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^{81}Kr-^{81}Br ground-state mass difference and implications for calibration of a ^{81}Br solar neutrino detector

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The ground-state mass difference between ^{81}Kr and ^{81}Br was determined by a Q-value comparison of the ^{82}Kr(d, t)^{81}Kr and ^{82}Kr(d, ^{3}He)^{81}Br reactions. Energy resolution was optimized by using an ion-implanted target. Implications for calibration of the proposed bromine solar neutrino detector are presented.

The discrepancy between the solar neutrino flux measured in the ^{37}Cl detector of Davis *et al.*[1] and the flux predicted by standard solar model calculations,[2] remains unexplained in spite of nearly two decades of close scrutiny. One approach to resolving this problem is the use of other neutrino detectors, such as ^{81}Br. The present work contributes to reduce the uncertainty in nuclear physics parameters for the ^{81}Br neutrino detector.

A principal concern with the ^{81}Br detector is the problem of calibration so that the results of a solar neutrino capture experiment can be interpreted. As shown in Fig. 1, several

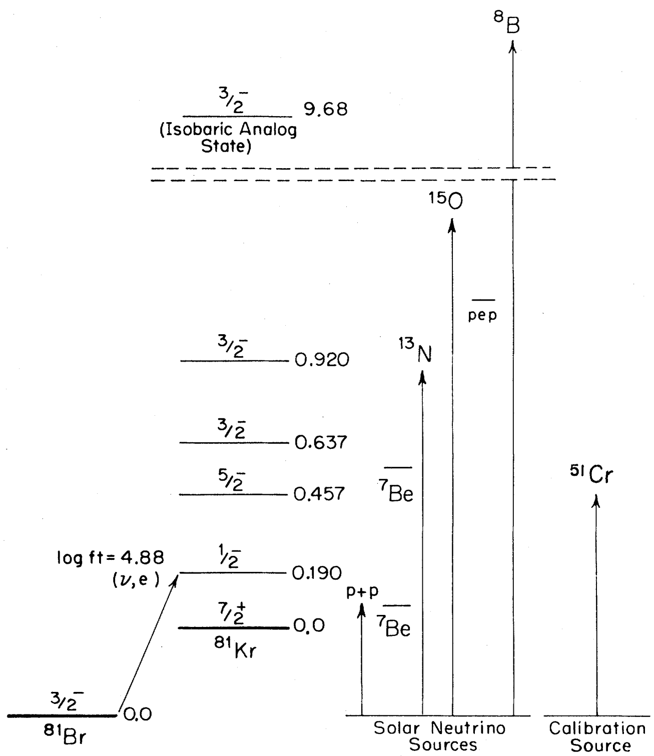

FIG. 1. The states in ^{81}Kr which would be populated by neutrino capture in ^{81}Br. The spin-parity assignments for excited states in ^{81}Kr are taken from Ref. 13. At right, the energies of neutrinos produced by reactions in the proton-proton chain and CNO cycle are schematically indicated in order of predicted abundance in the standard solar model. The ^{7}Be and pep neutrinos are emitted monoenergetically. Also shown is the energy of neutrinos from the proposed ^{51}Cr calibration source.

states in ^{81}Kr above 0.5-MeV excitation can be populated by capture of energetic neutrinos produced by neutrino sources less abundant than the ^{7}Be source. Only the 0.190-MeV ($J^{\pi}=\frac{1}{2}^{-}$) and 0.457-MeV ($J^{\pi}=\frac{5}{2}^{-}$) states in ^{81}Kr will be populated by the large number of ^{7}Be neutrinos. Theoretical investigations by Haxton,[3] Bahcall,[4] and Liu and Gabbard[5] predict that at least 80% of the neutrino capture rate for a ^{81}Br detector will be from population of these two states.

