Feasibility of a $^{81}Br(\nu,e^-)^{81}Kr$ Solar Neutrino Experiment

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A solar neutrino experiment utilizing the interaction of $^{81}Br(\nu,e^-)^{81}Kr$ to study the ^7Be neutrino source in the interior of the sun is shown to be feasible. Resonance ionization spectroscopy was used to count less than 1000 atoms of 2×10^5-yr ^{81}Kr, making the bromine experiment possible. Except for the method of counting product atoms, the bromine experiment would be very similar to the successful chlorine detector $^{37}Cl(\nu,e^-)^{37}Ar$, and thus it is a natural sequel to the only solar neutrino experiment to date.

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The flux of neutrinos on the Earth is believed to be due to several sources in the interior of the sun. Fluxes predicted by the standard solar model of Bahcall *et al.*[1] are given in column 2 of Table I. Mechanisms of energy generation within the sun could be clarified by measuring each of these neutrino flux components.

The only solar neutrino experiment ever undertaken, based on the reaction $^{37}Cl(\nu,e^-)^{37}Ar$ and using a volume of 380 m^3 of C_2Cl_4 at a depth of 410 kg/cm^2 in the Homestake Mine, is primarily sensitive to the weak ^8B neutrino source. The capture rate (the product of flux and cross section[2]) predicted by the standard solar model is 7.6 solar neutrino units (SNU), in disagreement with the value from the chlorine experiment[3] of 1.9 ± 0.3 SNU above estimated backgrounds. The proposed ^{71}Ga experiment[4] is most sensitive to the p-p neutrinos. This Letter considers use of the reaction $^{81}Br(\nu,e^-)^{81}Kr$, with an energy threshold of 470

TABLE I. Calculated ^{81}Br neutrino capture rates for the major solar nuclear reactions. 1 SNU (solar neutrino unit) equals 10^{-36} capture per target atom per second.

Source and energy (MeV)	Neutrino flux ($10^6/cm^2\cdot s$) Standard model	Consistent model	^{81}Br cross section (10^{-46} cm^2) Bahcall	Haxton	^{81}Br capture rate (SNU) 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
^{16}O (0–1.73)	400	130	41	44	1.7	0.6
					18.8	7.7

keV, which is primarily sensitive to the flux of ^{7}Be neutrinos from the sun.[5] We show that an experiment using ^{81}Br is feasible because ^{81}Kr, with a half-life too long (2×10^{5} yr) for radioactivity counting, can now be counted directly, by the method of resonance ionization spectroscopy (RIS). The ^{8}B neutrino flux integrated over the last several million years can be measured[6] by the reaction ^{98}Mo$(\nu,e^{-})^{98}$Tc. The above program of neutrino spectroscopy of the solar interior could provide otherwise unattainable information about stellar physics and about the weak interactions.

The flux of ^{8}B neutrinos is sensitive to the temperature of the sun. The low-Z solar model[7] and the homogenized model[8] would give a lower temperature and, therefore, would predict a ^{8}B solar neutrino flux in better agreement with the ^{37}Cl experiment. Another explanation of the chlorine result is the hypothesis that the neutrinos oscillate among two or more types. If neutrino mixing is maximal and the oscillation wavelength is considerably less than the Earth-to-sun distance, then the electron neutrino flux reaching the Earth would be reduced by the number of neutrino flavors, a factor of 3 or 4. A ^{81}Br experiment will help to differentiate among the several hypotheses.

The calculation of the neutrino-induced ^{81}Kr production rate from ^{81}Br requires the ^{81}Br cross section for neutrino capture. Measurements by Bennett *et al.*[9] imply that the $ft_{1/2}$ value for neutrino capture from the $\frac{3}{2}^{-}$ ground state of ^{81}Br to the $\frac{1}{2}^{-}$ excited state (at 190 keV) is $(7.6^{+2.2}_{-1.7})\times10^{4}$ s. On the basis of this value, Bahcall[10] and Haxton[11] calculated the cross sections for neutrino capture given in Table I. The calculations of Bahcall include only the ground state to first excited state transition; the Haxton calculation uses a nuclear shell model to estimate the magnitude of the neutrino capture transitions to many of the excited states of ^{81}Kr. A statistical model calculation by Itoh and Kohyama[12] considering all states in ^{81}Kr below the particle emission threshold yields a cross section for capture of ^{8}B neutrinos of 7.4×10^{-43} cm^{2}, in substantial agreement with Haxton. Uncertainty about neutrino capture to excited states, especially the $\frac{5}{2}^{-}$ level at 457 keV in ^{81}Kr, has been emphasized by Bahcall. An estimate of the cross section for this $\frac{5}{2}^{-}$ level by Liu and Gabbard,[13] based on ^{81}Br(^{3}He,t)^{81}Kr reaction data, suggests that its contribution to the total capture rate may be nearly half that of the $\frac{1}{2}^{-}$ state. Similarly, in the proposed ^{71}Ga experiment there is a $\frac{5}{2}^{-}$ excited state at an energy of 175 keV. Orihara *et al.*[14] show that neutrino capture to this level may be substantial. Charge exchange measurements, using (p,n) reactions at intermediate energies, are in progress to reduce uncertainties in the contribution due to these higher excited states. Preliminary (p,n) studies[15] on ^{81}Br have been made at the Indiana University Cyclotron Facility (IUCF).

