4.10: Experimental Evidence

objects large and small, slow and fast: many witnesses for the Canopus trip

Alfred Missouri has remained silent up to this point. Now he declares, "All this theory is too much for me. I won't believe a word you say unless you can show me an experimental demonstration."

"Airliner" test of twin effect

We reply, "Atomic clocks have been placed on commercial airliners and carried around Earth, some in an eastward direction, others in a westward direction. In each case the airliner clocks were compared with reference clocks at the U.S. Naval Observatory before and after their trips. These clocks disagreed. Results were consistent with the velocity-related predictions of special relativity."[1]

"This verification of special relativity has two minor difficulties and a major one. Minor difficulties: (1) Each leg of a commercial airliner's trip may be at a different speed, not always accurately known and for which the time-stretching effect must be separately calculated. Also, temperature and pressure effects on airborne clocks are hard to control in a commercial airliner. (2) More fundamentally, Earth rotates, carrying the reference Naval Observatory clocks eastward around the center of Earth. Earth center can be regarded as the inertial point in free-float around Sun. With respect to this center, one airborne clock moves even faster eastward than Earth's surface, while the other one—heading west with respect to the surface—with respect to Earth's center also moves eastward, but more slowly. Taking account of these various relative velocities adds further complication to analysis of results."

DO WE NEED GENERAL RELATIVITY? NO!

The group takes a break and mills around the conference room, chatting and eating refreshments. Joanne Short approaches us juggling coffee, a donut, and her notes.

"I didn't want to embarrass you in public," she says, "but isn't your plan faulty because of the turnaround? You can't be serious about leaping from one high-speed rocket to another rocket going in the opposite direction. That means certain death! Be realistic: You and your rocket will have to slow down over some time period, come to rest at Canopus, then speed up again, this time headed back toward Earth. During this change of velocity you will be thrown against the front of the rocket ship, as I'm thrown when I slam on my car brakes. Release a test particle from rest and it will hurtle forward! Surely you are not in an inertial (free-float) frame. Therefore you cannot use special relativity in your analysis of this time period. What does that do to your description of the 'jump ahead' of Earth clocks as you slow down and speed up again? Don't you need general relativity to analyze events in accelerated reference frames?"

"Oh yes, general relativity can describe events in the accelerated frame," we reply, "but so can special relativity if we take it in easy steps! l like to think of a freight yard with trains moving at different speeds along parallel tracks. Each train has its own string of recording clocks along its length, each string synchronized in that particular train frame. Each adjacent train is moving at a slightly different speed from the one next to it. Now we can change frames by walking across the trains, stepping from the top of one freight car to the top of the freight car rolling next to it at a slightly different speed."

"Let these trains become rocket trains in space. Each train then has an observer passing Earth as we step on that train. Each observer, by prearrangement, reads the Earth clock at the same time that we step onto his train ('at the same time' as recorded in that frame). When you assemble all these data later on, you find that the set of observers on the sequence of trains see the Earth clock jumping forward in time much faster than would be expected. The net result is similar to the single horrible jerk as you jump from the outgoing rocket to the incoming rocket."

"Notice that it takes a whole set of clocks in different frames, all reading the single Earth clock, to establish this result. So there is never any contradiction between a single clock in one frame and a single clock in any other frame. In this case special relativity can do the job just fine."

The directors reassemble and Joanne Short, smiling, takes her place with them.

"We overcome these two minor difficulties by having an airplane fly round and round in circles in the vicinity of a single ground-based reference atomic clock. Then - to a high accuracy - only *relative* motion of these two clocks enters into the special-relativity analysis.

"Circling airplane" test of twin effect

"On November 22, 1975, a U.S. Navy P3C antisubmarine patrol plane flew back and forth for 15 hours at an altitude of 25,000 to 35,000 feet (7600 to 10,700 meters) over Chesapeake Bay in an experiment arranged by Carroll Alley and collaborators. The plane carried atomic clocks that were compared by laser pulse with identical clocks on the ground. Traveling at an average speed of $270 \mathrm{knots} (140$ meters per second), the airborne clocks lost an average of 5.6 nanoseconds $= 5.6 \times 10^{-9}$ seconds due to velocity-related effects in the 15-hour flight. The expected special-relativity difference in clock readings for this relative speed is 5.7 nanoseconds. This result is remarkably accurate, considering the low relative velocity of the two clocks: 4.7×10^{-7} light speed.[2]

Trouble: Large frame is not inertial

"The *major* difficulty with all of these experiments is this: A high-flying airplane is significantly farther from Earth's center than is the ground-based clock. Think of an observer in a helicopter reading the clocks of passing airplanes and signaling these readings for comparison to a ground-based clock directly below. These two clocks the helicopter clock and the Earthbound clock - are at rest with respect to one another. Are they in the same inertial (free-float) frame? The answer is No."[3]

"We know that a single inertial reference frame near Earth cannot extend far in a vertical direction (Section 2.3). Even if the two clocks - helicopter and Earthbound - were dropped in free fall, they could not both be in the same inertial frame. Released from rest 30,000 feet one above the other, they would increase this relative distance by 1 millimeter in only 0.3 second of free fall - too rapid a change to be ignored. But the experiment went on not for 0.3 second but for 15 hours!"

