observational results that are put forward until they have been confirmed by theory," attributed to Eddington by G. S. Stent [*The Coming of the Golden Age* (Natural History Press, New York, 1969), p. 31]. Stent says this is "a realistic description of the psychological dynamics that obtain at the frontier of scientific advance."
36. M. Planck, *Philosophy of Physics* (Norton, New York, 1936), p. 97; *A Scientific Autobiography and Other Papers* (Williams & Norgate, London, 1950), pp. 33–34.
37. W. Heisenberg, *Physics and Beyond* (Harper & Row, New York, 1971).
38. In a private communication, I. Scheffler has pointed out that he locates objectivity not in the individual behavior of scientists, but in the "institutionalized controls by which science itself evaluates theoretical novelty" [see also (*32*, p. 72)]. I suppose one must then ask whether, in the historical cases cited in this article, other scientists followed the leader and thus collectively failed to exert these institutional controls. My opinion is that this is indeed what happened, but there is not enough space to debate the point here. Scheffler has published a further criticism of Kuhn's theory in *Philos. Sci.* **39**, 366 (1972).
39. S. G. Brush, *Br. J. Hist. Sci.* **5**, 145 (1970).
40. R. J. Morris, *Proc. Okla. Acad. Sci.* **42**, 195 (1962).
41. A.-M. Ampère, *Bibl. Univers.* **49**, 225 (1832); *Ann. Chim. Phys.* **58**, 432 (1835); *Philos. Mag.*, ser. 3, **7**, 342 (1835); T. S. T[raill], in *Encyclopaedia Britannica* (Edinburgh, ed. 7, 1842), vol. 11, p. 180; M. Somerville, *On the Connection of the Physical Sciences* (Key & Biddle, Philadelphia, 1834), p. 195; W. Whewell, *History of the Inductive Sciences* (Parker, London, 1837), vol. 2, pp. 180–184. [Other references are given in another article (*39*).]
42. S. G. Brush, *Am. J. Phys.* **39**, 631 (1971).
43. See his letter of 1860 to Stokes and statements quoted in S. G. Brush (Pergamon, Oxford, 1965), vol. 1, pp. 27, 150, and 171.
44. J. C. Maxwell, *Rep. 30th Meet. Br. Assoc. Adv. Sci.* (1860), p. 15. This short but important summary of Maxwell's conclusions was not included in his *Scientific Papers*, published by Cambridge University Press in 1890 and reprinted by Dover in 1952 and 1965.
45. S. G. Brush, *Synthese* **18**, 192 (1968); J. T. Blackmore, *Ernst Mach* (Univ. of California Press, Berkeley, 1972).
46. ———, *Arch. Ration. Mech. Anal.* **39**, 1 (1970).
47. See S. G. Brush, *Kinetic Theory* (Pergamon, Oxford, 1972), vol. 3, which includes an English translation of Enskog's monograph, and reprints of Chapman's shorter papers.
48. H. Butterfield, *The Whig Interpretation of History* (Bell, London, 1931), pp. 1–13.
49. See J. Hexter, *Reappraisals in History* (Northwestern Univ. Press, Evanston, Ill., 1961).
50. P. S. de Laplace, *Celestial Mechanics*, trans. by N. Bowditch (Chelsea, New York, 1966), vol. 4, p. 1015.
51. H. F. Kearney, *Science and Change 1500–1700* (McGraw-Hill, New York, 1971).
52. The suggestion that Copernicus was an adherent of Hermetism, deriving from the writings of Frances Yates on Bruno, has been denounced by Copernican scholar Edward Rosen. Rosen asserts that "out of Renaissance magic and astrology came, not modern science, but modern magic and astrology." See his article in *Historical and Philosophical Perspectives of Science*, R. H. Stuewer, Ed. (Univ. of Minnesota Press, Minneapolis, 1970), pp. 163–171; see also M. Hesse, *ibid.*, pp. 134–162. The importance of the role of mysticism and pseudoscience in the origin of modern science in Western Europe, as well as in ancient Chinese science, has been stressed by other historians of science: see, for example, O. Neugebauer, *Isis* **42**, 111 (1951); J. Needham, *The Grand Titration, Science and Society in East and West* (Univ. of Toronto Press, Toronto, 1969), p. 162. See also J. E. McGuire and P. M. Rattansi, *Notes Rec. R. Soc. Lond.* **21**, 108 (1966).
53. A. Koyré, *Isis* **34**, 209 (1943); but see also P. P. Wiener, *ibid.*, p. 301.
54. T. Settle, *Science* **133**, 19 (1961); S. Drake, *Isis* **64**, 291 (1973); J. MacLachlan, *ibid.*, p. 374.
55. T. S. Kuhn, *Isis* **49**, 132 (1958).
56. J. C. C. Smart, *Br. J. Philos. Sci.* **23**, 266 (1972). Herbert Feigl has admitted that "A few of us [philosophers of science] . . . for some time rather unashamedly 'made up' some phases of the history of science" [*Historical and Philosophical Perspectives of Science*, R. H. Stuewer, Ed. (Univ. of Minnesota Press, Minneapolis, 1970), p. 3].
57. D. S. L. Cardwell, *Mem. Proc. Manchester Lit. Philos. Soc.* **106**, 108 (1963–64).
58. L. Eisenbud, "Science for antiscientists," speech given at the American Physical Society meeting, Washington, D.C., 26 April 1972. Kuhn has protested "the description of my views as a defense of irrationality in science," but to no avail; see his article in *Boston Studies in Philosophy of Science*, R. C. Buck and R. S. Cohen, Eds. (Reidel, Dordrecht, 1971), vol. 8, pp. 137–146, and (*29*), p. 186.
59. W. J. Lyons, in *Science in America*, J. Burnham, Ed. (Holt, Rinehart & Winston, New York, 1971), pp. 377–384.
60. This article is based in part on research supported by the National Science Foundation. The author thanks Peter Bowman for his helpful suggestions.

