A reanalysis of radioisotope measurements of the $^9\text{Be}(\gamma, n)^8\text{Be}$ cross section

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The $^9\text{Be}(\gamma, n)^8\text{Be}$ reaction is enhanced by a near threshold $1/2^+$ state. Contradictions between existing measurements of this reaction cross section affect calculations of astrophysical r-process yields, dark matter detector calibrations, and the theory of the nuclear structure of $^9\text{Be}$. Select well-documented radioisotope $^9\text{Be}(\gamma, n)$ source yield measurements have been reanalyzed, providing a set of high-accuracy independently measured cross sections without the large systematic errors from recent beamline experiments 1 2. A single-level Breit-Wigner fit of these corrected measurements yields are $E_R = 1736.8(18)$ keV, $\Gamma_{\gamma} = 0.742(25)$ eV, and $\Gamma_n = 252(17)$ keV for the $1/2^+$ state, excluding a virtual state solution.

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The near threshold $1/2^+$ state of the $^9\text{Be}(\gamma, n)^8\text{Be}$ reaction is important for several processes in nuclear and astrophysics. This cross section is used to calculate the formation rate of $^9\text{Be}$ via the $^4\text{He}(\alpha, n)^9\text{Be}$ reaction, one of the most important light-element reactions for r-process nucleosynthesis 3. Neutrons from $^{86}\text{Y}/^8\text{Be}$ and other radioisotope sources using the $^9\text{Be}(\gamma, n)^8\text{Be}$ reaction near threshold are being used widely for dark matter detector energy scale and yield calibrations 4 5 as these low energy neutrons closely mimic dark matter recoils in detectors 6.

Recent experimental 2 and theoretical studies of $^9\text{Be}$ suggest that three-cluster dynamics are required to describe its photodissociation. This could imply that the astrophysical $^9\text{Be}$ production proceeds via a single step, with a much larger production rate at low energies than that calculated by the two-step process via $^8\text{Be}$ 7 8. Three-cluster models calculations using the complex scaling method do not find a resonant $1/2^+$ state 9 10, but a virtual $1/2^+$ state would not be found by these calculations. A virtual state has a complex energy eigenvalue of $|E_\lambda| = (E_R - S_n) + i\Gamma/2$ (1)

defined by the real quantities $E_R$, the resonance energy, $S_n$, the neutron separation energy, and $\Gamma$, the resonance width. These parameters defining the virtual or resonant nature of the $1/2^+$ state can be measured from the position and shape of the near threshold peak of the $^9\text{Be}(\gamma, n)$ cross section.

There is little agreement between many measurements of the parameters of this $1/2^+$ state. The yields of radioisotope photoneutron sources provide the simplest method to measure the cross section, a technique that has been used many times since 1935 12 19. These measurements use a limited set of precisely known photon energies and can use homogeneous and isotropic neutron detectors with well understood sensitivity to the low-energy neutrons produced by the reaction. Other measurements using bremsstrahlung photon beams 20 21, and more recently using inverse Compton photon beams 11 2 22, such as the High-Intensity $\gamma$ Source (HI$\gamma$S), provide cross sections over a range of energies inaccessible to photoneutron sources while sacrificing energy resolution and simplicity in experimental design. All these techniques rely on a comparison of absolute quantities. Accurate cross section measurements require knowledge of the absolute photon source strengths, the neutron detection efficiencies, and the photon energy spectra. The energy dependence and systematic uncertainty of the neutron detection efficiencies are improved when simple, homogeneous and isotropic neutron detectors are used. The cross section can also be found using the inelastic scattering of charged particles 23 29. These measurements require significant background subtraction and extrapolation to low momentum transfer to recover a cross section. A selection of measured and evaluated cross sections in Figure 1 show disagreements of up to 60%, with the strongest disagreements among recent measurements.

