HENRY SHACKLETON: Be a long 15 minutes. There you go. All right, hello everybody. My name's Henry and today, I'll be presenting my findings on an experiment that I conducted with my lab partner Adin over there. Thank you, Adin

During our experiment, we determined the angular dependency of the scattering rate of alpha particles through gold foil. Using this relation, we are able to determine that Rutherford's scattering presents an accurate model for these scattering of effects. In doing so, we are able to extract some information about the actual nature of atoms and their atomic makeup. So to give a bit of background, I'm going to go through two different historical models of the atom and talk about the different experimental predictions that they predict.

So back in the early 19th century, people weren't too sure what made up an atom. They knew there were some electrons and some positive stuff going around somewhere, but other than that, they weren't too sure. Now, the predominant theory at the time was JJ Thomson's Plum Pudding Model, shown here. In this model, you have these negatively charged electrons that sort of float around in this soup of positive charge. I apologize for the plum pudding and the soup. If you're getting hungry from all these metaphors, there is food back there.

Now, the experimental predictions that we want to get out of this model is what it says about scattering. So if we take one of these atoms and we shoot it through a material made up of other atoms, what kind of scattering do we expect to see ? And you can see in this model here, we don't really expect that much scattering. So the atom will go through. It might pass through a slightly more negatively charged region here and move a bit that way, deflect a little bit that way. But you don't expect that much scattering, overall.

Doing out all the math, we see that this predicts small angle scattering that dies off exponentially as a function of angle. This dying off is controlled by this theta sub m called the mean multiple scattering rate. For gold, we predict this is about 1. So Rutherford comes along and he looks at this and says, I don't know about this. Let me try something else.

This right here is the Rutherford model that he proposes. In this model we have our negatively charged electrons. But instead of this soup of positive charge, we have a densely packed nucleus in the middle. Now because this nucleus is so dense and so tightly packed, it allows for much stronger interactions between atoms, when it comes to scattering. For example, you can imagine if two atoms collided head on. The nuclei would interact and they'd just bounce straight off.

So doing out all the math again, we see that this larger scattering angle dies off as 1 over sine to the fourth of theta over 2. Now, this predicts much higher rate at larger angles than this exponential fall off, right here . A small point to clarify about this equation here is that this equation is derived assuming large angles. So for theta, roughly, larger than or equal to 10. This is not a limit of the Rutherford theory in and of itself. You can derive a Rutherford model for scattering for any angle, but it starts to get really gross at small angles.

You can actually see this diverges for theta equals to 0, which is not good. So this equation right here is only valid for theta roughly greater than or equal to 10. So for the purposes of this experiment, we will restrict our viewing to theta greater than or equal to 10. And these two models give us two different predictions that we can compare against actual data. So we experimentally measure scattering rates at various angles. And by taking this data we can fit it to both the predicted Rutherford and Thomsom model, and come to a conclusion about which one more accurately predicts our model.

Now let's talk a bit about the apparatus that lets us do this. The first part of our efforts is an alpha particle howitzer. This howitzer contains an Americium-241 source which emits alpha particles-- which are two protons and two neutrons-- at, approximately, a constant energy. These alpha particles shoot out of the howitzer right here in a sort of concentrated beam directed out of the howitzer.

These awful particles hit a gold foil where something happens, we don't know yet. And it scatters off at an angle theta, which is then detected by our state detector. This detector registers the count, as well as the energy of the incoming particle, and sends it to an MCA to be analyzed. Now, there's a bit of a complication in the geometry of our set up. You see, what we want to measure is this angle, theta, here, our scattering rate. What we actually control and what we measure in our experiments is this angle, phe which is the angle of our howitzer relative to our detector.

So at phe equals to 0, the howitzer points dead on at our detector. Now, in a sort of theoretical world where this solid state detector is infinitesimally small and our beam is also this infinitesimally point source, we would expect phe to correspond exactly to theta. So at phe equals to 0, the howitzer pointed dead on, we would expect any non-zero scattering to cause the particles to shoot off in a direction and not be detected by our detector.

However, in practice, this is not actually the case. Our solid state detector is a few centimeters wide. And because of this, it allows for a range of angles theta that are detected given a certain howitzer angle. In addition, our beam has some width, which allows for further angles that can be detected given a certain howitzer angle phe.

