

DETECTION OF SINGLE ATOMS BY RESONANCE
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CONF-8606166--1

DE86 011974

ABSTRACT

Rutherford's idea for counting individual atoms can, in principle, be implemented for nearly any type of atom, whether stable or radioactive, by using methods of resonance ionization. With the RIS technique, a laser is tuned to a wavelength which will promote a valence electron in a Z-selected atom to an excited level. Additional resonance or nonresonance photoabsorption steps are used to achieve nearly 100% ionization efficiencies. Hence, the RIS process can be saturated for the Z-selected atoms; and since detectors are available for counting either single electrons or positive ions, one-atom detection is possible.

Some examples are given of one-atom detection, including that of the noble gases, in order to show complementarity with AMS methods. For instance, the detection of ^{81}Kr using RIS has interesting applications for solar neutrino research, ice-cap dating, and groundwater dating.

* Research sponsored by Office of Health and Environmental Research, U.S. Department of Energy under contract DE AC05 84OR21400 with Martin Marietta Energy Systems, Inc.

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1. Introduction and Scope

The physical process known as resonance ionization spectroscopy (RIS) was discovered in 1975 when it was used as a method to measure the population of the He(2^1S) state following the interaction of radiation with helium gas (Hurst et al. 1975). Nearly all applications of the method have involved atoms in their ground state, since the need to count individual atoms has overwhelmed the application of RIS to radiation physics problems. The proceedings of the Second International Symposium on RIS and Its Applications (Hurst and Payne 1984) summarize applications up to 1984.

Resonance ionization spectroscopy is used to selectively ionize atoms (or molecules) based on known spectroscopy of the species. When using the process, a laser is tuned to a wavelength which will promote a valence electron in a Z-selected atom from its ground state to an excited state. Additional resonance or nonresonance steps are used to achieve nearly 100% ionization efficiencies. Hence, the process can be saturated for the Z-selected atoms. One-atom detection is accomplished by using detectors for counting[^] either single electrons_^ or single positive ions_^.

In this article the RIS principle will be discussed

briefly and the status of the technology associated with practical use of atom counting will be summarized. Some examples of the application of one-atom detection will be given to show complementarity with AMS methods. For instance, the detection of ^{81}Kr using RIS has a range of interesting uses, including solar neutrino research, ice-cap dating, and groundwater dating.

2. The RIS Principle

Each atom contains electrons which orbit around a nucleus with positive charge. Normally, these electrons are packed near the nucleus in a configuration of orbits determined from quantum mechanics. An atom in its ground state can be excited by the absorption of a photon of the proper energy (wavelength). Each type of atom has its own unique set of ground states and excited states, and one can take advantage of this to detect only those atoms of a given kind.

Now suppose that the atom of a preferred type has been excited, i.e., an electron was promoted from its ground state to some excited state due to the absorption of a photon from a laser beam which was tuned to the exact wavelength acceptable by the type of atom to be detected. An atom in its excited state can also absorb photons and be excited to a higher discrete state. Or, if the photon carries enough energy, the excited electron in the atom can be totally removed from the atom. We now need to stress the most important feature of

RIS. If a laser is tuned to a wavelength such that direct ionization cannot occur from the ground state, and if the wavelength is precisely tuned so that excitation can occur, then resonance ionization can occur provided the sum of the energy carried by the two photons is greater than the ionization potential (I) of the atom. In other words, only the photons having a narrow range of energies will ionize an atom, and this was called resonance ionization spectroscopy (RIS) (Hurst et al. 1975)

Modern laser technology provides means for using many colors in the same beam; thus, more than one resonance excitation step can be employed. This makes it possible to achieve resonance ionization with atoms having the larger values of I , e.g., hydrogen and the noble gases. In figure 1 we show that by using various RIS schemes it is possible to achieve selective ionization of nearly every element in the periodic table. The noble gases helium and neon are the most difficult since lasers are not yet available for promoting the first transition from the ground state to first excited state.

If a laser provides enough photons in a single pulse, a truly remarkable process is possible. Suppose a real sample is composed of free atoms of several types. A tuned laser can be pulsed one time to ionize all of the atoms of a selected type, yet will leave undisturbed all of the other types of atoms. This is known as saturation of the RIS process. It has been shown (Hurst et al. 1979) that the saturated RIS process can be achieved for nearly all of the elements as shown in figure 1. However, the effective ionization volume

depends very much on the type of atom. This is due to several factors. First, lasers can be used to generate photons in certain wavelength regions more easily than in others. Generally, it is easy to saturate the discrete transition from the ground state but more difficult to saturate the photoionization step. However, since the cross section for photoionization of an excited state depends on photon wavelength and the quantum mechanical description of the level in question, some types of atoms are more easily ionized than are others. At one extreme, with the cesium atom, a laser producing 1 J per pulse at 4555 Å would saturate an area of several cm^2 ; and, because the laser beam has a low divergence, effective volumes could be several liters! On the other hand, for RIS of krypton it is difficult to produce more than about 1 μJ per pulse at the VUV wavelength needed to excite the first (one-photon allowed) level in krypton (Hurst et al. 1985). Consequently, the first step is the limiting step and effective volumes are only about 10^{-3} cm^3 . Furthermore, the effective ionization volume which can actually be utilized depends also on the type of sensitive ionization detector used.

The enormous potential for sensitive analyses based on RIS principles cannot be realized until technology is available for counting individual atoms. One-atom detection has been clearly demonstrated in three fundamental ways. It was shown (Hurst et al. 1977) that individual cesium atoms diffusing from a metal source could be counted. Furthermore, cesium atoms were detected (Grossman et al. 1977) following

their dissociation from molecules of CsI. Finally, it was shown (Kramer et al. 1978) that daughter atoms could be detected at the instant of their birth from the decay of a parent atom. All of these basic demonstrations used proportional counters to detect single electrons created from the RIS process on individual atoms. These interesting demonstrations do not, however, constitute proof that sensitive analyses can be done in practical applications. Widespread applications for routine analytical problems require some additional steps.