Radioisotope measurements of the $^9\text{Be}(\gamma, n)^8\text{Be}$ cross section using simple detector designs should have low systematic uncertainties. However, discrepancies among some of these measurements are as severe as those from more complicated experiments at accelerator facilities. Most of the radioisotope measurements were performed in the 1940s, 50s, and 60s, before high precision neutron standards, cross sections, and simulation programs were available. Fortunately, several of these experiments have been well documented with results that are traceable to modern calibrations. This paper will apply corrections to these originally measured cross section values to construct a trusted set of high-accuracy measured radioisotope source neutron yields near the $^9\text{Be}(\gamma, n)$ threshold.
Table I. Corrections to the measured \(^9\text{Be}(\gamma, n)\) cross section from an \(^{124}\text{Sb}/\text{Be}\) source, reproduced from Table I in John and Prosser \cite{18} and extended with recalculated corrections. These corrections reconstruct the measured neutron production cross section compared to that of a 1.69 MeV photon through a thin beryllium target. The finite source size (3) and gamma attenuation (4) effects are combined and reported with other source geometry effects (6) in an MCNPX-Polimi simulation in the reevaluation. See text for descriptions of other recalculated corrections.

| Item | Correction | Uncertainty | Recalculated | Uncertainty |
|------|------------|-------------|--------------|-------------|
| 1. Gamma-ray source strength | | | | |
| (a) peak-to-total ratio | — | 5.0 | +3.88 | 3.5 |
| (b) subtraction of other \(\gamma\)-ray lines | — | 2.0 | +0.42 | 2.0 |
| (c) half-life of \(^{124}\text{Sb}\) | — | 0.8 | —0.8 | 0.1 |
| 2. Neutron source strength | | | | |
| (a) absolute strength of NBS source | — | 3.0 | +0.4 | 0.85 |
| (b) neutron escape from MnSO\(_4\) bath | −0.9 | 0.3 | −0.84 | 0.05 |
| (c) capture of fast neutrons in bath | −2.8 | 0.5 | −2.34 | 0.12 |
| (d) neutron counting statistics | — | 0.8 | — | 0.8 |
| 3. Finite source size | −0.6 | < 0.1 | — | — |
| 4. Attenuation of gamma rays in Be shell | +2.5 | < 0.1 | — | — |
| 5. Neutrons produced by other \(\gamma\)-ray lines | −4.4 | 1.0 | −2.49 | — |
| 6. Source geometry effects | | | +2.65 | 2.0 |
| Total Correction | −6.2% | | 1.007 | |
| Overall uncertainty (square root of sum of squares) | 6.4% | | 4.7% | |

\(a\) Not applied when calculating neutron yields (see text).

I. RADIOISOTOPE MEASUREMENTS

A. John and Prosser

John and Prosser \cite{18} used the MnSO\(_4\) bath technique \cite{31} to measure the yield of a \(^{124}\text{Sb}/\text{Be}\) source and traced their measured neutron yield to NBS-1, the world’s most precisely calibrated neutron standard. The strength of their \(^{124}\text{Sb}\) source was measured using a scintillating NaI crystal.

In 1962, only the 1.69 MeV and the 2.09 MeV lines were well established in the high energy \(^{124}\text{Sb}\) photon spectrum \cite{34}. John and Prosser \cite{18} subtracted from the measured photon yield the contribution from the Compton tail from the 2.09-MeV line. Several percent and sub-percent intensity sub-threshold photon lines have been found since 1962 that lie within the NaI detector resolution of the 1.69-MeV peak \cite{35}. Assuming a NaI(Tl) detector with 5.4% energy resolution at the peak, an additional 0.42% background subtraction is applied. The \(^{124}\text{Sb}\) half-life has been revised to 60.20(3) days from 60.4±0.2 days. As the neutron counting significantly pre-
ceeded the photon counting, the decay correction was increased.

To calibrate the neutron yield against NBS-1, an intermediate $^{226}$Ra/Be ($\alpha, n$) source was used. Correction factors for this comparison were recalculated using MCNPX-Polimi simulations, replacing the original analytic corrections made by John and Prosser. Photoneutrons were generated in the simulation by generating photons and simulating the $^9$Be($\gamma, n$)$^8$Be reaction. An MCNP library [30] based on the cross section measured by Arnold et al. [1] was used. The $^{226}$Ra/Be neutron spectrum used to generate source particles in the simulation was calculated using the JENDL-AN/05 evaluated $^9$Be($\alpha, n$) cross section [37] and a modified version of the SOURCES-4C program [38, 39]. Neutron propagation was modelled using the ENDF/B-VII.1 cross section libraries [40]. The ratio of the number of neutrons captured on manganese and the number of neutrons produced was calculated from these simulations and used to compare the $^{226}$Ra/Be and $^{124}$Sb/Be neutron yield measurements. The largest difference in yield is due to the increased probability of neutron capture on sulfur and oxygen for high energy neutrons from the $^{226}$Ra/Be source.