The neutrino capture cross section, σ_{ν}, to the 0.190-MeV state is well known since the logft for the inverse transition has been measured.[6] The value of σ_{ν} for the 0.457-MeV state is uncertain because the inverse transition cannot be observed, hence the logft value cannot be determined directly. Typical logft values[7] for beta-decay transitions between $\frac{3}{2}^{-}$ and $\frac{5}{2}^{-}$ states with similar energy separations of 1 MeV are about 6.3, compared to 4.58 for decay of the 0.190-MeV state. The large-basis shell model calculation of Haxton[3] predicted a logft of 8.6 for the transition to the 0.457-MeV state, but failed to describe adequately properties of the lowest observed $\frac{5}{2}^{-}$ state in ^{81}Kr, although describing quite well the properties of other states in ^{81}Kr. Bahcall[4] argues that σ_{ν} to this state is highly uncertain and could be quite large, based on the possibility of configuration mixing in the ^{81}Br ground state and 0.457-MeV state in ^{81}Kr. Liu and Gabbard[5] analyzed data from charge exchange reactions at low energies and found that σ_{ν} for the 0.457-MeV state in ^{81}Kr could be as large as 50% of that for the 0.190-MeV state. Thus, a large uncertainty remains in the predicted solar neutrino capture rate for a ^{81}Br detector because of the evidence that the 0.457-MeV state may contribute significantly to the capture rate in this detector.

Bahcall[4] suggested that σ_{ν} for the two states at 0.190 and 0.457 MeV could be calibrated by using an intense reactor activated ^{51}Cr neutrino source, or that the Gamow-Teller strength for transitions to states in ^{81}Kr could be determined from 0° (p,n) reactions at proton energies above 100 MeV. Both techniques have experimental difficulties. The ^{81}Br(p, n)^{81}Kr measurements need a resolution between 100 and 200 keV full width at half maximum (FWHM), which requires considerable improvement over routinely obtained (p,n) energy resolution for energies above 100 MeV. The feasibility of using a ^{51}Cr neutrino source for this calibration is in question because the neutrinos emitted may not be energetic enough to populate the 0.457-MeV state in ^{81}Kr. In Ref. 4 Bahcall defines and calculates the energy difference, Δ, between the neutrino energy of a ^{51}Cr source and the energy required to populate the 0.457-MeV state in ^{81}Kr. If Δ is positive, then this calibration method is possible. Bahcall calculated Δ to be about −30 keV, with a large uncertainty because of the poorly known mass excess of ^{81}Kr.

Following the suggestion of Bahcall, a more precise measurement of the ^{81}Kr ground-state mass was determined by Kouzes *et al.*,[8] who used two different calibration reactions to determine the Q value of the ^{81}Br(^{3}He, t)^{81}Kr reaction. The two calibrants, ^{51}V(^{3}He, t)^{51}Cr and ^{87}Rb(^{3}He, t)^{87}Sr, gave values of the ^{81}Kr mass excess which differ by 10 keV, $-77\,696 \pm 6$ keV, and $-77\,686 \pm 6$ keV, respectively. The corresponding Δ values are $+8.2 \pm 1.8$ keV and -1.6 ± 2.2 keV. In the present work the ground-state mass difference between ^{81}Kr and ^{81}Br has been measured by direct comparison of the Q values for ^{82}Kr(d, t)^{81}Kr and ^{82}Kr(d, ^{3}He)^{81}Br. From this mass difference Δ can now be determined independently of the measurements of Kouzes *et al.*, so that the discrepancy that they reported can be resolved. We confirm that the 0.457-MeV state in ^{81}Kr can be populated by capture of ^{51}Cr neutrinos.

The ^{82}Kr(d, t)^{81}Kr and ^{82}Kr(d, ^{3}He)^{81}Br reactions were measured simultaneously in experiments performed at Triangle Universities Nuclear Laboratory (TUNL) using a 17.0-MeV incident deuteron beam. The t and ^{3}He reaction products were detected using an E-ΔE detector telescope at a laboratory angle of 55°. The slit system used with the detector limited the angular acceptance to $\pm 0.5°$.

