PROFESSOR: We've talked a lot about de Broglie saying that the wavelength is given by h over p. But we have not said much yet about the frequency of the waves. So what is the frequency of those matter waves?

So what is the frequency--

frequency--

of the matter waves.

So de Broglie did answer that same question. And the answer was obtained by analogy. We have p equal h bar k.

And he said, well, just like the wavelength is determined by the momentum, we'll have e equal h bar omega. So the frequency-- so this equation is the one that now completes the story. Omega is equal to e over h bar.

Fixes omega in terms of the energy. And we're going to say a few things. In fact, this will be an interesting digression into an important subject about waves that illustrates why this answer makes a lot of sense.

And that's, really, all you can do at this moment. This is a postulate of quantum mechanics. That you do this thing, and with this, you get quantum mechanics. So the best thing we can do is to explain why it makes sense in a number of ways, and then hope that the theory that you built makes full sense.

So I want to remind you about velocities of waves. So if you have a wave now that it has k and omega-- you have this thing. k minus omega, wave with a phase.

kx minus omega t. Then there is something called the phase velocity.

And it's given by omega over k.

It's the velocity in which the nodes and maxima of this plane wave move. So let's see if this makes some sense. Omega over k is the same thing as e over p.

We're nonrelativistic, so let's continue.

1/2 mv squared over mv. And this seems a little strange. 1/2--

v. So if I have a particle, you see, this is matter waves of energy e and momentum p. And e is 1/2 mv squared, the velocity of the particle. p is equal to mv. And now, somehow this wave seems to be moving with half the speed of the particle. That looks pretty bad. What's going on?

Well, this is the usual story with waves. If the wave itself doesn't-- a wave, a plane wave carries no real information. It's not the signal.

So many times when you try to represent the particle-- a little bit of information traveling-- representing it with a plane wave is actually quite wrong. You have to represent it with a wave packet.

And therefore, this phase wave velocity being one half of the velocity of the particles seems to just confirm the idea that, first, these waves are a little strange. And second, phase velocity is not very meaningful physically.

The velocity that this more meaningful is v group velocity.

And it's d omega dk evaluated at the value k that you're using. k is a proxy for momentum. So d omega dk may depend on k and omega. So if it's d omega, dk is a function. Which value should you use? Well, the value at the k that you're propagating.

And this would be the same as d omega dk.

Is because of the constant separating-- the same as de vp.

But what is the kinetic energy in terms of the momentum? We wrote it last time. p squared over 2m. That's the kinetic energy expressed in terms of momentum. So this is d dp of p squared over 2m.

Write p equal mv and you'll recover the kinetic energy. And this is just-- because of the 2-- p over m, which is the velocity of the particle. And this is the reason people believe de Broglie.

De Broglie made sense because the group velocity of this [? package ?] would be correct. And that's a very beautiful result. Actually, it's true relativistically, as well.

If you put the energy and the momentum in relativity, this answer comes out exactly the same, perfectly well. So to a large degree, since it also works for energy and momentum in relativity, there was a motivation from relativity that I want to quote, although not elaborate on it too much. So--

the motivation--

is that in special relativity--

relativity--

the components of the energy divided by c and the momentum form a 4-vector.

Just like position and time forms a 4-vector and transform nicely about-- with Lorenz transformation-- e and p form a 4-vector. Nevertheless, when you consider phases--

like this, and you have x and t that form a 4-vector, the good behavior of phases also imply that k and omega form a 4-vector. In fact, omega-- in relativity, omega over c and the k vector--

form a 4-vector. You see, in all the equations we've written-- and de Broglie-- de Broglie in three dimensions or more, really, is p vector equal h bar k vector. And k is usually used for the magnitude of this k vector.

So this is also 4-vector in special relativity. And therefore, vectors are things that transform nicely. So it makes sense to say that one 4-vector is equal to another 4-vector. Because if it's true in one reference frame, it will be true in every reference frame.

So it's almost irresistible to make them equal. And de Broglie, in some sense, said this is equal to h bar. That's de Broglie.

The interesting thing is that this is true relativistically. But actually, nonrelativistically, you can make sense of this and set it equal to be the same things. And the phase velocities, group velocities all makes sense.

Certainly, we've now said for [? minor ?] particles that e is equal to j bar omega. But another statement would be that, yes, indeed, Einstein said that. That for photons, e was equal to h bar omega or h nu.

And therefore, yes, whatever happens for photons happens for this matter waves. And so also, so this is another argument. Group velocities is one. Special relativity is another reason. And of, course photons.

Einstein--

said that e is equal h nu, which is equal to h bar omega.