3. Maxwell's Sorting Demon

Noble gas atoms do not bond with each other or with other materials. Thus, they are free atoms -- already in a state ready for RIS detection. However, these atoms owe their chemical inertness to the fact that their ionization potentials and other energy levels are greater than for other atoms, making the RIS process more difficult. For this reason, rather special methods based on a process called four-wave mixing (Payne et al. 1984) had to be developed for RIS of the noble gases (Kramer 1984). Even with these elaborate techniques, it is not possible to ionize an atom in a large volume of free spaces -- volumes of 10^{-4} are typical. The apparatus illustrated in figure 2 is known as the Maxwell demon because it sorts individual atoms (Hurst et al. 1985). An "atom buncher" was incorporated to increase the probability

that an atom would be ionized in the RIS process. After an atom is selected for Z, it is then mass selected with a small quadrupole filter. Following both Z and A selection, an atom is accelerated and implanted into a target where it is counted and stored until all like atoms have been counted. Figure 3 shows some results in which 1000 atoms of ^{81}Kr were counted in about 2 hours.

A new generation device is now being developed at Atom Sciences, Inc. by N. Thonnard and associates (Thonnard et al. 1984) which first uses a time-of-flight principle for isotopic enrichment, then for atom counting. Furthermore, major improvements have been made in the atom buncher and in the laser method of RIS. We can anticipate that commercial services will be available for counting ~~argon~~, krypton and xenon with isotopic selectivity in the near future. But the method will continue to be a difficult one, requiring elaborate apparatus and skilled personnel for a few years to come. Some examples of the use of Maxwell's demon are given in section 5.

4. Analysis of Solids

The analysis of trace elements in solids requires an "atomization" step before RIS methods are applicable. The desired objective of the atomization step is the liberation of neutral atoms representative of the atomic composition of the solid. After atomization, RIS is used for Z-selective

ionization, often followed with a mass spectrometer for additional selectivity. Even when the analysis does not require isotopic selection, it can be important to include a mass spectrometer to reduce backgrounds due to nonresonant multiphoton ionization (MPI). Several methods have been used to atomize a sample, including thermal, laser ablation, and ion sputtering.

Laser ablation holds much potential, but to date certain fundamental problems such as plasma processes near the sample which can interfere with ion optics have not been solved. When thermal methods are used with RIS, they are usually called resonance ionization mass spectrometry (RIMS) (Donohue et al. 1984, Young et al. 1984, Travis et al. 1984, Clark et al. 1984, Nogar et al. 1984, Harrison et al. 1984). Finally, when sputtering is employed to initiate the RIS process, it can be referred to as SIRIS (Parks et al. 1983,1984). Early work on the use of sputtering to atomize samples for RIS analyses was advanced by Winograd and his collaborators (Kimock et al. 1984) for bulk materials and by the Atom Sciences group (Parks et al. 1983,1984) for trace element analyses.

Since the sputtering process has been characterized in detail and is understood as a simple first-order process, it is reasonable to believe that SIRIS is almost independent of matrix effects. To elaborate, with secondary ion mass spectrometry (SIMS), the signal is due to secondary ions released from the solid when a primary ion (e.g., 10 keV Ar⁺) strikes. The yield of these ions (per neutral atom of the

trace element originally in the sample to be analyzed) depends substantially on the host material (matrix). But this may be due to complex chemistry involving ions; and if so, matrix effects should be much less when the signal is derived from neutral atoms ejected during the sputtering process. However, some recent results cast doubt on this optimism; and as a result, SIRIS analyses will also have to be calibrated with standards. It is too early to know how often such calibrations are required. There is also a large advantage to the extra sensitivity of SIRIS compared to SIMS. A schematic diagram of SIRIS as developed by Atoms Sciences, Inc. is shown in figure 4, while figure 5 shows some representative data. Note that the full potential of SIRIS would be about 10 to 100 times that shown in figure 5. Thus, it is hoped that parts-per-billion analyses will be routine with only moderate matrix effects. Applications of the SIRIS method (Parks *et al.* 1983,1984) range from measurement of impurity levels in electronics grade semiconducting materials to the detection of trace elements in the blood of prenatal children.

5. The $^{81}\text{Br}(\nu, e)^{81}\text{Kr}$ Solar Neutrino Detector

Modern astrophysics has made remarkable progress in understanding the interior of stars and the mechanisms of energy production (see Chandrasekhar 1984). From the early suggestion of Russell (1919), Eddington (1919) followed up the idea of an internal energy source (in addition to gravity) and

speculated that the sun produces energy by the burning of hydrogen atoms. Bethe (1939) showed that hydrogen atoms are fused to make helium atoms in two ways, the P-P chain and the C-N-O cycle. Fowler (1984) credits Fred Hoyle with the "grand concept of nucleosynthesis in stars." S. Chandrasekhar and William A. Fowler shared the Nobel prize in physics in 1983 for their contributions to the development of modern astrophysics.

It is believed that the sun and its internal energy source are understood well enough to make an accurate prediction of solar neutrino production. However, a careful experiment has been done (see below) and the result is a neutrino flux that is significantly lower than predicted. Because of this problem, the calculations by Bahcall and associates, as well as experimental refinements by Davis and associates, have continued but have not resolved the problem. The origin of the discrepancy is still unknown; it may be due to a flaw in the standard astronomical model, or it could be due to a lack of knowledge in neutrino physics.

A review by Bahcall et al. 1982 gives a critical evaluation of uncertainties in predicting capture rates in solar neutrino detectors, using standard solar models (Bahcall 1978,1979). The standard theory of main-sequence stars (Schwarzschild 1958) assumes local hydrostatic equilibrium, energy transport by radiation and convection, and energy production by hydrogen burning. These assumptions are expressed by differential equations, but to solve them requires additional information. An equation of state is

used, together with the radiative opacity (which depends on detailed composition of the sun), and nuclear energy cross sections for the various reactions. Models based on this standard theory, with reasonable assumptions of the initial composition, are referred to as standard solar models. Examples of non-standard models involve unusual assumptions of initial composition, black holes in the sun, fractional charges, etc.

The results of folding nuclear reaction cross sections, the solar constant, elemental abundance, mean opacity, equation of state, and solar age into the standard solar model are shown in figure 6, based on a presentation by Burkes (19). According to the currently accepted solar model of Bahcall, the fraction of energy produced by the P-P chain is 0.985 and only 0.015 for the C-N-O cycle.

The only solar neutrino flux measurement to date was made in the landmark experiment by Ray Davis, Jr. and his associates, using the reaction $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$. For a very interesting history of this classic experiment, see the account by Bahcall and Davis (1982). This difficult experiment has been done, refined, and repeated over the last two decades; for recent reviews, see Davis et al. (19) or Cleveland et al. (1984). Table 1 shows some results of typical runs of the Cl experiment where it is seen that the total rate of ^{37}Ar production is just 0.38 atoms per day. After background correction, the 0.30 ± 0.08 atoms per day corresponds to 1.6 ± 0.4 SNU. Thus, the solar neutrino problem...the measured flux is a factor of 3.6 smaller than

the value calculated from the standard model. These low values persisted in a series of experiments from 1971 until 1983, ~~(see figure 7)~~.