The target was prepared by implanting a carbon foil with 110-keV ^{82}Kr ions until saturation occurred. This substrate was then implanted with 50-keV ^{14}N ions to provide for energy calibration by the ^{14}N(d, t) and ^{14}N(d, ^{3}He) reactions. At these implant energies the ^{82}Kr and ^{14}N ion distributions were centered at approximately equal depths in the carbon foil. A carbon foil thickness of 0.087 mg/cm^{2} remained after the implantations with doses of 0.025 mg/cm^{2} ^{82}Kr and 0.002 mg/cm^{2} ^{14}N ions.

Peak centroids and widths were determined using a peak-fitting program. Peak positions from elastic and inelastic deuteron scattering on ^{12}C were used to monitor the stability of the electronics during each 30-min run. The final spectra were formed by correcting some of the runs for gain shifts seen in the deuteron peaks, then combining these gain-normalized runs. The gain drift was generally about 5 keV in a 2-h counting time, presumably from thermal drifts in the electronics. Figures 2 and 3 show the resulting pulse-height spectra for tritons and helions, respectively.

The energy calibration of the triton spectrum in Fig. 2 was obtained from peak centroids for the ^{13}C(d,t)^{12}C(0.0 MeV) and ^{14}N(d,t)^{13}N(0.0 MeV) states. The energies of the peaks corresponding to states in ^{81}Kr were determined using this calibration. The accuracy of the triton spectrum energy calibration was confirmed by noting that the energy determined for the centroid of the peak corresponding to the 4.439-MeV state in ^{12}C was correct to within 1 keV. Also, this calibration agreed with the energy calibration determined from the deuteron spectrum using elastic and inelastic scattering from ^{12}C.

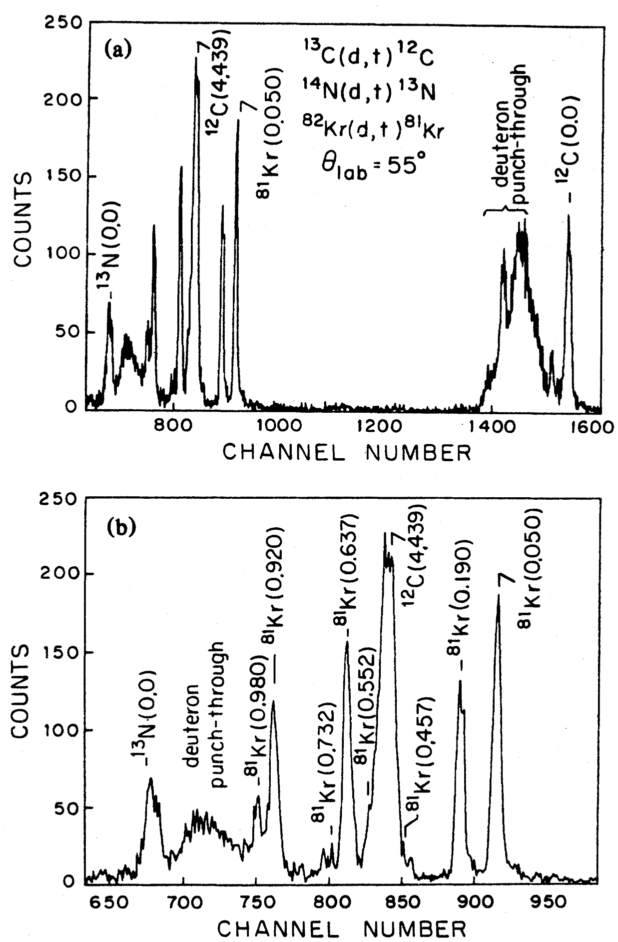

FIG. 2. The triton spectrum produced at 55° by a 17.0-MeV deuteron beam incident upon a carbon foil implanted with ^{82}Kr and ^{14}N ions. The deuteron events correspond to signals from intense deuteron elastic and inelastic peaks in the two-dimensional mass spectrum. The edges of these broad deuteron groups extended into the two-dimensional triton gate. Part (a) shows a region spanning about 5 MeV, including all of the triton peaks of interest. Part (b) gives a magnified picture of the spectrum region where peaks from the ^{82}Kr(d,t)^{81}Kr, and ^{14}N(d,t)^{13}N reactions are found.