Combining the cross sections in Table I with the fluxes of the standard and chlorine-consistent solar models yields capture rates for the bromine detector. Approximately 65% of the total signal in both of these models is due to the ^{7}Be 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 ^{7}Be 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 4.5–6.0 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, $C_2H_2Br_4$, and $C_2H_4Br_2$. 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.

Background effects have to be considered for any proposed solar neutrino experiment.[16] 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}Br$(p,n)^{81}$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}Br$(\alpha,p)^{84}$Rb followed by ^{81}Br$(p,n)^{81}$Kr. Furthermore, the α process ^{78}Se$(\alpha,n)^{81}$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, as-

suming impurity levels to be the same as in the chlorine solution. Similarly, $^{81}Br(n,p)^{81}Se$ followed by $^{81}Br(p,n)^{81}Kr$ is a neutron-induced background. And $^{84}Sr(n,\alpha)^{81}Kr$ 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 $^{79}Br(p,n)^{79}Kr$ 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.[17] 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.

A method for counting a small number of ^{81}Kr atoms was proposed some time ago,[18,19] and it was shown[20] recently that fewer than 1000 atoms of ^{81}Kr can be counted without waiting for radioactive decay. The method utilizes a resonance ionization process[21] to selectively ionize krypton atoms which are then mass selected with a quadrupole mass filter (A selection). An atom buncher[22] reduces the time required to ionize the krypton atoms, using the RIS scheme described elsewhere.[23] After Z and A selection, these ions are accelerated to about 10 keV and implanted in a silicon target. Assume that a sample of 500 atoms of ^{81}Kr and not more than 10^{8} atoms of ^{82}Kr were recovered from the neutrino tank and introduced into the static detector system. After nearly all of the ^{81}Kr atoms are implanted (requiring about 1 h), there will also be about 2×10^{4} atoms of ^{82}Kr in the target, as a result of limited abundance sensitivity of the mass filter. The residual gas-phase atoms, essentially 10^{8} atoms of ^{82}Kr, are then pumped out before the atoms in the silicon target are removed by laser annealing. During a second cycle the 500 atoms of ^{81}Kr are implanted along with about 40 atoms of ^{82}Kr. If desired, a further isotopic enrichment could be done, but in any case the final implantation will utilize a Cu-Be target which emits enough electrons per pulse to insure nearly absolute atom counting.

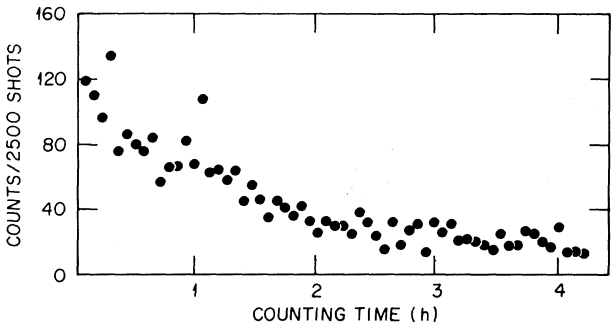

FIG. 1. Demonstration that less than 1000 atoms of ^{81}Kr can be detected by RIS. Atoms are counted individually and then grouped into 2500 laser shots to show exponential decay of the free atoms as they are implanted into a target. When the laser is operated at 10 Hz, the free-atom sample of ^{81}Kr appears to have about 1 h half-life compared to the 2×10^{5}-yr radioactive decay of ^{81}Kr.

In Fig. 1 we show recent data on the direct counting of approximately 1000 atoms of ^{81}Kr that had been enriched at the National Bureau of Standards to simulate a solar neutrino experiment. In the experiment, all the lasers (buncher and RIS lasers) were pulsed at a rate of 10 Hz and individual counts due to ^{81}Kr were recorded and then plotted in groups of 2500 laser shots. It is seen that the free-atom concentration of ^{81}Kr decays with about a 1 h half-life as the ^{81}Kr ions are implanted in a target of Cu-Be. Background associated with nonresonant laser ionization is observed. Calibrations based on the decay counting of ^{81}Kr and our calibrations based solely on knowledge of the detector are in good agreement. The estimated detection limit is about 300 atoms of ^{81}Kr; however, laser improvements to increase vacuum ultraviolet generation and to reduce backgrounds should make it possible to count less than 100 atoms in the near future. The data of Fig. 1 can be regarded as a simulation of a typical neutrino run; thus, we believe that all the steps of a bromine solar neutrino experiment are feasible.

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