The large discrepancy between predictions of the standard model and experimental results from the Cl experiment has set the stage for a number of interesting speculations. In very general terms, the problem must be in the standard model or in neutrino physics. In the standard model it is possible that some astrophysics or nuclear physics facts are missing, or that some uncertainties come into the transport calculations. In the area of neutrino physics, perhaps all types of neutrinos have rest mass. A difference in mass amongst ν_e , ν_μ , and ν_τ could lead to oscillations between neutrino types. ~~Several~~ **N**ew theories involving the concept of

resonance scattering of neutrinos in the high density matter have been put forth (*Bethe 1984 in an attempt to solve the solar neutrino mystery*).

It is not surprising that a number of new experiments have been seriously considered and proposed to try to resolve the solar neutrino mystery. Other radiochemical experiments, following the original chlorine experiment, are the gallium and the bromine experiments. With gallium, low-energy neutrinos could be measured since the interaction ${}^{71}\text{Ga}(\nu, e^-){}^{71}\text{Ge}$ has a threshold at 233 keV. The inverse decay, by electron capture, occurs with a half-life of 11.4 days; thus, detection of ${}^{71}\text{Ge}$ decay is a measure of the neutrino flux provided cross sections are well known. This experiment was first developed at Brookhaven National Laboratory (Davis et al. 19) with theoretical support by Bahcall (19).

Problem.

Currently, an experiment is planned in West Germany (Kirsten 1984, Hampel 1985) and in the USSR (Barabanov et al. 1985).

The bromine experiment would utilize the reaction $^{81}\text{Br}(\nu, e^-)^{81}\text{Kr}$ which has a threshold at 470 keV and would measure the neutrinos of intermediate energy, primarily the ^7Be source in the sun. Since ^{81}Kr has a half-life of 2.1×10^5 , a solar neutrino experiment using this reaction cannot be done by decay counting. Since it appears that RIS is the only feasible way to count small numbers of ^{81}Kr atoms, we will discuss this important experiment in more detail (Hurst et al. 1984). Scott (1976) first suggested the use of bromine as a geophysical experiment -- here we are discussing a Davis type radiochemical solar neutrino detector.

Combining the cross sections in table 2 with the fluxes of the standard and chlorine-consistent solar models yields capture rates for the Br detector. Approximately 65% of the total signal in both of these models is due to the ^7Be neutrinos. Fortunately, the bromine experiment is dominated by a single solar-neutrino-flux component even if higher excited states contribute to the capture rate. The gallium experiment, in contrast, is dominated by the P-P neutrinos if excited states are neglected, but becomes increasingly sensitive to the ^7Be neutrinos as the effect of excited states increases. Results from a bromine experiment may thus be essential to interpret a gallium experiment.

The chlorine-consistent model predicts a capture rate for the bromine experiment of 8 SNU; and the standard model, assuming that neutrino oscillations are responsible for the

low result of the chlorine experiment, predicts a result in the range of 4.5 to 6.0 SNU. With a detector size comparable to that of the present chlorine experiment, the rate of production of ^{81}Kr is about two atoms per day for the bromine compounds CHBr_3 , CH_2 , Br_2 , $\text{C}_2\text{H}_2\text{Br}_4$, and $\text{C}_2\text{H}_2\text{Br}_2$. Each run of six months to a year will then contain several hundred atoms. Extraction of ^{81}Kr from a bromine-containing compound can be performed by using a helium purge system like that used for extracting ^{37}Ar from C_2Cl_4 . The entire krypton extraction process using the 380- m^3 tank of C_2Cl_4 at Homestake has been demonstrated (see figure 7). *Leif Davis and Cleveland.*

Background effects have to be considered for any proposed solar neutrino experiment (Rowley et al. 1980). These arise from the penetrating cosmic-ray muons, from α decay in the target itself, and from neutrons generated by fission decay or (α, n) reactions in surrounding rock. Cosmic-ray muons can create protons by the photonuclear process and the reaction $^{81}\text{Br}(p, n)^{81}\text{Kr}$ leads to a background. At the depth of the Homestake mine (410 kg/cm^2 or 4100 hg/cm^2 , where hg = hectogram) this background is reduced to about 0.07 atom of ^{81}Kr per day, with the assumption of a volume of 380 m^3 for the bromine-rich organic solution. Alpha particles from the decay of uranium or thorium in the target would initiate $^{81}\text{Br}(\alpha, p)^{81}\text{Rb}$ followed by $^{81}\text{Br}(p, n)^{81}\text{Kr}$. Furthermore, the α process $^{78}\text{Se}(\alpha, n)^{81}\text{Kr}$ leads to background if ^{78}Se is an impurity. The total α -induced background is about 0.03 atom of ^{81}Kr per day, assuming impurity levels to be the same as in the chlorine solution. Similarly, $^{81}\text{Br}(n, p)^{81}\text{Se}$ followed by

$^{81}\text{Br}(p,n)^{81}\text{Kr}$ is a neutron-induced background. And $^{84}\text{Sr}(n,\alpha)^{81}\text{Kr}$ leads to ^{81}Kr if ^{84}Sr is an impurity (unlikely). These neutron-induced reactions would produce about 0.1 atom of ^{81}Kr per day in the target; however, the neutron flux can be easily reduced by a water shield around the tank. Thus, we are left with a total background rate of about 0.1 atom per day, considerably less than the expected rate of about 2.0 per day due to solar neutrinos. The reaction $^{79}\text{Br}(p,n)^{79}\text{Kr}$ could provide a monitor of (p,n) associated backgrounds. More frequent recovery of krypton atoms, followed by decay counting of ^{79}Kr (electron capture, $T_{1/2} = 35$ h) could confirm that the (p,n) background is negligible.

Any krypton from air leaks will contain the atmospheric abundance of ^{81}Kr , viz., 1.6×10^7 atoms of ^{81}Kr per cubic centimeter of krypton (Loosli and Oeschger 1969, Barabanov et al. 1980). The measurements ~~that we have~~ made of krypton extraction from the 380-m^3 C_2Cl_4 tank give an upper limit of 10^{-6} cm^3 , and that will not be a serious source of background. Excessive ^{82}Kr could interfere with the RIS detection of ^{81}Kr ; thus, one step of isotopic enrichment could be necessary to reduce the number of ^{82}Kr atoms due to air contamination before doing the RIS counting.