The absolute neutron yield of the NBS-1 neutron source has been revised slightly upward by 0.4% and the yield uncertainty reduced to 0.85% since its 1955 calibration [31, 41]. John and Prosser and most other neutron yield measurements, present cross sections after correcting for the neutron production from sub-dominant photon energies using other known points of the $^9$Be($\gamma, n$) cross section, such as with Item 5 in Table I. Radioisotope source neutron yields, the number of neutrons produced per decay, may be alternatively expressed as the sum of the photon branching ratios $\alpha_i$ and cross sections $\sigma_i$. This re-analysis will present results in terms of radioisotope neutron yields. For John and Prosser’s $^{124}$Sb/Be measurement, a yield of $\sum \alpha_i \sigma_i = 0.678(32)$ mb is found. This expression ignores the contribution of bremsstrahlung photons from high energy $\beta$ decays, or neutron production from high energy betas that reach the beryllium. The bremsstrahlung and beta contribution to the neutron yield was calculated [42] and found to be negligible for $^{124}$Sb and all other isotopes considered by John and Prosser [43]. Gibbons et al. [44] and Snell et al. [45]. This and all other reanalyzed yields and yield ratios are given in Table II [1].

| Measurement | Isotope | Yield or Yield Ratio | Ratio to original |
|-------------|---------|----------------------|-------------------|
| John and Prosser | $^{124}$Sb | 0.678(32) mb | 1.079 |
| $^{28}$Al/$^{124}$Sb | 1.311(43) mb | 0.978 |
| $^{208}$Bi/$^{124}$Sb | 0.620(30) mb | 1 |
| Gibbons et al. | $^{124}$Sb | 0.669(29) mb | 1.004 |
| $^{88}$Y | 0.660(29) mb | 1.004 |
| Snell et al. | $^{24}$Na | 0.620(19) mb | 0.920 |
| $^{76}$Ga | 0.171(5) mb | 0.792 |
| Fujishiro et al. | $^{58}$Co | 0.0083(6) mb | 1.83 |
| $^{108}$Ru | 0.00256(17) mb | 1.79 |
| $^{60}$Ni | 0.0074(5) mb | 1.68 |
| $^{28}$Al | 1.21(9) mb | 1.66 |
| $^{88}$Y | 0.80(8) mb | 1.71 |
| $^{38}$Cl | < 0.135(14) mb | < 1.69 |

Table II. Reanalyzed source yields, $\sum \alpha_i \sigma_i$, for the given radioisotopes paired with $^9$Be. Except for the $^{24}$Na/Be yield, these are used to fit the parameters of the $1/2^+$ state. The values derived from Fujishiro et al. [19] shown above are freely scaled in the fit. The yield for $^{38}$Cl includes $\leq 10\%$ contributions from inelastic scattering of $\beta$-rays on beryllium and bremsstrahlung photons; an upper limit is set for the yield from $^{38}$Cl $\gamma$-rays.

B. Gibbons et al.

Gibbons et al. [17] measured both $^{124}$Sb/Be and $^{88}$Y/Be neutron sources to high precision using different techniques from those of John and Prosser [1]. The decay rate of their sources were determined using a 4$\pi$ ionization counter. Their neutron source strengths were measured using a 5-foot diameter graphite moderating sphere and BF$_3$ thermal neutron detectors. The neutron count rate was calibrated against a source traceable to NBS-1. Gibbons et al. [17] Table I had calculated several corrections to the their source yield. These corrections were recalculated, and found to be almost entirely in agreement with the original analysis. Only the source strength of the NBS neutron source was changed, increasing the yield by 0.4% and reducing its uncertainty to 0.85%.

