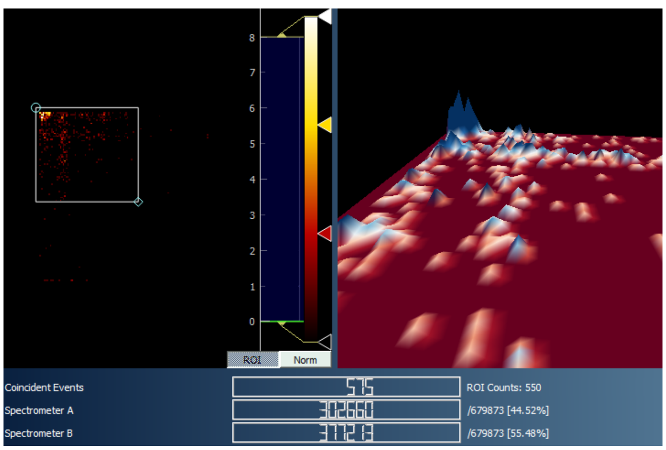
(b) Coincidence count of the red channel w.r.t. the blue channel = 1380



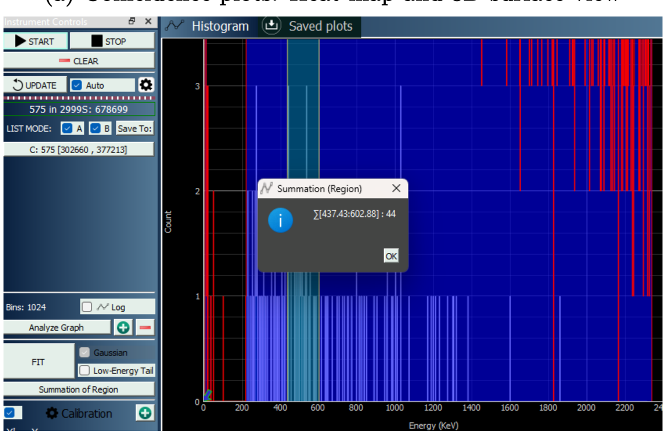
(c) Coincidence count of the blue channel w.r.t. the red channel = 1370

FIG. 6: CNSPEC screenshots for $\gamma - \gamma$ coincidence with the detectors placed 190° to each other

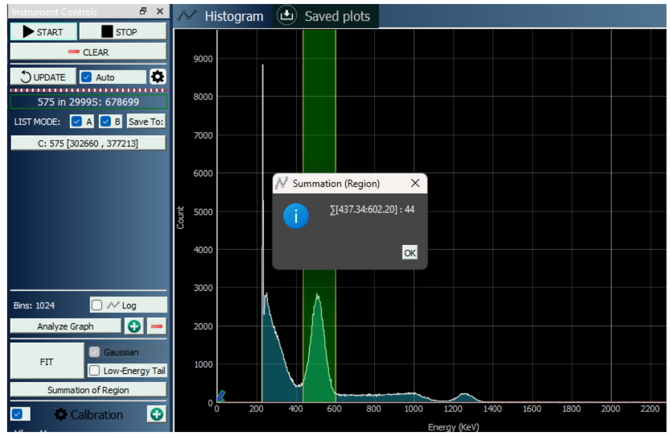
D. 90°



(a) Coincidence plots: Heat map and 3D surface view



(b) Coincidence count of the red channel w.r.t. the blue channel = 44



(c) Coincidence count of the red channel w.r.t. the blue channel = 44

FIG. 7: CNSPEC screenshots for $\gamma - \gamma$ coincidence with the detectors placed 90° to each other

The average coincidence counts for each angle in 15 minutes is:

- for 90°: 44 counts
- for 170°: 2917 counts
- for 180°: 5097 counts
- for 190°: 1375 counts

The count rates are plotted against their corresponding angles in Fig. 8.