6. A ^{81}Kr Dating Method for Ice Caps

It has long been recognized that ^{81}Kr could be used for dating groundwater or polar ice core samples in the range 50,000 to 1,000,000 years. A ^{81}Kr -based technique would

considerably extend the range that is accessible to ^{14}C dating and is expected to have definite advantages over other dating methods because of (1) the inert chemical character of krypton, (2) the fact that the atmosphere is the main reservoir with a concentration that has probably been constant for a long time, and (3) the expectation that underground production should be small (Workshop on Dating Old Groundwater, U.S. Department of Energy, Tucson, Arizona, 1978) (Davis and Bentley 1981).

With a solubility of krypton in groundwater of 9.2×10^{-5} cc of krypton per liter of water (10°C) and a $\text{Kr}/^{81}\text{Kr}$ ratio of 1.9×10^{12} , we expect to find only 1300 atoms of ^{81}Kr in 1 liter of modern water. Because of this very low concentration, it has been impossible to use this isotope in geophysical studies. Even the best low-level decay counting techniques would require hundreds of tons of water. Furthermore, contamination with as little as 0.1% of modern air would add enough ^{85}Kr activity to completely mask the ^{81}Kr signal (Lehmann and Loosli 1984).

Obviously, it would be very desirable to have a technique for counting ^{81}Kr atoms directly rather than having to wait for their decay. The recently developed accelerator-based atom-counting systems have successfully been used for several cosmic-ray-produced radioisotopes, such as ^{14}C , ^{10}Be , and ^{36}Cl in geophysical studies (Suter et al. 1985, Beer et al. 1984, Finkel et al. 1980). They cannot be used, however, for ^{81}Kr analyses because krypton does not easily form negative ions for use in a tandem accelerator. Cyclotron

machines operating with Kr^+ ions could, in principle, be used for noble gas work, but the current estimates for sample size again are in the range of several hundred thousand liters of water (Workshop on Dating Old Groundwater, Tucson, Arizona 1978).

Lehmann et al. (1985), using RIS, demonstrated for the first time that ^{81}Kr atoms originating from a groundwater sample of only a few liters can be detected. The complete chain of sample processing, including sampling and degassing of water, separation and purification of noble gases, two cycles of isotope enrichment, and the final detection of ^{81}Kr atoms, has been successfully completed. The procedure does not allow for any direct monitoring of ^{81}Kr until the final counting step. The fact that we were able to detect 1200 (± 300) atoms of ^{81}Kr from an initial calculated level of 1500 atoms proves that losses in the two isotope enrichment cycles, where ions are implanted into and recovered from different targets, can be kept reasonably small. Since these losses are not yet quantified and since the overall accuracy was not very high in this first demonstration, it is too early to assign an "age" to our ^{81}Kr determination. We might, at best, estimate a rough upper limit for the age of this sample or get a preliminary indication that ^{81}Kr underground production in this sandstone aquifer is small.

In order to make the step from a first demonstration of the technique to a ^{81}Kr dating method, *the effort directed by V. Thorne of ASI is* we now concentrate ~~our~~ ~~efforts~~ on the following aspects: (1) Since the enrichment procedure ~~we had to use~~ *d* for this first demonstration is

certainly inadequate for more routine measurements, ~~we have~~
~~built~~ a new facility ^{has before into operation} for the first enrichment cycle by using a
commercial isotope enricher (COLUTRON) with a plasma ion
source and a velocity filter to reduce all unwanted krypton
isotopes by a factor of at least 10,000. The second cycle of
enrichment is now performed in a separate quadrupole system,
which is never used at high krypton pressures. The overall
enrichment factor will be at least 10 times larger than in
this first demonstration and will enable us to completely
separate the ^{81}Kr signal from ^{82}Kr interference in the
counting step. (2) Relative calibration will be achieved by
using ^{78}Kr as an internal standard. The initial modern
 $^{78}\text{Kr}/^{81}\text{Kr}$ ratio of 6.0×10^9 will be reduced by a factor of
200 in each enrichment step by simply switching for short time
intervals from a channel 81 to channel 78. A total of about
 10^8 atoms of ^{78}Kr , together with 1000 atoms of ^{81}Kr , will be
introduced to the counting system. A $^{78}\text{Kr}/^{81}\text{Kr}$ ratio
measurement will then be the basis for dating applications
where only isotope ratios are needed.

With an improved calibration and with the capability of
processing samples in a more routine procedure, we will
investigate the potential of this new isotope for dating polar
ice core and groundwater samples in the range 50,000 to
1,000,000 years. Deep polar ice cores from the Greenland and
Antarctic ice shields contain an invaluable record of past
climatic conditions, probably extending several hundred
thousand years into the past. Establishing a chronology for
these ice cores is clearly of great scientific importance, but

a reliable dating technique for the deepest parts of such cores, where the ice is older than about 10,000 years, does not exist (Patterson 1984). Since 1 kg of modern ice contains roughly the same amount of krypton as 1 L of modern groundwater, the sample processing for ^{81}Kr analysis for ice is analogous to the one outlined for groundwater.

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Figure Legends

Figure 1. With modern pulsed lasers it is possible to saturate the RIS process for nearly all of the elements. At saturation, any atom in the effective volume has a probability of resonance ionization approaching 100%. However, the size of the effective volume varies greatly from atom to atom. R(See text.)

Figure 2. Illustration of a device that can be used to count each atom of a noble gas with isotopic selectivity. The principle of operation is the same as that of Maxwell's sorting "demon."

Figure 3. Illustration of the use of Maxwell's demon to count 1000 atoms of ^{81}Kr in an atmosphere of other isotopes of krypton.

Figure 4. Diagram of a device known as sputter-initiated RIS (SIRIS) as developed by Atom Sciences, Inc. for the analysis of impurities in solids.

Figure 5. Data illustrating the use of SIRIS to detect impurities of gallium atoms in electronics grade silicon.

Figure 6. Calculated flux, F , of solar neutrinos on the earth, according to the standard stellar model of Bahcall.

Figure 7. Extraction of krypton from the C_2Cl_4 tank at Homestake. An initial volume of 1 cm^3 of krypton was added to the 380-m^3 tank, and the extracted volume of krypton was measured for 15 solar neutrino runs. The horizontal bar indicates helium flow of each run. Accumulated percent of krypton recovered is indicated for the first three runs (unpublished data from B. T. Cleveland and R. Davis, Jr.).