C. Snell et al.

Snell et al. [15] measured the neutron yields from beryllium and deuterium targets using $^{72}$Ga and $^{24}$Na radioisotopes. Both isotopes produce photons above the 2.2 MeV deuterium dissociation threshold. The absolute neutron yields and the ratio of beryllium to deuterium neutron yields were measured for each radioisotope. The
measured ratios can be compared to the well known modern cross section for the photodissociation of deuterium \[19\]. Both the reported absolute and the relative yields were reanalysed and found to be consistent within their final 5% and 3% uncertainties \[29\]. The yield measurement relative to the deuterium target is used in this reanalysis.

Snell et al. measured neutrons by sampling epithermal neutrons in large volume of paraﬃn moderator using in- dium foil sandwiched between two cadmium foils. The activated indium was counted using a thin-walled Geiger counter. The neutron energy dependence of the neutron yield measurements of Snell et al. has been validated using MCNPX-Polimi \[44\]. One additional correction, for the thermalization of neutrons reentering the deuterium or beryllium from the surrounding moderator, leads to an small additional loss of efficiency. The ratio of the detection efficiency for each source was recalculated. The original uncertainty in the relative source activity is retained, and it dominates the total uncertainty of 3%.

D. Fujishiro et al.

The measurements of Fujishiro et al. \[19\] are the most recently published radioisotope measurements of the \(^9\)Be(\(\gamma\), \(n\))\(^8\)Be and have heavily influenced modern evaluations of the cross section \[29, 45, 46\]. Fujishiro et al. used a reactor to irradiate a large variety of short-lived radioisotopes that produce photons with energies near the 1\(/2^+\) state, shown in Table \[III\].

In contrast to the other radioisotope measurements noted above, Fujishiro et al. used a non-homogeneous neutron detector: a ring of four BF\(_3\) detectors embedded in a paraﬃn cylinder. The neutron energy dependence of this detector was originally calculated using a one-dimensional Monte Carlo code and normalized to the ﬂux of a \(^{24}\)Na–D\(_2\)O neutron source. The relative neutron detection efﬁciency was recalculated using MCNPX-Polimi simulations of the three-dimensional geometry given by Fujishiro et al. The sensitivity, but not the model number, of the BF\(_3\) counters used were given. The simulations use LND model 2025 BF\(_3\) detectors ﬁlled to 500 torr for the 5.0 cps/\(\nu\) thermal neutron detectors \[54\]. The energy dependence of the neutron efﬁciencies calculated by MCNPX-Polimi match that found by Fujishiro et al., but the new calculation ﬁnds an absolute efﬁciency that is much lower. The calculated sensitivity to \(^{24}\)Na/deuterium neutrons is 6.2% versus the 9.2\(\pm\)0.7% measured and used as a calibration by Fujishiro et al.

The cross section calculation of Fujishiro et al. was reproduced using the original neutron detection efﬁciency, background subtracted neutron count rates, source intensities, beryllium geometry, and calculation method presented in their paper. Assuming a beryllium density of 1.85 g/cm\(^3\), the recalculated cross sections are 12% larger than those presented by Fujishiro et al. Given the normalization discrepancies in this calculation and the neutron detection efﬁciency, only the ratios of the neutron yields measured by Fujishiro et al. will be used.

The neutron yields are calculated using the MCNP calculated detector efﬁciency, and the neutron count rate, source intensities, and uncertainties given by Fujishiro et al. Fujishiro et al. included a 6% uncertainty in the absolute normalization of their source intensities that is excluded when calculating relative source intensities in this reanalysis. As the source intensities had been measured after they had decayed to \(\sim 10^3\) Bq, a correction is made to account for updated half-life values. The source intensities are also corrected to account for updated values of the branching fraction of the photon energy used to measure the source intensities. These corrections are shown in Table \[III\].