So this is a bunch of stuff going on. We've got a lot of different things contributing to uncertainty. But we can account for this by, essentially, asking the simple question, all right, we have a howitzer at an angle phe. What is the probability of a detection that we see having come from a particle being scattered at an angle theta? Again, in this theoretical case, where we have point sources and point detectors, this probably would just correspond to a delta function centered at phe.

However this is not practically the case. And from simple geometric considerations, which I can go into more detail later, we expect as a first approximation a sort of triangle shaped distribution around phe. This is called the angular response function. And we determine it by removing the gold foil from our detectors, so we just have our howitzer and our detector, and we see how deviations in our phe affect our counting rates.

Now, again, to reference back in this theoretical scenario with point sources and point detectors, we would expect to only see counts at phe equals to 0, with our howitzer pointed dead on the detector. And as soon as we move it a little bit, the counts go away. However, this is not actually the case. And by measuring these deviations, we can determine our angular response function. So we move or howitzer around, we determine how our angle phe affects our counts, and we get something like this. This is fitted to a triangle distribution.

Now, we can take a few things out of this. I see a fellow in the crowd laughing at my chi squared. The chi squared is not that good. This is because we acknowledge that a triangle is only a first approximation. We don't expect our data to actually perfectly model this triangle distribution. However, it simplifies our math greatly. So we use this triangle distribution, and try to extract some data from this.

The second thing that we can see from this is that this distribution is actually a bit off center at theta equals to negative 2. Now, normally, we would expect the highest count rate when our howitzer is pointed dead on at our detector at theta equals to 0. This offset indicates that the protractor that we used to measure our angles is actually a little bit off. And putting that on actually corresponds to theta equals to 2. Finally, this gives us our angular response function. If we replace zero with our howitzer angle phe, this gives us the spread around phe of scattering angles theta that we detect.

We accommodate this in our equations via a convolution. Now, this can intuitively be thought as taking these two rates which are given Thomson and Rutherford the probability of having a scattering at angle theta. We then multiply it by the probability of a scattering angle theta being detected by our howitzer positioned at an angle phe. And then we integrate over all theta. This gives us two different counting rates as a function of our howitzer angle phe, one for our Rutherford theory, and one for our Thomson theory. This gives us two equations that we can use to compare our data, given geometric considerations about our apparatus.

So after that, we are finally ready to go. So we take our gold foil, we put it back in. We measure at different angles between phe equals to 10 degrees and 60 degrees. We let a detector detect for a while. And over the period of time at any one of our measuring rates, we get something that looks a bit like this. Now, this MCA bin number down here corresponds to the energy of the particles that we're detecting. And on the y-axis, here, is our count rate.

Now, the first thing that you might think, and the first thing that we thought as well, is well, this is about a Gaussian right here. That's our particle, and everything below that is just noise. However, as we found out, the energy loss through a material is actually described by a Landau distribution, which is a Gaussian, but with a slightly longer tail on one side. What you see here is a Gaussian with a slightly longer tail on one side. So by fitting this Landau distri--

We fit this to a Landau distribution and get chi squared's between 0.5 and 2, which suggests that all this did actually come from a Landau distribution. And all of these are valid scattering data points, and not just noise. We further confirm this by measuring our noise, by taking our howitzer pointed away from our detector, and just letting our detector collect. We ultimately determined that the noise within our energy range of interest is very small, much smaller than any count rate that we care about in our experiment. Therefore, because of this and the fact that our distribution models a Landau distribution, which is what we expect, we conclude that we can use all of the points that we detect as valid scattering data points. But of course, it comes with some good old counting uncertainty.

In addition, we have some uncertainty in our angles. We read the angles of our howitzer by eye from a little protractor that we have in our apparatus. But our eyes aren't so good, so we tack a plus or minus 1 degree uncertainty to angular measurements. My lab partner thinks 0.5. I think 1 because I'm not as certain.

So we take all these measurements. We divide by the amount of time that we collected to get a count rate. We graph this as a function of our angle that we measure to that, and fit this to a Rutherford and Thomson convolved fit. And we see something like this. And I think this really speaks for itself. This is not an error in my code. Thomson is really just that bad in accounting for our data.