~~Table 735~~

table 1

16.5

SUMMARY OF RESULTS

Run No.	Production Rate (³⁷ Ar/day)	
	Most Likely Value	68% Confidence Range
18 → 39	0.38	0.31-0.46
40 → 47	0.39	0.27-0.50
18 → 47	0.38	0.33-0.45

Average ³⁷Ar production rate (18→47) = 0.38 ± 0.07

Cosmic-ray background (muons and ν_{μ}) = 0.08 ± 0.03

Rate above known backgrounds = 0.30 ± 0.08

Possible solar neutrino rate = 5.24 x (0.30 ± 0.08) = 1.6 ± 0.4 SNU

12

Table 1

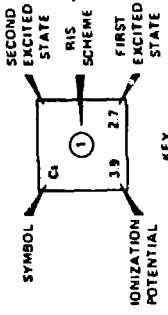
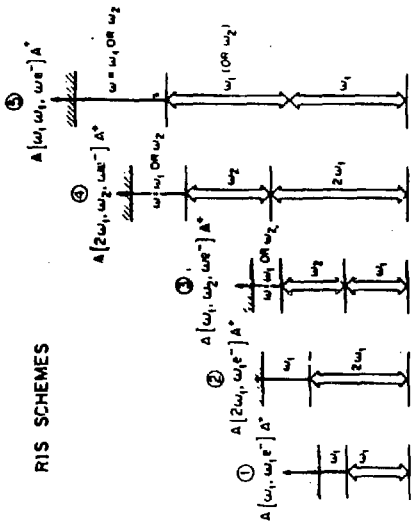
16.5

Table 2

TABLE 2. Calculated ^{81}Br neutrino capture rates for the major solar nuclear reactions. 1 SNU (solar neutrino unit) equals 10^{-26} capture per target atom per second.

Source and energy (MeV)	Neutrino flux ($10^5/\text{cm}^2 \cdot \text{s}$)		^{81}Br cross section (10^{-46} cm^2)		^{81}Br capture rate (SNU)	
	Standard model	Consistent model	Bahcall	Haxton	Standard model	Consistent model
$p-p$ (0-0.42)	61 000	64 000	0	0	0	0
pep (1.44)	150	150	78	85	1.3	1.3
^7Be (0.862)	4300	1800	25	27	11.8	4.9
^8B (0-14)	5.6	1.1	1700	5400	3.0	0.6
^{13}N (0-1.20)	500	160	19	20	1.0	0.3
^{14}O (0-1.73)	400	130	41	44	1.7	0.6
					18.8	7.7

RIS SCHEMES



GROUP	Ia	IIa	IIIa	IVa	Va	VIa	VIIa	VIIIa	IXa	Xa	XIa	XIIa	IIIb	IVb	Vb	VIb	VIIb	VIIIb	IXb	Xb	XIb	XIIb	IIIc	IVc	Vc	VIc	VIIc	VIIIc	IXc	Xc	XIc	XIIc	Inert Gases																																																																			
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100

Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Au	Hg	Tl	Pb	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
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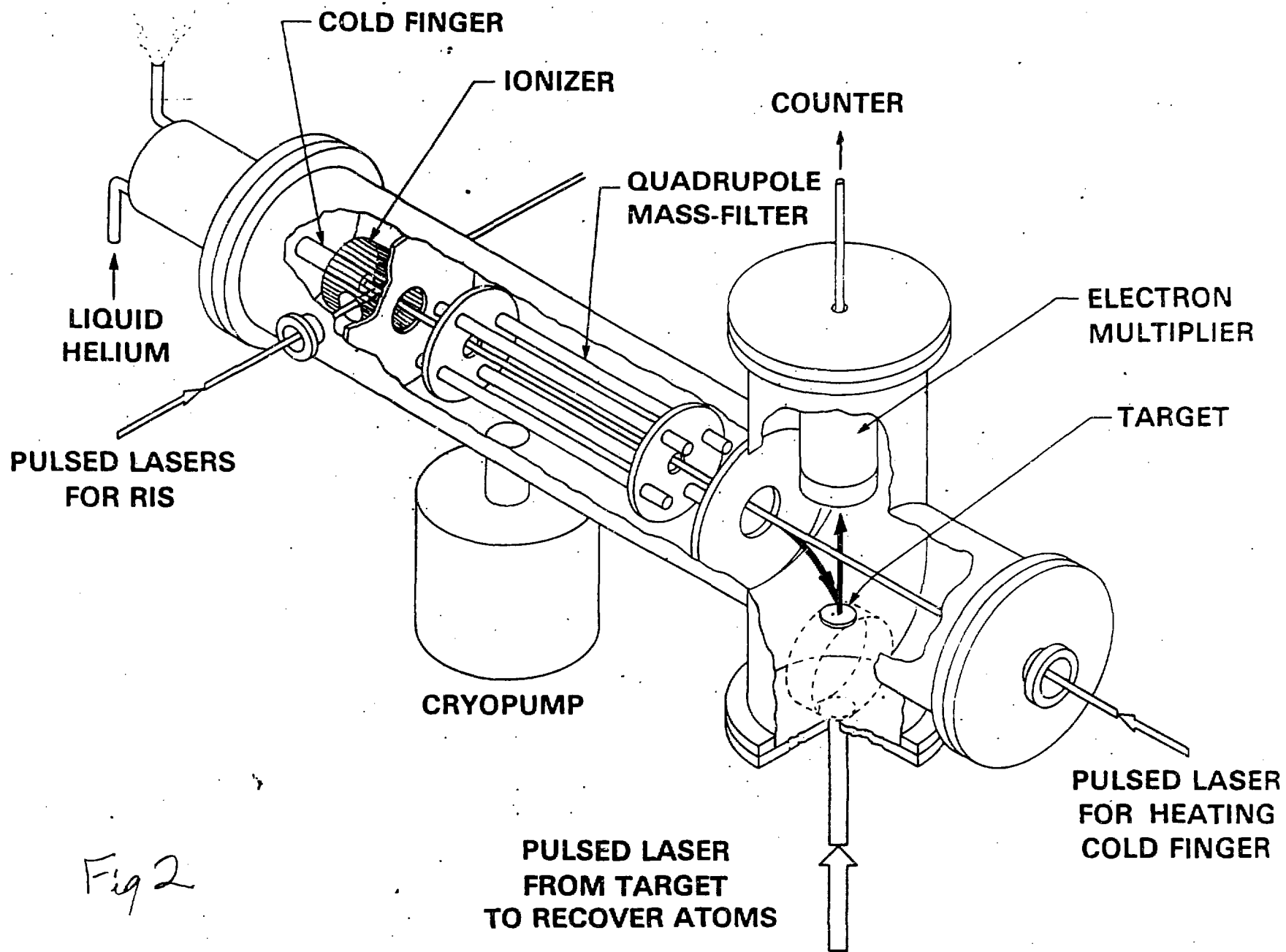