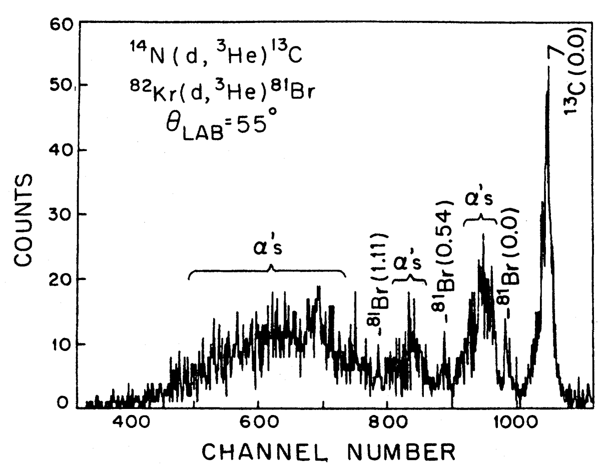

FIG. 3. The helion spectrum produced at 55° by a 17.0-MeV deuteron beam incident upon a carbon foil implanted with ^{82}Kr and ^{14}N ions. The alpha events correspond to signals from intense alpha-particle peaks in the two-dimensional mass spectrum produced by the ^{12}C(d,α)^{10}B reaction. The edges of these broad alpha groups extended into the two-dimensional ^{3}He particle gate.

TABLE I. Ground-state mass excesses for ^{81}Kr. The quantity Δ is defined in Ref. 4. Where measured, the ^{81}Kr-^{81}Br mass difference is used to calculate Δ. Otherwise, a value of the mass excess for ^{81}Br of −77 976 ± 6 keV as given in Refs. 9 and 10 is assumed.

^{81}Kr Mass excess (keV)	Δ (keV)	Reference
−77 654 (+32, −15)	−33 (+33, −16)	Ref. 11
−77 671 (+38, −30)	−16 (+39, −31)	Ref. 11
−77 709 ± 15[a]	+22 ± 16	Ref. 12
−77 707 ± 18	+20 ± 19	Ref. 9
−77 696 ± 6	+8.2 ± 1.8	Ref. 8
−77 686 ± 6	−1.6 ± 2.2	Ref. 8
−77 699 ± 8	+12 ± 6	This work

[a]Corrected downward by 50 keV. (See text.)

The standard deviation in peak energy for ^{81}Kr states was estimated to be less than 2 keV. This figure was calculated by combining in quadrature uncertainties from energy losses in the target, the energy calibration, and the extracted peak centroids. The calculated energy loss in the target for tritons near 11 MeV varies by only about 1 keV for reasonable variations in the estimates of the target thicknesses and implanted ion distributions.

For the helion spectrum only one calibration transition was available (Fig. 3). Therefore, the energy of the ^{81}Br ground-state peak was determined relative to ^{14}N(d, ^{3}He)^{13}C(0.0 MeV) only. The dispersion of the ^{3}He spectrum was assumed to be equal to that for the triton, deuteron, and alpha spectra, since the same detectors and electronics were used to process signals for each spectrum. An error in the (d, ^{3}He) spectrum dispersion of the same order as the difference between the dispersions in the (d,d) (d,t), and (d, α) spectra would produce an error of less than 1 keV in the energy of the ^{81}Br ground state. Under this assumption, the standard deviation in the energy of the ^{81}Br ground-state peak is less than 6 keV.