Solution: Use general relativity

"Since the helicopter clock and Earthbound clock are not in the same inertial frame, their behavior cannot be analyzed by special relativity.[4] Instead we must use general relativity - the theory of gravitation. General relativity predicts that during the 15-hour flight the higher-altitude clock in the Chesapeake Bay experiment will record *greater* elapsed time by 52.8 nanoseconds due to the slightly reduced gravitational field at altitudes at which the plane flew. From this must be subtracted the 5.7 nanoseconds by which the airborne clock is predicted to record *less* elapsed time due to effects of relative velocity. These velocity effects are predicted by both special relativity and general relativity and were the only results quoted above. The overall predicted result equals $52.8 - 5.7 = 47.1$ nanoseconds net gain by the high-altitude clock compared with the clock on the ground. Contrast this with the measured value of 47.2 nanoseconds."

"Hence for airplanes flying at conventional speeds and conventional altitudes, tidal-gravitational effects on clocks can be greater than velocity-dependent effects to which special relativity is limited. In fact, the Chesapeake Bay experiment was conducted to verify the results of general relativity: The airplane pilot was instructed to fly as slowly as possible to reduce velocity effects! The P3C patrol plane is likely to stall below 200 knots, so a speed of 270 knots was chosen."

"In all these experiments the time-stretching effect is small because the speed of an airplane is small compared to the speed of light, but atomic clocks are now so accurate that these speed effects are routinely taken into account when such clocks are brought together for direct comparison."

“High-speed radioactive particle' test of twin effect

Professor Bright chimes in. "What the astronaut says is correct: We do not have large clocks moving fast on Earth. On the other hand, we have a great many small clocks moving very fast indeed. When particles collide in high-speed accelerators, radioactive fragments emerge that decay into other particles after an average lifetime that is well known when measured in the rest frame of the particle. When the radioactive particle moves at high speed in the laboratory, its average lifetime is significantly longer as measured on laboratory clocks than when the particle is at rest The amount of lengthening of this lifetime is easily calculated from the particle speed in the same way the astronaut calculates time stretching on the way to and from Canopus. The time-stretch factor can be as great as 10 for some of these particles: the fast-moving particles are measured to live 10 times longer, on average, than their measured lifetime when at rest! The experimental results agree with these calculations in all cases we have tried. Such time stretching is part of the everyday experience of high-energy particle physicists."[5]

Earth frame: Free-float for particle experiments

"And for these increased-lifetime experiments there is no problem of principle in making observations in an inertial, free-float frame. While they are decaying, particles cover at most a few tens of meters of space. Think of the flight of each particle as a separate experiment. An individual experiment lasts as long as it takes one high-speed particle to move through the apparatus - a few tens of meters of light-travel time. Ten meters of light-travel time equals about 33 nanoseconds, or 33×10^{-9} seconds."[6]

"Can we construct an inertial frame for such happenings? Two ball bearings released from rest say 20 meters apart do not move together very far in 33 nanoseconds! Therefore these increased-lifetime experiments could be done, in principle, in free-float frames. It follows that special relativity suffices to describe the behavior of the 'radioactive-decay clocks' employed in these experiments. We do not need the theory of gravitation provided by general relativity."

"Oscillating iron nucleus" test of twin effect

"Of course, in none of these high-speed particle experiments do particles move back and forth the way our astronaut friend proposes to do between Earth and Canopus. Even that back-and-forth result has been verified for certain radioactive iron nuclei vibrating with thermal agitation in a solid sample of iron. Atoms in a hotter sample vibrate back and forth faster, on average, and thus stay younger, on average, than atoms in a cooler sample. In this case the 'tick of the clock' carried by an iron atom is the period of electromagnetic radiation ('gamma ray') given off when its nucleus makes the transition from a radioactive state to one that is not radioactive. For detailed reasons that we need not go into here, this particular 'clock' can be read with very high accuracy. Beyond all such details, the experimental outcome is simply stated: Clocks that take one or many round trips at higher speed record a smaller elapsed time than clocks that take one or many round trips at lower speed."[7]

Twin effect verified!

"These various results - plus many others we have not described - combine to give overwhelming experimental support for the predictions of the astronaut concerning the proposed trip to Canopus."[8]

Dr. Bright sits back in his chair with a smile, obviously believing that he has disposed of all objections single-handedly.

"Yes," we conclude, "about the reality of the effect there is no question. Therefore if you all approve, and the Space Agency provides that new and very fast rocket, we can be on our way."

The meeting votes approval and our little story ends.

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1 "Airliner" test of twin effect

2 "Circling airplane" test of twin effect

3 Trouble: Large frame is not inertial

4 Solution: Use general relativity

5 "High-speed radioactive particle" test of twin effect

6 Earth frame: Free-float for particle experiments

7 "Oscillating iron nucleus" test of twin effect

8 Twin effect verified!