Fig 2

Fig. 2

Fig 3

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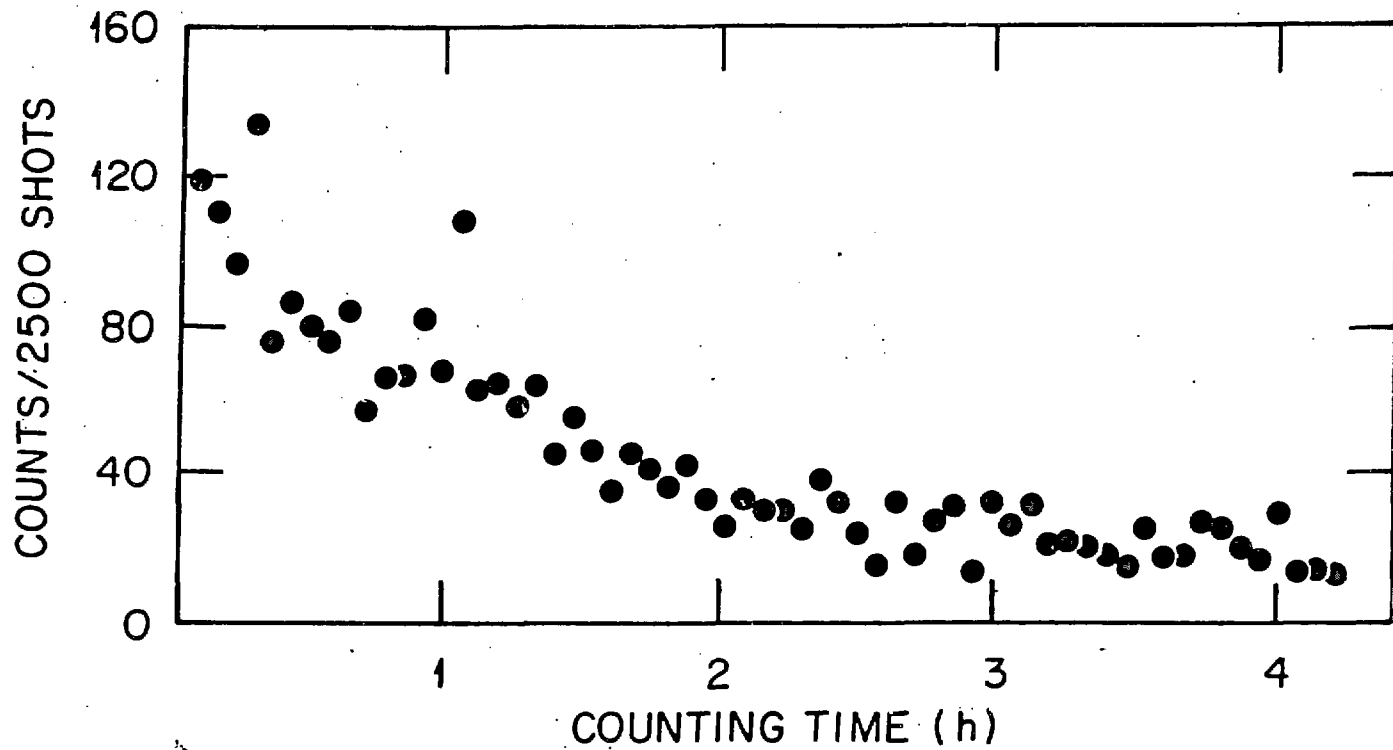
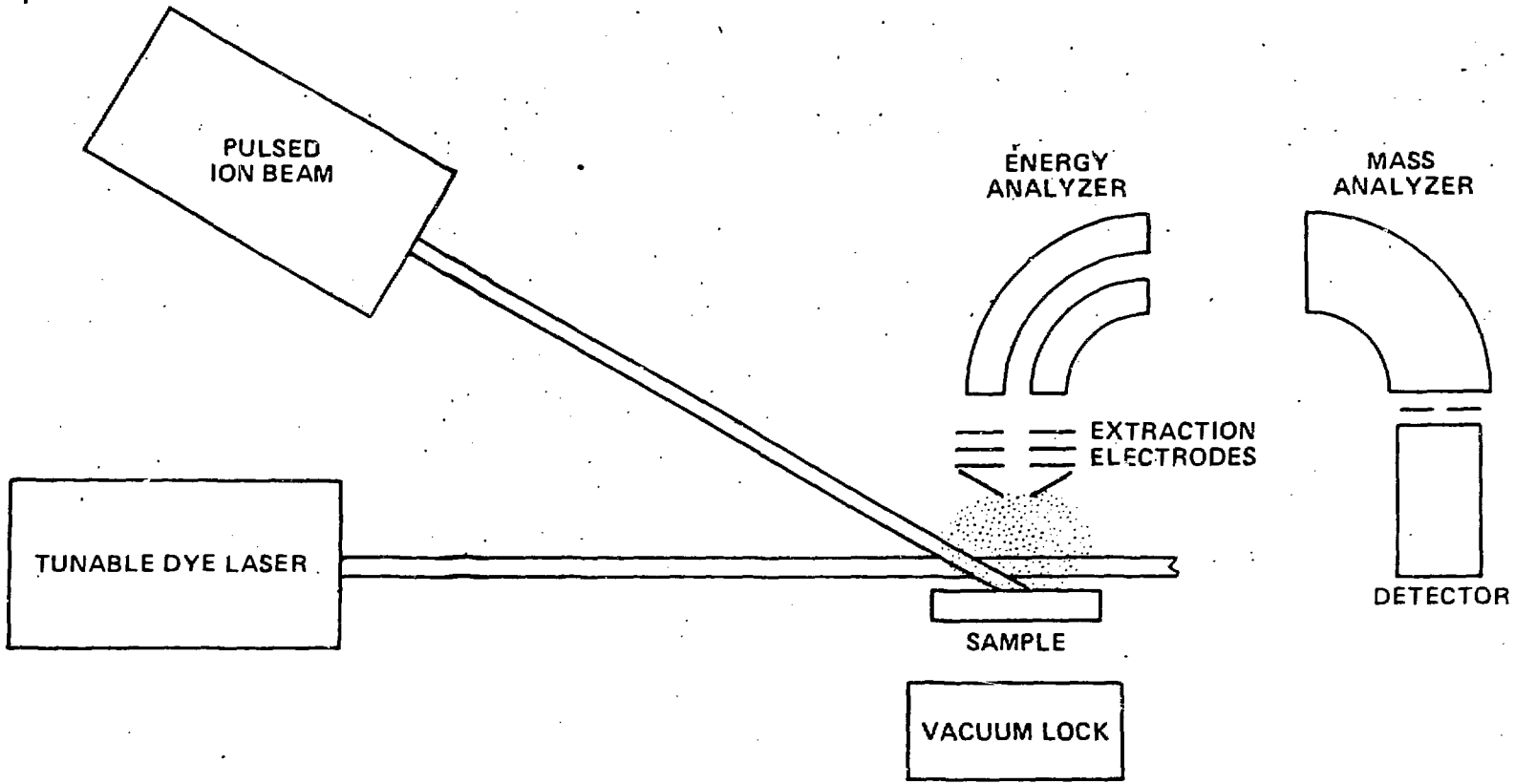


