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^{81}Br and ^{79}Br as detectors of solar neutrinos

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Uncertainties in nuclear matrix elements that are important for the interpretation of proposed bromine solar neutrino experiments are evaluated. Some laboratory measurements that could reduce these uncertainties are suggested. The question of what can be learned about the interior of the sun by performing a bromine solar neutrino experiment is discussed with the aid of neutrino absorption cross sections that are calculated using simplifying assumptions.

[RADIOACTIVITY ^{79}Br, ^{81}Br calculated neutrino absorption cross sections. ^{81}Kr excited states considered.]

I. INTRODUCTION

The possibility of performing a solar neutrino experiment with bromine has recently been discussed by a number of authors following the pioneering measurement by Bennett *et al.*[1] of the important beta-decay rate between the $\frac{1}{2}^-$ metastable state of ^{81}Kr and the ground state of ^{81}Br. The use of ^{81}Br as a detector of solar neutrinos was suggested independently by Scott[2,3] and Hampel and Kirsten.[4] Rowley *et al.*,[5] Hurst *et al.*,[6,7] and Davis[8] have all discussed recently the practical advantages of an experiment with an inexpensive and convenient detector in which bromine is the target material. However, major uncertainties were pointed out by Bahcall[9] in our knowledge of the nuclear matrix elements that are necessary in order to interpret a bromine solar neutrino experiment. These uncertainties have now been addressed experimentally and theoretically by several authors.[1,10,11] The purpose of the present paper is to provide an answer to the question of what can be learned from a bromine solar neutrino experiment with the present and forseeable state of our knowledge of the relevant nuclear matrix elements.

The plan of this paper is as follows. Section II discusses the possible importance of the $\frac{5}{2}^-$ state at an excitation energy of 0.46 MeV in ^{81}Kr. Section III presents the results of the calculated phase-space factors (Table I) for all the transitions of interest as well as the estimated cross sections (Table II) that are obtained with the aid of the simplifying assumptions regarding the nuclear states. Also given in Table II are the predicted solar neutrino capture rates that are implied by a standard solar model and the estimated cross sections. Section IV contains a discussion of what can be learned about the sun from a bromine solar neutrino experiment.

II. THE $\frac{5}{2}^-$ STATE AT 0.46 MeV IN ^{81}Kr

The $\frac{5}{2}^-$ state at an excitation energy of 0.46 MeV in ^{81}Kr has been studied by Liptak *et al.*[12] and Toyoshima.[13] These authors have established the spin and parity of the state in question by studying the $E1$ γ decay to the $\frac{7}{2}^+$ ground state of ^{81}Kr and the $E2$ decay to the $\frac{1}{2}^-$ excited state at an excitation energy of 0.19 MeV.

This $\frac{5}{2}^-$ state can be excited by all the important neutrino sources that are expected to populate, in a solar neutrino experiment, the $\frac{1}{2}^-$ state, the latter being the only state in ^{81}Kr that is usually discussed. It is important, therefore, to consider whether or not transitions from the $\frac{3}{2}^-$ ground state of ^{81}Br to the $\frac{5}{2}^-$ state of ^{81}Kr could also be significant.

I shall not attempt to prove that the matrix element to the $\frac{5}{2}^-$ state is large since any attempt to make such a proof would require detailed calculations with model Hamiltonians and would involve special assumptions regarding the basis sets for the wave functions, all of uncertain reliability. Here I shall limit myself to showing that some qualitative considerations suggest that the transition $^{81}\mathrm{Br}(\frac{3}{2}^-) \rightarrow {}^{81}\mathrm{Kr}(\frac{5}{2}^-)$ could be important. Small admixtures in the wave functions of the components discussed below could give rise to a significant neutrino absorption cross section.

The ground-state wave function for $^{81}_{35}Br_{46}$ probably contains a significant component, that is, for the neutrons: $(2p_{3/2})^4(1f_{5/2})^6(2p_{1/2})^2(1g_{9/2})^6$ and, for the protons: either $(2p_{3/2})^3(1f_{5/2})^4$ or $(2p_{3/2})^4(1f_{5/2})^3$. The $\frac{5}{2}^-$ excited state of ^{81}Kr probably has a large component in its wave function that is represented by $(2p_{3/2})^4(1f_{5/2})^5(2p_{1/2})^2(1g_{9/2})^6$ for the neutrons and $(2p_{3/2})^4(1f_{5/2})^4$ for the protons. Thus, the transition $^{81}Br(\frac{3}{2}^-)\rightarrow{}^{81}Kr(\frac{5}{2}^-)$ is proportional, for the components mentioned, to the large radial matrix element $\langle 1f_{5/2} \mid 1f_{5/2} \rangle$.