NEWS AND COMMENT

Uranium Enrichment: Rumors of Israeli Progress with Lasers

Rumors have been circulating through the classified research community for the past several weeks that two Israeli scientists have succeeded in enriching uranium with a cheap but sophisticated new laser process. The rumors—which appear to have started with some casual inquiries among U.S. scientists by the Central Intelligence Agency (CIA)—represent an exaggeration, according to one of the two Israeli researchers. There is, nevertheless, an important kernel of truth in the tale—enough to suggest that Israeli researchers are not far behind their American counterparts in developing a technology that promises to greatly reduce the cost and difficulty of obtaining enriched uranium, both for nuclear power plants and for nuclear weapons.

"We have demonstrated the feasibility of laser enrichment, but not the economic feasibility," Isaiah Nebenzahl, a physicist with Israel's Ministry of Defense, told *Science* by telephone from Haifa. Nebenzahl was reluctant to discuss details of the research and took pains to play down the scale of the effort, which he said was "very small."

Last October, Exxon Nuclear, Inc., revealed to a congressional committee that a joint research venture with Avco Everett Research Laboratories had successfully enriched small amounts of uranium by laser, and that the process "is practical today on a laboratory scale." The two Israeli scientists appear to have duplicated this feat. Nebenzahl, however, indicated that he and his colleague, Tel Aviv University physicist Menahem Levin, had not yet produced gram amounts of fissionable material, as was rumored. "We are not near a macroscopic separation," he said.

Nevertheless, some U.S. authorities regard even this small success as a "very significant" indicator both of Israel's technical sophistication and of its interest in what promises to be an extraordinarily cheap method of enriching uranium.

"Enrichment" is a term used to describe any of several ways of artificially concentrating the fissionable isotope ^{235}U, which makes up only 0.7 percent of natural uranium. To make the fuel for conventional, light-water cooled reactors, this concentration is increased to between 2 and 3 percent. Fission weapons normally require an enrichment of more than 90 percent.

The sheer difficulty and expense of enriching uranium have worked for 30 years as effective restraints on the availability of nuclear fuel and weapons. So far only the United States, U.S.S.R., Britain, France, and presumably China have seen fit to build the enormous gaseous diffusion plants necessary to produce large amounts of even modestly enriched uranium. The expense of this process has motivated a continuing search for cheaper and less conspicuous techniques; the leading contender now is the gas centrifuge.