Fig. 3

Fig 4



SPUTTER INITIATED RESONANCE IONIZATION SPECTROSCOPY
(SIRIS)

Fig. 4

Fig 5

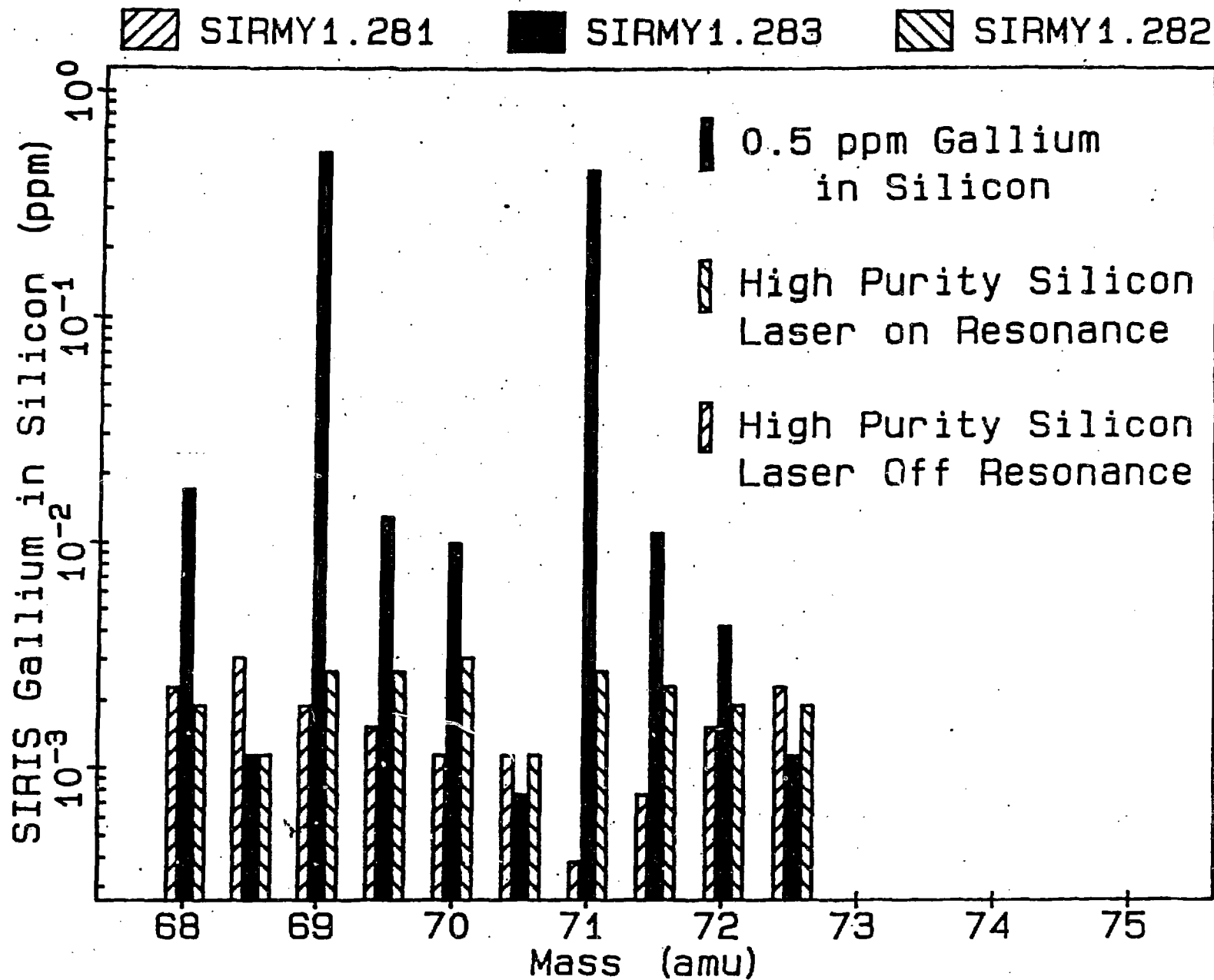


Fig. 5

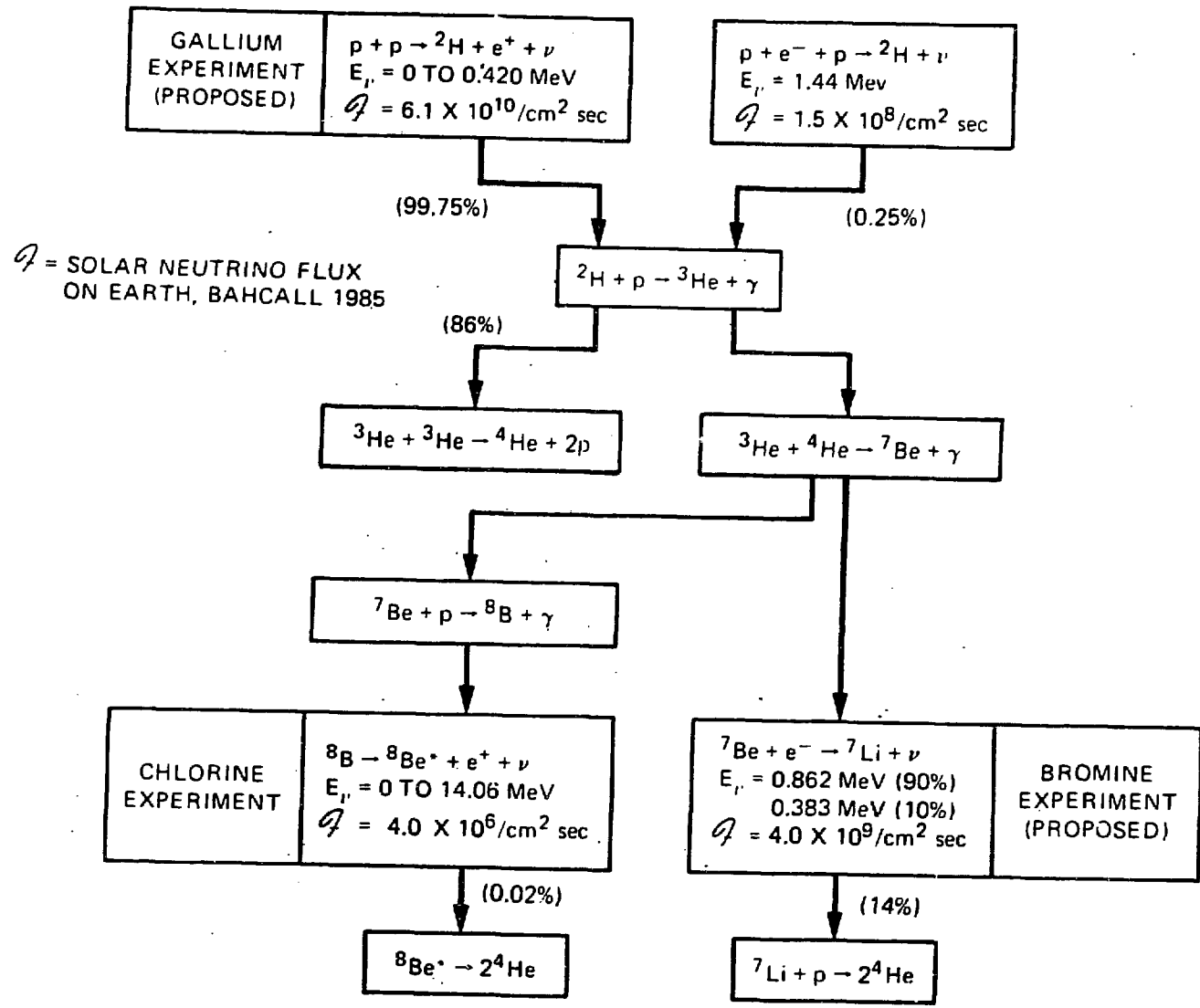


