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LECTURE 3

WEAK INTERACTION STUDIES USING RESONANCE IONIZATION SPECTROSCOPY*

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MASTER

WEAK INTERACTION STUDIES USING RESONANCE IONIZATION SPECTROSCOPY*

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1. Counting Atoms with Resonance Ionization Spectroscopy (RIS)

Important developments in laser sources for the vacuum ultraviolet (VUV) region of the spectrum (see Lecture 1) are making it possible to carry out resonance ionization (for a review, see Ref. 1) of some of the noble gases. It has already been shown that xenon can be ionized in a two-photon allowed excitation from the ground state. Recently a new method of generating radiation by four-wave mixing in mercury vapor² enables excitation of xenon in a one-photon resonance process. With these new laser sources³ we expect to have effective ionization volumes of 10^{-3} - 10^{-2} cm³ for the cases of argon, krypton, and xenon. This has important consequences in weak interaction physics and environmental research.

Widespread applications of noble gas detectors are due to the fact that small numbers of the chemically inert atoms can be recovered from very large targets of materials where they may be generated by rare events. In this lecture we show how lasers can be combined with mass spectrometers to detect a few noble gas atoms of one isotope in the presence of very large numbers of atoms of a neighboring isotope.

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This technique [which we have called Maxwell's demon because of the atom-sorting functions performed in the apparatus] is described and then followed with a brief discussion of two applications in weak interaction physics - double-beta decay and the solar neutrino problem. Other applications of atom counting have been reviewed in a Physics Today article.⁴

2. Development of Maxwell's Demon

Since Resonance Ionization Spectroscopy (RIS) schemes all involve one or more bound-bound transitions, atomic number (Z) selectivity is virtually assured. A RIS source for a mass spectrometer provides a combination of Z and A (atomic mass) selectivity for the analysis of individual atoms. This two-fold selectivity can be put to use in counting atoms of a particular isotope (see Fig. 1).

Since the effective volume of the high-vacuum chamber is rather large (~2.5 liters) and the volume that can be saturated in the resonance ionization process is quite small ($3 \times 10^{-3} \text{ cm}^3$), it is necessary in a practical application of the one-atom detector to find a way to increase the chance of a noble gas atom being in the beam at the time the laser is fired. In our case the sample is frozen onto a liquid helium cold finger. When the light of a pulsed visible laser strikes the cold finger, the noble gas atoms are released instantly and travel a few millimeters before the time-delayed ultraviolet laser is pulsed just above the cold finger and ionizes a significant fraction of the sample. The ionization probability for a single atom of a selected isotope can be adjusted to approximately 10% in order to achieve true digital counting.

The ability to sort xenon atoms from other atoms in a small volume by means of selective laser ionization and ion implantation⁵ has been demonstrated.⁶ We have shown the depletion of xenon atoms in volumes of 50 and 15 cm³, using pulsed dye lasers pumped by harmonics of a Nd-YAG laser to produce Xe⁺ ions followed by implantation of the ions into a channeltron detector. When an ion strikes a metal, electrons are emitted in sufficient quantity⁷ to insure the counting of each ion.

Since the abundance of sensitivity of the quadrupole mass spectrometer is only 10³, many atoms of neighboring isotopes will be implanted for samples in which the selected isotope has a very low abundance, e.g., 1:10¹⁵. The system, therefore, is designed to allow for an indium target to be heated or melted inside the high vacuum in order to release all of the implanted atoms, which will then be collected again on the liquid helium cold finger. After a small number, n, of these cycles, an enrichment of 10³ⁿ will be achieved and the selected atoms will be counted by implantation into a copper-beryllium target.

3. Studies of Double-Beta Decay

Double-beta ($\beta\beta$) within a nucleus can be either a two-neutrino (2ν) process or a neutrinoless (0ν) process, depending on the nature of the neutrino.⁸ This is illustrated by starting with the Majorana neutrino in the Racah sequence:

$$n \rightarrow p + e^{-} + \bar{\nu}_M,$$

$$\bar{\nu}_M + n \rightarrow p + e^{-}.$$

Such a sequence in a nucleus converts two neutrons to two protons plus two electrons and is a 0ν process. If lepton number conservation holds, this sequence does not occur. Such a (Majorana) particle is identical with its own antiparticle and violates lepton conservation. A Dirac neutrino has a distinct antiparticle; hence, $\beta\beta$ decay must proceed as a 2ν process, i.e.,

if lepton number is conserved. Rosen argued that the observation of a 0ν mode in $\beta\beta$ decay would prove that lepton number is not conserved and would be an extremely important discovery for building grand unified models. These are strong motivations for examining the role that one-atom detection could play in the study of $\beta\beta$ decay.

Kirsten's group^{9,10} at Heidelberg made extensive studies of ^{82}Se by detecting ^{82}Kr in geologically old selenium ores. A later result on this total decay rate made by Srinivassan et al.¹¹ gave a half-life of $(2.76 \pm 0.88) \times 10^{20}$ yr. On the other hand, in a cloud-chamber experiment, Moe and Lowenthal¹² found a much higher decay rate with $T_{1/2} = (1.0 \pm 0.04) \times 10^{19}$ yr.

The present work could provide a third type of experiment on $\beta\beta$ decay and would fall in the category of a radiochemical tank experiment, similar to the approach which Ray Davis uses for solar neutrino flux measurements. The use of one-atom detection for $\beta\beta$ decay of ^{82}Se could proceed as follows. If 10 kg of natural selenium (9.2% ^{82}Se) is put into a well-evacuated enclosure, 100 atoms of ^{82}Kr will be produced each day if the half-life is 1.5×10^{20} yr. At least once each week an easily measurable signal of ^{82}Kr would be generated.