These considerations can be consistent with the fact that the $\frac{5}{2}^-$ state is not measurably populated in the beta decay of $^{81}Rb(\frac{3}{2}^-)$ although the logft value to the $\frac{1}{2}^-$ state is about 5.1 (see, e.g., Ref. 14). One would not be surprised if there were a significant component of the ^{81}Rb ground-state wave function with a configuration $(2p_{3/2})^4(1f_{5/2})^5(2p_{1/2})^1(1g_{9/2})^6$ and a proton configuration of $(2p_{3/2})^4(1f_{5/2})^5$. This configuration permits a normal allowed decay of ^{81}Rb to the simplest shell model representation of the $\frac{1}{2}^-$ state of ^{81}Kr but not to the $\frac{5}{2}^-$ state discussed above.

The above remarks suggest that the beta-decay matrix element for the transition ^{81}Br (g.s.)$\rightarrow{}^{81}$Kr $(\frac{5}{2}^-)$ (excitation = 0.46 MeV) could be appreciable. However, the four seemingly analogous measured beta-decay matrix elements in the mass range $A=79-83$ all have log$ft>6.5$ [examples are: $^{79}As\rightarrow{}^{79}Se$ (6.8); $^{81}As\rightarrow{}^{81}Se$ (6.5); $^{83}Br\rightarrow{}^{83}Kr$ (6.8); and $^{83}Rb\rightarrow{}^{83}Kr$ (6.5); see Ref. 15]. Since the state of interest is presumably rather complicated, it would be useful to test the strength of the Gamow-Teller matrix element connecting the ground state of ^{81}Br to the $\frac{5}{2}^-$ state in ^{81}Kr by measuring at energies above 100 MeV the ratio of the forward differential scattering cross sections to the $\frac{1}{2}^-$ and the $\frac{5}{2}^-$ states in the reaction $^{81}Br(p,n)^{81}Kr$.

III. THE CROSS SECTIONS

The formula for an allowed neutrino capture cross section can be written in terms of the product of a dimensionless phase-space factor D_{AV}, times a quantity σ_0 that depends on the matrix element for the particular transition and which has the dimensions of a cross section. Thus[9]

$$\sigma=\sigma_0 D_{AV} , \tag{1a}$$

where

$$\sigma_0=1.206\times10^{-42}[Z/(ft_{1/2})_{I'\rightarrow I}] \times(2I'+1)/(2I+1)\ \text{cm}^2 \tag{1b}$$

and

$$D_{AV}=\langle pwF(Z,w)/(2\pi\alpha Z)\rangle . \tag{1c}$$

Here, Z is the atomic number of the product nucleus, I (I') is the spin of the initial (final) nucleus, p and w are the momentum and energy of the electron that is produced (in units of m_ec and m_ec^2, respectively), and F is the Fermi function.

Table I gives the calculated dimensionless phase-space factors for all solar neutrino sources of interest and for two possible callibration sources, ^{51}Cr and ^{65}Zn. The procedures used in deriving these numbers have been described in detail elsewhere.[9] The average over the shape of the ^{8}Be state that is populated by ^{8}B decay was approximated using Eq. (34) of Ref. 9.

In previous theoretical discussions, only the ^{81}Br cross sections have been presented. In principle, however, both (or either) ^{79}Kr and ^{81}Kr could be detected and I have therefore given the results for both isotopes in Table I. In fact, the ft value for the transition from the $\frac{3}{2}^-$ ground state of ^{79}Br to $\frac{1}{2}^-$ ground state of ^{79}Kr is known with greater certainty (see below) than for the corresponding ^{81}Br to ^{81}Kr transition.