But we see here that the Rutherford scattering prediction more accurately describes the gradual falloff of our scattering rates as the howitzer angle gets bigger, as opposed to the Thomson fit, with the chi squared of 2000. Now, there are different ways of potentially giving Thomson a better shot, accommodating for it, may be giving it a better chance of describing our data. And I can go into this in more detail later, if people are interested. But, ultimately, we see that Thomson is fundamentally unable to account for this data. Whereas Rutherford describes it quite well.

Now, there's an additional caveat to this chi squared that we have here. So this chi squared comes from fitting from our Rutherford and Thomson data convolved with our beam profile. However, our beam profile does have some uncertainty associated. In that fit that we had, there is some uncertainty in the triangle. So to sort of estimate how this uncertainty affects our data, we vary our beam profile within one standard deviation of its fit parameters, and see how our goodness of fit changes.

And we see here that the goodness of fit for a Rutherford model, while it varies somewhat depending on the convolution that we use, it doesn't change a significant amount. And it certainly doesn't change enough to warrant considering the Thomson model. The discrepancy between the chi squareds and the visual discrepancy you see here very clearly suggests that Rutherford does a much better job of predicting our data than Thomson. Which, again, suggests a more Rutherford make up of the atom, as opposed to the Thomson Plum Pudding model.

So in conclusion, Thomson's Plum Pudding model is found to fundamentally be unable to describe the scattering rates that we observe at large angles. The Rutherford model more accurately predicts this gradual fall off, which suggests a more Rutherford-like view of our atom. And that's it. Thank you. [APPLAUSE]

INSTRUCTOR: All right, the paper is open for questions.

HENRY SHACKLETON: Yeah.

AUDIENCE: Did you try the fit without using the triangular correction?

HENRY SHACKLETON: Yes I did. And this is another interesting point, which shows that our convolution does benefit our data, does a much better-- not a much better, not as bad as Thomson, relatively speaking. But it does a noticeably better job at describing our data than the pure Rutherford scattering, 1 over sine to the fourth fit.

AUDIENCE: So the difference between 2.14--

HENRY SHACKLETON: And, sorry, 8.18.

AUDIENCE: Oh, I see it.

HENRY SHACKLETON: That's a chi squared of eight for just fitting with the raw Rutherford scattering without the convolution. Yes.

AUDIENCE: Do you have any plots that show your Landau distribution fits to the data?

HENRY SHACKLETON: I thought I did. You saw me switch forward and then, realize that it wasn't there. So I switched back. No, so I don't have a picture of the Landau fit. One thing that I can describe, which is a small caveat to this, is that the Landau distribution describes energy loss.

And this is usually a Gaussian with one tail on-- this isn't too well. It's a Gaussian with a slightly longer tail on the right hand side. Now, this is a Gaussian with a slightly longer tail on the left hand side. However, what we see here is energy. And energy loss is sort of the inverse of this. So we actually fit this to a reverse Landau distribution. And throughout all our data, we get reduced chi squareds between 0.5 and 2, which indicates a good fit.

INSTRUCTOR: A different question for Henry? All right, let's--

HENRY SHACKLETON: Yep, Shawn?

SHAWN: What was the largest angle you were able to use the data from?

HENRY SHACKLETON: Sorry?

SHAWN: What was the largest angle you were able to get your data?

HENRY SHACKLETON: 60 degrees. 60 degrees, we collected over the course of five days. And I don't think we could have actually collected data at much higher angles than that because our noise rate right here is 0.0002. Now, this is still a bit smaller than our counting rate for 60 degrees. But if we started to go further, we would start to enter the regime where noise becomes much more dominant.

SHAWN: Do you happen to know how many total counts was that over five days?

HENRY SHACKLETON: Over five days? Off the top of my head, I believe 400. You can actually see-- I know the rate here, which you can very easily go backwards in the math, I guess.

SHAWN: So if the rate--

HENRY SHACKLETON: This is somewhere down here.

SHAWN: --100 counts per day--

HENRY SHACKLETON: Yeah, something like that.

SHAWN: Or a couple counts per hour.

HENRY SHACKLETON: Yes, something like that.

SHAWN: All right, thank you. The noise that we mentioned here is actually restricted to our energy of interest. So there's a fair bit of noise at much lower energy levels, specifically between this MCA bin number of 0 and 50, down here. There's a fair bit of noise there. But once you start getting up to this larger area right here between 50 and 1500, we start to see much less noise.

INSTRUCTOR: Another question? All right, let's thank Henry again.

[APPLAUSE]