Krypton could be recovered from the selenium and then introduced into the Maxwell demon apparatus for counting each atom.

Recent theoretical results¹³ for the $\beta\beta$ decay in ^{128}Te and ^{130}Te also show that the rates are much greater than the geochemical values. Thus, new experiments on tellurium isotopes are especially attractive as a check on the geochemical measurements. Furthermore, Rosen⁸ points out that if nuclear matrix elements are assumed to be equal for the transitions $^{128}\text{Te} \rightarrow ^{128}\text{Xe}$ and $^{130}\text{Te} \rightarrow ^{130}\text{Xe}$, then the ratio of their lifetimes just depends on phase space considerations. This argument is used to predict that the ^{128}Te lifetime is 200 times longer than the ^{130}Te lifetime if the decay is pure $2\nu\beta\beta$; whereas if pure $0\nu\beta\beta$, the same lifetime ratio is 6×10^3 .

The new kind of $\beta\beta$ -decay experiment based on counting the atoms should apply to the tellurium cases. Assume, for example, that $T_{1/2} = 3 \times 10^{24}$ yr for ^{128}Te and 3×10^{21} yr for ^{130}Te . A 200-liter tank filled with 1000 kg of tellurium would produce one atom of ^{128}Xe per day and 1000 atoms of ^{130}Xe per day. Such an experiment could reveal whether the neutrino is a Dirac or a Majorana particle.

4. Solar Neutrino Flux Determination

Neutrinos are the only particles that are able to escape from the center of the sun where thermonuclear processes occur. They thus serve as the only direct means of testing the standard theory of solar fusion processes.¹⁴ Recent measurements¹⁵ with a $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ detector indicate that the neutrino flux due to the ^8B source in the sun is less than one-third of that expected from standard models. This discrepancy can apparently only be resolved by rather drastic

changes in the solar model or in weak-interaction theory.¹⁶ Due to the large discrepancy between the only available measurements and theory, it is highly desirable to perform additional experiments.

The present development of a counter of noble gas atoms with isotopic selectivity should make it possible to perform a significant variation of the Ray Davis chlorine experiment. Imagine that the large tank shown in Fig. 2 is filled with ethylene dibromide ($\text{CH}_2\text{BrCH}_2\text{Br}$) instead of C_2Cl_4 . The neutrino capture $^{81}\text{Br}(\nu, e^-)^{81}\text{Kr}$ (due to ^7Be solar neutrinos) can then be used as a detector provided that the $2.1 \times 10^5\text{-yr } ^{81}\text{Kr}$ can be counted. Clearly, since only 500 atoms of ^{81}Kr are produced in 862 tons of ethylene dibromide in one year, decay counting is not possible. The success of such an experiment will depend on our ability to count about 100 atoms of ^{81}Kr in the presence of 10^8 atoms of ^{82}Kr which could be collected from the tank due to atmospheric contamination. New experiments on solar neutrinos, neutrino oscillation, and $\beta\beta$ decay are being implemented to test fundamental assumptions in weak interaction physics. These depend on ultrasensitive analytical methods made possible by lasers.

References

1. G. S. Hurst, M. G. Payne, S. D. Kramer, and J. P. Young, Rev. Mod. Phys. 51, 767 (October 1979).
2. F. S. Tomkins and R. Mahon, Opt. Lett. 6(4), 179 (1981).
3. Yun-Mui Yiu, K. D. Bonin, and T. J. McIlrath, Opt. Lett. 7(6), 268 (1982).
4. G. S. Hurst, M. G. Payne, S. D. Kramer, and C. H. Chen, Phys. Today 33(9), 24 (1980)
5. R. G. Wilson and G. R. Brewer, ION BEAMS (Wiley, New York, 1973).
6. C. H. Chen, G. S. Hurst, and M. G. Payne, Chem. Phys. Lett. 75, 473 (1980).
7. K. H. Krebs, Fortschr. Phys. 16, 419 (1968).
8. S. P. Rosen, "Double Beta Decay and Limits on the Mass of Majorana Neutrinos," paper presented at the Workshop on Neutrino Masses, October 2-4, 1980, Cable, Wisconsin. (Based on a chapter of a forthcoming review of baryon and lepton nonconservation by H. Primakoff and S. P. Rosen.)
9. T. Kirsten, W. Gentner, and O. A. Schaeffer, Z. Physik 202, 273 (1967).
10. T. Kirsten and H. W. Mueller, Earth Planet. Sci. Lett. 6, 271 (1969).
11. B. Srinivassan, E. C. Alexander, Jr., R. D. Beaty, D. E. Sinclair, and O. K. Manuel, Econ. Geol. 68, 252 (1973).
12. M. K. Moe and D. D. Lowenthal, Phys. Rev. C 22, 2186 (1980).
13. W. C. Haxton, G. J. Stephenson, and D. Strottman, to be published.
14. J. N. Bahcall and R. L. Sears, Ann. Rev. Astron. Astrophys. 10, 25 (1972)

15. R. Davis, Jr. and J. M. Evans, in PROCEEDINGS 13th COSMIC RADIATION CONFERENCE, Vol. 3, p. 2001 (1973).
16. J. N. Bahcall, Rev. Mod. Phys. 50, 881 (1978).

Figure Captions

Fig. 1. Schematic of a method for counting individual atoms of the noble gases. Isotope resolution leads to applications such as a ^{81}Kr detector for solar neutrinos on a ^{82}Kr detector for $\beta\beta$ decay.

Fig. 2. Photograph of the large tank used by Ray Davis, Jr. to study the flux of solar neutrinos on the earth.

Fig. 2