The states in ^{81}Kr that are included in the results presented in Table I are the $\frac{1}{2}^-$ level (at $Ex=0.190$ MeV), the $\frac{5}{2}^-$ level (at $Ex=0.459$ MeV), the $\frac{3}{2}^-$ level (at $Ex=$ 0.637 MeV), and the analog $T=\frac{11}{2}$, $j=\frac{3}{2}^-$ state at an excitation energy[10] of 9.68 MeV. The states that are included for ^{79}Kr are the $\frac{1}{2}^-$ ground state, the $\frac{5}{2}^-$ state at an excitation energy of 0.147 MeV, and the analog state at 8.41 MeV.[10]

The excitation energy for the $T=\frac{11}{2}$ analog state of ^{81}Kr was originally estimated in two different ways to be 9.80$\pm$0.05 MeV using the semiempirical results discussed by Janecke[15] on Coulomb energy differences. The corresponding estimate for ^{79}Kr was 8.3$\pm$0.3 MeV. The estimates are in good agreement with the precise values measures[10] by Kouzes, Lowry, and Bennett that were cited above. An error of $\pm$50 keV in the excitation energy of either of the analog states would correspond to a change of about $\pm$4% in the value of the relevant phase-space factor given in Table I. The values of Q_{EC} (where EC is electron capture) used in com-

TABLE I. The weighted-average dimensionless phase factors for neutrino sources on ^{81}Br and ^{79}Br.

Source	Maximum neutrino energy (MeV)	^{81}Br $D_{AV}(0.19)$	$D_{AV}(0.46)$	$D_{AV}(0.64)$	$D_{AV}(9.7)$	^{79}Br $D_{AV}(0.0)$	$D_{AV}(0.15)$	$D_{AV}(8.4)$
p-p	0.420	0	0	0	0	0	0	0
p-e-p	1.442[a]	13.6	9.05	6.5	0	0	0	0
^{7}Be	0.862[a]	4.80	2.17	0	0	0	0	0
^{7}Be	0.384[a]	0	0	0	0	0	0	0
^{8}B	14.02	294	276	264	3.0	222	213	2.9
^{13}N	1.199	3.38	1.23	0.40	0	0	0	0
^{15}O	1.732	7.18	4.06	2.50	0	0.03	0	0
^{51}Cr	0.426[a]	0	0	0	0	0	0	0
^{51}Cr	0.746[a]	3.54	0[b]	0	0	0	0	0
^{65}Zn	0.0227[a]	0	0	0	0	0	0	0
^{65}Zn	0.330	0	0	0	0	0	0	0
^{65}Zn	1.343	11.8	7.58	5.2	0	0	0	0

[a]Neutrino line.
[b]1.6 if $\Delta > 0$.

puting Table I were[16] $Q_{EC}(81) = 0.322$ MeV and $Q_{EC}(79) = 1.631$ MeV.

The energy difference Δ defined below is of great importance for possible calibration of the ^{81}Br target:

$$\Delta \equiv M(^{81}\text{Br}) - M(^{81}\text{Kr}) - Ex(\tfrac{5}{2}^-) + q(^{51}\text{Cr}) . \tag{2}$$

Here, $M(^{81}\text{Br})$ and $M(^{81}\text{Kr})$ are the ground-state energies of ^{81}Br and ^{81}Kr, $Ex(\frac{5}{2}^-)$ is the excitation energy (0.46 MeV) of the $\frac{5}{2}^-$ level in ^{81}Kr, and q is the higher-energy neutrino line from the decay of ^{51}Cr ($q = 0.746$ MeV). With the nominal values of these quantities given in the seventh edition of the *Table of Isotopes* (Ref. 16) (and cited above), the $\frac{5}{2}^-$ state in ^{81}Kr is approximately 30 keV too high in excitation to be populated in a ^{51}Cr calibration experiment. It would be important to make a more precise measurement of the energy difference Δ. In a footnote to Table I, I give the expected value for the phase-space factor if the energy difference does turn out to be slightly positive.