In diffusion plants, uranium hexafluoride gas is pumped at high pressure through porous barriers that preferentially pass the lighter ^{235}U. Thousands of successive steps are required to reach high levels of enrichment. At Oak Ridge, Tennessee, and two other locations in the southeastern United States, "cascades" of diffusion cells fill cavernous buildings as large as 60 acres and half a mile long. One of the hardest things on earth to hide is a gaseous diffusion plant; its mere presence on the landscape, easily detected by satellites, is a dead giveaway of a nation's nuclear intentions.

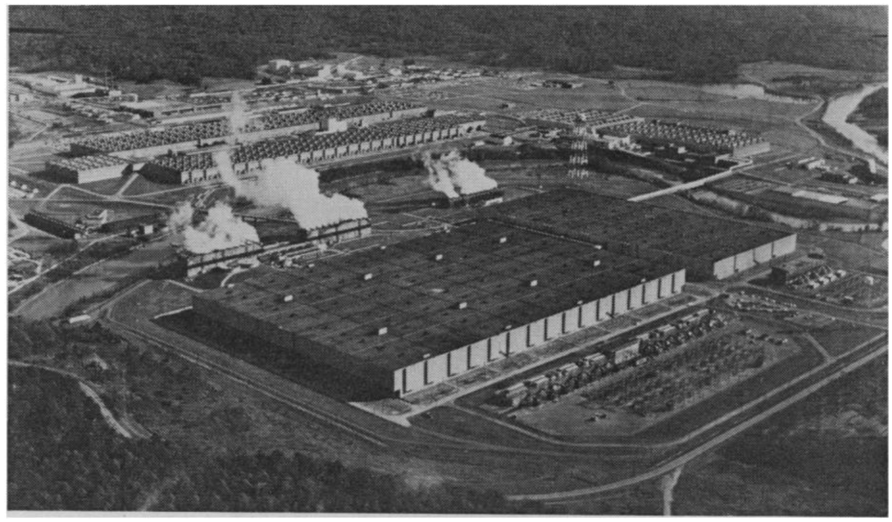
A diffusion plant's capital costs and appetite for electric power are, moreover, fully in keeping with its size. The three U.S. facilities consume about 6000 megawatts at peak production, or roughly 1.5 percent of the nation's entire electrical output. The three plants are now being modernized at a cost of nearly $1 billion, and the Atomic Energy Commission (AEC) estimates the tag for a new diffusion plant at about $2 billion.

Around the mid-1980's, as the world enrichment market rises toward its full profit potential, the gas centrifuge is expected to begin supplanting diffusion technology. France, the Soviet Union, Japan, and a joint British-Dutch–West German combine are all planning centrifuge plants for the 1980's, but the AEC hopes that private industry in the United States will corner a large share of the market. (The AEC estimates the foreign exchange potential of enrichment at $50 billion to $70 billion during the half-century preceding the large-scale advent of commercial nuclear fusion.) Classified centrifuge research, supported by the AEC since 1960, has pushed the state of the art to a point where capital costs would be about the same as for diffusion plants, but power consumption would be only one-tenth as large. Overall costs of centrifuge enrichment are estimated at 20 to 30 percent less.

Even so, enrichment would still be a high-stakes game. In this context, the prospect of laser enrichment—a radically different approach to the problem—has emerged in recent months as something of a wild card.

Both the AEC and the Exxon-Avco group have kept a tight blanket of classification over laser enrichment work, partly because of its potential strategic importance and partly to protect patent security. As one researcher at the Sandia weapons laboratories at Los Alamos describes it, "This is a field a lot of people are talking about without saying very much . . . it's all very hush-hush."

Rudiments of laser isotope separation have been discussed recently in unclassified publications, however.* Basically, the process employs tunable dye lasers—adjusted to very precise frequencies—to excite atoms or molecules of one isotope of a particular element without exciting other isotopes. The excited isotope can then be ionized and separated by electrical or magnetic forces, or it can be extracted by chemical processes.



Gaseous diffusion plants at Oak Ridge, Tennessee.