Subtraction of the energy determined for the peak at 0.050-MeV excitation in ^{81}Kr [in ^{82}Kr(d, t)^{81}Kr] from the energy determined for the ground-state peak in ^{81}Br [in ^{82}Kr(d, ^{3}He)^{81}Br] gives the Q-value difference for the two reactions. The energy difference at 55° for peaks from these two reactions was determined to be 330 ± 6 keV. This is 8 keV higher than the value predicted using the ^{81}Kr and ^{81}Br mass excesses given in Wapstra and Bos.[9] After accounting for kinematic variations with scattering angle, the Q-value difference is found to be 346 ± 6 keV. The ^{81}Kr-^{81}Br ground-state mass difference is found by subtracting the excitation energy of the ^{81}Kr state, 50 keV, and subtracting 19 keV for the difference in triton and helion masses from the Q-value difference. The resulting mass excess of ^{81}Kr over ^{81}Br is 277 ± 6 keV. Combining this measurement with the reported mass excess of ^{81}Br, −77 976 ± 6 keV in both Refs. 9 and 10, gives a ground-state mass excess of ^{81}Kr of −77 699 ± 8 keV.

In Table I we summarize values from various determinations of the mass excess of ^{81}Kr and the quantity Δ relevant for the ^{81}Br solar-neutrino detector calibration. Chew *et al.*[11] used the ^{80}Kr(n, γ)^{81}Kr reaction to populate the ground state of ^{81}Kr and then studied the electron capture decays of this state to the 0.0 and 0.276-MeV states in ^{81}Br. Their results suggest a mass difference of 305 (+38, −29) keV, assuming decay to the ^{81}Br ground state only, and 322 (+31, −14) keV assuming a 4% decay branch to the ^{81}Br excited state at 0.276 MeV. The mass excess of ^{81}Kr was determined as −77 671 (+37, −30) keV or −77 654 (+32, −15) keV, respectively, from the two ^{81}Kr electron capture Q values. The latter value was adopted in the 1978 Table of Isotopes.[10]

The mass excess of ^{81}Kr was also determined previously using the ^{80}Kr(d,p)^{81}Kr reaction.[12] The excitation energies reported in that study are in error by −0.050 MeV because the ground state was not populated and the 0.050-MeV state was erroneously identified as the ground state. The mass excess reported by Chao *et al.*,[12] −77 659 ± 15 keV, must be corrected downward by 50 keV to −77 709 ± 15 keV. Although this mass determination was published before the Table of Isotopes[12] and is more precise than the measurement of Chew *et al.*,[11] it was not the adopted value. If the 50-keV correction had been ignored, then the value reported by Chao *et al.*[12] would agree well with the adopted value. The mass tables[9] list a mass excess of −77 707 ± 18 keV for ^{81}Kr.

The result of the present work resolves the discrepancy between the two ^{81}Kr ground-state mass excesses reported by Kouzes *et al.*[8] The reported Q value of the ^{87}Rb(^{3}He,t)^{87}Sr reaction is apparently too low by about 10 keV. Our direct ^{81}Kr-^{81}Br mass difference measurement yields 277 ± 6 keV, compared to 290 ± 2.0 keV or 280.9 ± 1.5 keV calculated using the two ^{81}Kr ground-state mass excesses reported by Kouzes *et al.* From the present ^{81}Kr-^{81}Br mass difference, the quantity Δ is calculated as 12 ± 6 keV. Although the experimental standard deviation in the present work is larger than those reported by Kouzes *et al.*,[8] the results from the present work are sufficiently accurate to resolve the discrepancy in the ^{81}Kr-^{81}Br mass difference reported by Kouzes *et al.*[8] We thus confirm that a ^{51}Cr neutrino source could produce neutrinos with energies above the threshold for populating the 0.457-MeV state in ^{81}Kr by inverse beta decay in ^{81}Br, and is therefore possible as a calibrant for a ^{81}Br solar-neutrino detector.

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