Table II gives the neutrino absorption cross sections that were estimated for $^{81}\text{Br} \to {}^{81}\text{Kr}$ and $^{79}\text{Br} \to {}^{79}\text{Kr}$ by assuming that only the first $\frac{1}{2}^-$ state and the analog state are populated by solar neutrinos. For the population of the $\frac{1}{2}^-$ state in ^{81}Kr, I have used the experimental ft value of Bennett *et al.*[1] for the $\frac{3}{2}^- \to \frac{1}{2}^-$ transition ($ft_{1/2} = 7.59 \times 10^4$ sec), which corresponds to a value of [cf. Eq. (1b)]

$$\sigma_0(\tfrac{1}{2}^-;\ ^{81}\text{Kr}) = 5.72 \times 10^{-46}\ \text{cm}^2 . \tag{3a}$$

I calculate an ft value for the corresponding transition in ^{79}Br to ^{79}Kr of

$$(fg_{1/2}) = 4.9 \times 10^5\ \text{sec} , \tag{3b}$$

using data from Ref. 16 and the procedures described in Ref. 9. This ft value is a factor of 6.5 times larger than the ft value reported by Bennett for the corresponding transition in the mass 81 system. The dimensional cross section factor for the excitation of the $\frac{1}{2}^-$ state in ^{79}Kr is then

$$\sigma_0(\tfrac{1}{2}^-;^{79}\text{Kr}) = 0.89 \times 10^{-46}\ \text{cm}^2 . \tag{3c}$$

The cross section factors are, of course, inversely proportional to the assumed ft values.

The cross section factors for the superallowed (SA) transitions to the analog states have been calculated assuming that only Fermi matrix elements are important (which is a good approximation for both $^{81}\text{Br} \to {}^{81}\text{Kr}$ and $^{79}\text{Br} \to {}^{79}\text{Kr}$ because the isotopic spin values are so large, $T = \frac{11}{2}$ and $\frac{9}{2}$, respectively). I find, for ^{81}Br,

$$\sigma_0(\text{SA}) = 770 \times 10^{-46}\ \text{cm}^2 \tag{4a}$$

and, for ^{79}Br,

$$\sigma_0(\text{SA}) = 630 \times 10^{-46}\ \text{cm}^2 . \tag{4b}$$

The ratio of the rate of the transition to the analog

TABLE II. The average cross sections and predicted capture rates. The only transitions considered are from the ground state of Br to either the $\frac{1}{2}^-$ state or the analog state of Kr. I have assumed $(ft)_{3/2\to1/2}=7.59\times10^4$ sec for ^{81}Br and 4.9×10^5 sec for ^{79}Br. The neutrino fluxes for the standard solar model are taken from Ref. 17.

Source	^{81}Br σ (10^{-46} cm^2)	$(\phi\sigma)$ STD SNU	^{79}Br σ (10^{-46} cm^2)	$(\phi\sigma)$ STD SNU
p-p	0	0	0	0
p-e-p	77.8	1.2	0	0
^{7}Be	24.6	10.1	0	0
^{8}B	4007	2.3	2027	1.2
^{13}N	19.3	0.9	0	0
^{15}O	41.1	1.5	0.03	0.0
Total SNU		16.0		1.2
^{31}Cr	18.3		0	
^{65}Zn	32.3		0	

state to the rate of the transition to the $\frac{1}{2}^-$ state is 1.4 for ^{81}Br and 9.25 for ^{79}Br, according to Eqs. (3) and (4).

Table II also contains the predicted neutrino capture rate obtained with the cross sections estimated as described above and the solar neutrino fluxes from a standard solar model.[17] The total expected capture rate for ^{81}Br is 16.0 solar neutrino units (SNU) and for ^{79}Br it is 1.2 SNU.

In principle, one might try to measure with a bromine detector the ^{8}B neutrino flux (as well as, or instead of, the ^{7}Be neutrino flux). One could search for the decay products of the relevant analog states in ^{81}Kr and ^{79}Kr; these highly excited states in krypton are populated only by ^{8}B neutrinos. It is not known at present to what extent the analog states will particle decay (instead of γ decay) and to which isotopes. However, one can estimate from the results stated above (and those given in Table II) the capture rate that might be associated with transitions to the analog states. I find, for $^{81}\text{Br}\to{}^{81}\text{Kr}$,

$$(\phi\sigma)_{\text{analog state}}=1.4\epsilon \text{ SNU} \tag{5a}$$

and, for $^{79}\text{Br}\to{}^{79}\text{Kr}$,

$$(\phi\sigma)_{\text{analog state}}=1.1\epsilon \text{ SNU}\ . \tag{5b}$$

Here ϵ is the ratio of the true ^{8}B solar neutrino flux to the value predicted by the standard solar model. A comparison of various suggested solutions to the solar neutrino problem with the results obtained from the ^{37}Cl experiment indicates[9] that ϵ may be of order one-third or less. Unfortunately, however, the most plausible products of particle decay by the analog states are isotopes of krypton and selenium, which could not be separated chemically from a large volume of a bromine compound.