The process theoretically can be applied to any element; in fact, one early application may be the production of heavy water. Applied to uranium, laser enrichment appears, in principle, to offer several major advantages over gaseous diffusion and centrifuge techniques. Physical size and capital cost of an enrichment plant could be reduced; the laser process would use no more energy, and possibly less, than the centrifuge; and lasers could, in theory, remove essentially all the ^{235}U from a flow of natural uranium, something not now practical.

'A Staggering Advance'

Economics of the process are only roughly calculable, and there's always the danger of a bright new technology being oversold. Excitement, though, is running high at the two national laboratories where most of the AEC's work on laser enrichment has been done in the past few years—the Los Alamos Scientific Laboratory and, to a lesser extent, the Lawrence Livermore Laboratory in California. At Livermore, for instance, one senior physicist told *Science* that he had been skeptical of laser enrichment's promise, but had recently changed his mind. "When you rough out the figures," he said, "you can see that it's just a staggering advance."

Two scraps of public information tend to substantiate this view. Last October, Exxon Nuclear president Raymond L. Dickeman told the congressional Joint Committee on Atomic Energy that a commercial laser enrichment process could be operating by the mid-1980's at an overall cost of 10 to 20 percent less than the cost of gas centrifuge techniques. In January, the AEC's general manager, John A. Erlewine, discussed the implications of this development in a letter to the Joint Committee. If laser techniques lived up to their current promise of low cost and high efficiency, Erlewine said, such a process would "make alternative enrichment processes economically obsolete."

There were implications for the nation's breeder reactor program as well, Erlewine acknowledged. The AEC has predicated its argument for pressing rapidly ahead with the breeder—which would make plutonium fuel—on a prediction that the present low cost of uranium fuel will begin to soar in the mid-1980's as reserves of high grade ore diminish. Commercial laser enrichment, Erlewine said, could reduce natural uranium demand by 10 to 40 percent and "establish a more difficult economic target for the commercialization of the breeder."

Since then the AEC has announced its intention to increase its support of laser enrichment R&D from less than $1 million in the current year to $10.7 million in fiscal 1975.

Rumors of Israeli interest in laser enrichment have popped up sporadically in the past couple of years, but they began flying in earnest last month. It all seems to have started on 31 January, when a man from the CIA paid a visit to Michael M. Hercher, an associate professor of optics at the

* *Science*, 4 May 1973, p. 451; Laser-Fusion Program Semiannual Report (January–June 1973) (Lawrence Livermore Laboratory, UCRL-50021-73-1).

University of Rochester. Hercher says he doesn't recall the CIA man's name, but that it's not unusual for intelligence operatives to circulate around universities inquiring into the significance of newly reported foreign research.

In this case, the agent wanted Hercher to look over some abstracts of papers and patent applications dealing with tunable lasers. Among the abstracts was one describing a laser enrichment process for which the two Israeli scientists, Nebenzahl and Levin, had sought a patent in West Germany in March 1972. (The patent was granted on 4 October 1973.)

The date of the application is significant, because Nebenzahl was a postdoctoral research associate at Cornell University's plasma physics laboratory from September 1970 to July 1972. Lab director Peter L. Auer remembers Nebenzahl as a "brilliant fellow," but one who expressed no interest in isotope separation. Officials at Avco are wondering when he had time to do the experimental work underlying a patent application dated 4 months before his return to Haifa. One senior Avco official said the company knew of no connection between its staff and Nebenzahl, but said the possibility had not been ruled out. The official added, however, that he suspected nothing dubious on Nebenzahl's part and noted that laser isotope separation had been widely discussed since the late 1960's. "The difference was," he said, "that we did something about it."

The 100-word abstract described rather vaguely a process whereby natural uranium vapor was run through two dye lasers; these lasers excited ^{235}U atoms to a level high enough so that they could be ionized in the infrared light of a carbon dioxide laser, then to be collected on electrically charged plates.

The process seemed sophisticated enough to warrant attention in its own right. But the part of the abstract that was to send a chill up the collective spine of the weapons establishment told how, in 24 hours, the process produced a "yield of 7 grams [of ^{235}U] of purity 60 percent." According to one weapons authority, a clever designer would need just under 50 kilograms of uranium enriched to 60 percent ^{235}U to make a fission bomb.