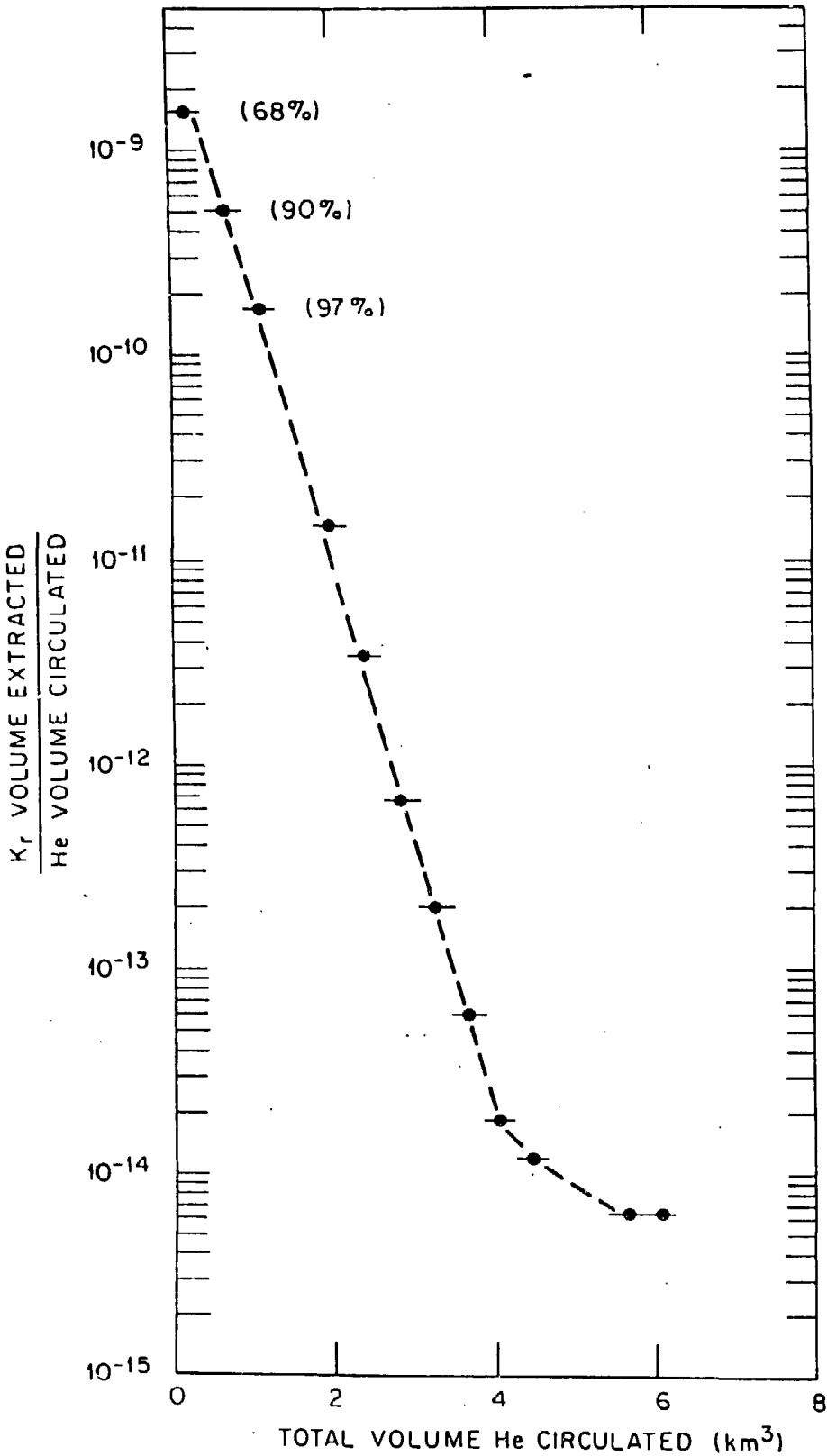
Fig 6

Fig. 6

16.
7/79

Recovery of Krypton from the Savannah Tank

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Recovery of Krypton from
the Savannah Tank
Fig 7

~~1621~~
1291