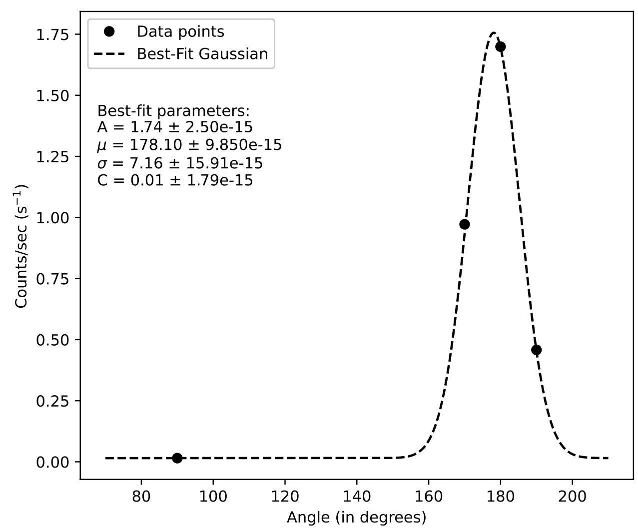


FIG. 8: Count rates vs. angle plot

IV. SOURCES OF ERROR

1. The sample might not be placed fully perpendicular to the detectors.

2. The sample may get disturbed by external vibrations which could affect the angle at which ait is placed.
3. The background noise may vary along the time of taking observations, which usually last around an hour.
4. The angular measurements might not be entirely accurate.

V. DISCUSSION & CONCLUSION

In this experiment, we have studied $\gamma - \gamma$ coincidence and have successfully shown that the coincidence rates maximise when the detectors are placed 180° to each other and decrease as the angle changes in either direction. While this is as expected, it also shows that there that there exists a significant amount of positronium with non-zero velocities in the lab frame. The summarised values of the coincidence rates are shown below:

- for 90°: 0.015 counts/sec
- for 170°: 0.972 counts/sec
- for 180°: 1.699 counts/sec
- for 190°: 0.458 counts/sec

As we can see, the count rates do not uniformly decrease in the $+10°$ direction as it does in the $-10°$ direction. This could be because of a number of reasons like the sample not being placed exactly perpendicular to the detectors, or inaccuracies in measurement of the angle. Since we have not subtracted the background noise for any of these measurements, they could also be an affecting variable. Moreover, from the best-fit Gaussian plot, we can see that the mean value is around 178°, which could mean that the sample was tilted by an average of 12°. However, more data number of observations are required to conclusively say anything.

We have seen that besides the photopeak at 0.511 MeV, we also see a small distribution of counts at 1.274 MeV as expected. There is also some significant amount of counts seen for energies less than 0.511 MeV. These are primarily the Compton peaks caused by the β electrons scattering of neighbouring atoms. Hence, the 3D surface plots of the measurements show 4 peaks, i.e. all the combinations of photopeak and the compton peaks of the two detectors coinciding (Fig. 9).

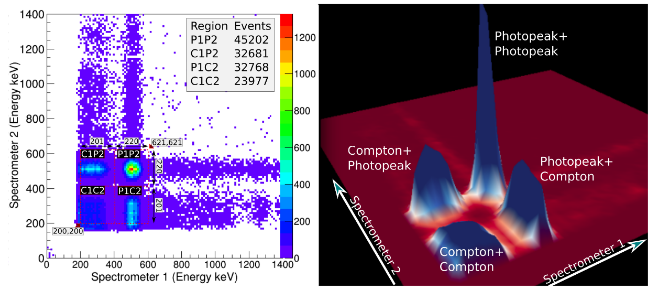


FIG. 9: The heat map and surface plot of the ^{22}Na energy spectrum showing four significant peaks [2]

VI. PRECAUTIONS

1. The sample shouldn't be touched, even though it's in a case. After setting the appartus, it should not be disturbed.
2. The histogram should be saved before starting the experiment.
3. The coincidences should be measured in a longer time period, to increase the signal-to-noise ratio.

[1] J. B.P. and O. Sastri, *Indigenously developed gamma spectrometer*, Vol. 63 (Proceedings of the DAE Symp. on Nucl. Phys., 2018).

[2] J. B.P. and O. Sastri, *User Manual: GammaSpec-1K*, CSpark Research (2023).