Hercher says he didn't believe the Israelis had done what they seemed to claim, least of all 2 years ago. But his skepticism didn't keep him from taking the abstract with him to a February meeting in Chicago of the program committee for the 8th International Quantum Electronics Conference. The meeting, sponsored by the Institute of Electrical and Electronics Engineers, was scheduled in San Francisco this June, and the committee was still casting about for promising papers; this seemed promising indeed.

Joseph A. Giordmaine of the Bell Laboratories, the committee chairman, quickly began a futile attempt to locate the two Israelis and invite them to the meeting. Other committee members ran off Xerox copies of the abstract. From there, it spread like a chain letter through Los Alamos and Livermore and back to Avco and the AEC in Washington. The general reaction appears to have been one of astonishment tinged with disbelief. Thoughts of weapons implications were foremost in mind: Said one laser researcher at Los Alamos, "I guess it means the Israelis are building bombs in their basements." Avco vice-president Richard H. Levy said he hoped it wasn't true, but that if it was, "it's a peculiar way to announce a nuclear weapons program." Levy added, "It shook a lot of us up."

Israel's Ambiguity

One of the great mysteries of the nuclear age is whether Israel is, or even wants to be, a nuclear power. The laser enrichment episode has only compounded the mystery.

The Israeli government has traditionally fostered uncertainty about its nuclear capability, apparently in the belief that ambiguity offers some of the advantages of a nuclear deterrent without the disadvantage of obliging its neighbors to go nuclear. Thus, on the one hand, there is good reason to believe that no nation has or would supply Israel with nuclear weapons, and Israel has never tested one of its own. (The United States, it should be noted, never tested the uranium bomb it dropped on Hiroshima.)

On the other hand, Israel has declined to sign the nuclear nonproliferation treaty, and experienced weapons designers here have no difficulty believing that Israeli technicians could assemble a fission bomb if the necessary uranium or plutonium were available. Israel's tightly guarded reactor at Dimona, built by the French in the mid-1960's when relations between the two countries were much warmer, probably has produced enough plutonium for a bomb or two, but arrangements covering ownership of the spent fuel containing the plutonium have never been disclosed.

Attempts to clarify the laser enrichment abstract have added new layers of cloud cover to the debate. In Tel Aviv, a spokesman for the Ministry of Defense said that Nebenzahl and Levin "had been engaged by us," but added that "their present work has nothing to do with the [patent] application." Nebenzahl himself said he hadn't written the abstract. At one point in a telephone interview, he called it "quite an exaggeration." At another point he said it was "quite near to what had been done."

Nebenzahl apologized for his vagueness, saying, "I mustn't give too many details," but for reasons of patent protection, not national security. The work, he said, had been carried out in a "government nuclear center" with very little funding.

Was a laser technique used to separate *any* amount of ^{235}U? "It's more complicated than that," he said. "It is an experiment plus a calculation plus an extrapolation."

Some U.S. experts deflated almost audibly when told the news. Said Avco's Levy: "You can demonstrate feasibility of the process with 100 atoms . . . this is in the range of almost anyone these days with a couple of good quality lasers." Others, including one high official of the AEC's division of military applications, nevertheless regard the Israeli work as a significant measure of their prowess in a field of strategic importance. (Two sources who have read the full 16-page patent application in German say something may have been gained in translation. The laser technique is described more as a hypothetical process than as an accomplished fact.)

The rumors, it seems, sent through the weapons establishment a premature but perhaps premonitory shiver of things to come. Technology is eroding the cost and conspicuousness of enriching uranium; as a result, smaller and less affluent nations may eventually find their nuclear intentions easier to fulfill and harder for others to discover.

It is probable that no one is yet lasing natural uranium into gram lots of bomb-quality material. But the possibility is no longer farfetched. If, or when, that day arrives, one researcher at Los Alamos observes, "The whole world had better be a little bit uneasy, because it will be a whole lot easier to make bombs."—ROBERT GILLETTE