IV. DISCUSSION

What does one need to know about the weak interaction matrix elements and other theoretical or experimental quantities in order to derive unique inferences about solar neutrinos from a bromine experiment? (I assume for simplicity in what follows that the experimental solar neutrino capture rate can be measured to arbitrary accuracy.)

In order to make any useful inference, one obviously must know accurately the (ft) value for *either* the $\frac{3}{2}^-\to\frac{1}{2}^-$ transition *or* the $\frac{3}{2}^-\to\frac{5}{2}^-$ transition between ^{81}Br and ^{81}Kr. Otherwise, with two unknown cross sections it will not be possible to derive any unique conclusions. Suppose that the ft value for the $\frac{3}{2}^-\to\frac{1}{2}^-$ transition is known exactly from the Bennett *et al.*[1] or some related experiment. In order to obtain information on the dominant ^{7}Be flux, one still must know how to subtract the contributions from other neutrino sources (*p-e-p*, ^{8}B, ^{13}N, and ^{15}O), which collectively make up about one-third of the total expected counting rate. This subtraction is not possible unless one knows at least the ratio of the cross sections to the $\frac{1}{2}^-$ and the $\frac{5}{2}^-$ states. Moreover, one must also make some assumption for each neutrino source (other than ^{7}Be) about the ratio of the true solar neutrino flux to the flux computed with the standard model. If one knows the true neutrino fluxes for all except ^{7}Be and knows only the ratio of the $\frac{5}{2}^-$ to $\frac{1}{2}^-$ neutrino excitation cross sections, then one can obtain an *upper limit* to the ^{7}Be neutrino flux. However, one cannot obtain, even with all these assumptions, a specific value for an "observed" ^{7}Be solar neutrino flux.

If one (1) knows the ft values for both the $\frac{3}{2}^- \to \frac{1}{2}^-$ and the $\frac{3}{2}^-$ to $\frac{5}{2}^-$ transitions for ^{81}Br $\to {}^{81}$Kr; (2) assumes that the first $\frac{3}{2}^-$ state in ^{81}Kr does not contribute significantly to the net capture rate; (3) assumes that the fluxes from p-e-p, ^{13}N, and ^{15}O are known from stellar evolution theory; and (4) assumes that the ^{8}B flux is determined by the ^{37}Cl experiment; then one can make a unique inference regarding the ^{7}Be flux (if measurement uncertainties in the solar neutrino observation are negligible).

I conclude that a solar neutrino experiment with bromine will be informative only if the capture rate to the $\frac{5}{2}^-$ state in ^{81}Kr can be estimated from a separate experiment. Unfortunately, a ^{51}Cr source may not be able to excite the $\frac{5}{2}^-$ state [see discussion following Eq. (2) and the footnote to Table I]. The calibration measurement with ^{65}Zn would be difficult but not impossible, in principle (see Table I). Perhaps a more promising technique would be to measure the ratio of the forward differential scattering cross section at moderate energies (>100 MeV) to the $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states for ^{81}Br(p,n)^{81}Kr. These cross sections can give reasonably accurate values for the Gamow-Teller matrix elements.[18]

Some conceivable inferences from a bromine solar neutrino experiment would be independent of nuclear physics uncertainties provided only that the rate measured by Bennett *et al.*[1] for the decay of the $\frac{1}{2}^-$ metastable state of ^{81}Kr is accurate. An observed capture rate of less than 10 SNU would imply that the number of ^{7}Be solar neutrinos reaching the earth is less than is predicted with the aid of standard solar models (see Table II). Similarly, an observed capture rate of more than of order 30 SNU would imply (for reasonable values of nuclear matrix elements) that the flux of ^{7}Be solar neutrinos at earth is not much less than is implied by a standard solar model.

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