Additional contributions to the neutron yield from high-energy \(\beta\)-rays and their bremsstrahlung photons were calculated. The contributions are negligible (< 0.1% of the total yield) for all measured radioisotopes except \(^{38}\)Cl. The majority of \(^{38}\)Cl decays produce a \(\beta\) with a 4.9 MeV endpoint energy. Depending on the geometry of the source and encapsulation used by Fujishiro et al., \(~ 10\)% of the measured neutron ﬂux from their \(^{38}\)Cl/Be source could be caused by these high energy electrons. A similarly unaccounted high-energy \(\beta\) contribution had been incorrectly claimed by Fujishiro et al. \[50\] as evidence for the three-body breakup reaction of \(^9\)Be below the two-body threshold of \(S_\beta = 1664.54\) MeV \[57\]. No correction is applied for these additional neutron production mechanisms. Instead, the measured \(^{38}\)Cl neutron yield is used an upper limit for the yield produced by the \(^{38}\)Cl \(\gamma\) emissions.

E. Other Radioisotope Measurements

Other radioisotope measurements of the \(^9\)Be(\(\gamma\), \(n\))\(^8\)Be cross section exist that are not used in this reanalysis. These measurements were either not calibrated against neutron standards, or insufﬁcient information about the experiments were available to correct their measured yields.

Hamermesh and Kimball \[16\] measured the neutron yield from a \(^{144}\)Pr/Be source with its dominant emission at 2.185 MeV. They used an unspecified NaI detector to measure the photon yield, and compared the strength of the 1.49-MeV \(\gamma\) from \(^{144}\)Pr against the 1.38-MeV \(\gamma\) from \(^{24}\)Na without correcting for the difference in detector efﬁciency between the two energies. The change in detection efﬁciency depends by \(O(10\%)\) on the size and geometry of crystal used. Their measurement is consistent with the \(^{72}\)Ga measurement of Snell et al. and \(^{38}\)Cl measurement of Fujishiro et al. within this large uncertainty.

Russell et al. \[13\] measured the neutron yield of a set of six radioisotopes paired with beryllium and a subset of four radioisotopes paired with deuterium. Their measurement of the neutron ﬂux used a ‘long counter’ calibrated using a \(^{226}\)Ra–Be(\(\alpha\), \(n\)) neutron source. This
calibration source produces neutrons with far greater energies than the radioisotope sources and is used with a detector design whose sensitivity varies with neutron energy. Their photon source activities were calculated from thermal neutron capture cross sections and the measured neutron flux of the nuclear reactors in which they were activated. While improvements in the analysis of this measurement are possible, very large systematic uncertainties in both the neutron and photon yields would remain, and little information would be gained from a reanalysis.

Earlier measurement of $^9$Be($\gamma$, $n$)$^8$Be source yields [12,13,58] lack detailed information or the precision required for reanalysis.

### II. FIT

The $^9$Be($\gamma$, $n$)$^8$Be cross section was fit using least squares to a sum of isolated Breit-Wigner states. The $1/2^+$ state was fit to the form

$$\sigma_{1/2^+}(E_\gamma) = \frac{\pi (hc)^2}{4E_\gamma^2} \frac{\Gamma_n}{(E_\gamma - E_R)^2 + \frac{E_\gamma - S_n}{E_R - S_n} \frac{\Gamma_n}{(\Gamma_n/2)^2}}$$

where the neutron separation energy $S_n = 1664.54$ keV, $E_R$ is the resonance energy, and $E_\gamma$ is the incoming photon energy.

The contribution to the cross section from other higher energy resonances may affect the measured width of the $1/2^+$ resonance. Arnold et al. [11] provides the best direct measurement of the shape of the $^9$Be($\gamma$, $n$) cross section between 2 MeV and 4 MeV. The contribution from higher energy resonances was fixed using their resonance parameterization shown in Table IV. The widths of the fitted $3/2^+$ and $3/2^-$ resonances given by Arnold et al. were multiplied by 1.57 in order to match their reported experimental data (see Table IV caption). Ten percent level discrepancies exist in the neutron detector efficiency calibration of Arnold et al. [53] and between their measurement and radioisotope measurements at low energy shown in Figure 4. A smaller $5\% \pm 3\%$ discrepancy exists between the $^{23}$Na/Be source yield measured by Snell et al. [15] and the adopted contribution from high energy resonances. Given these discrepancies, a 10% scale uncertainty, larger than the 4.6% systematic uncertainty given by Arnold et al. was applied to the summed contribution from the higher energy resonances.

The photon energies, branching ratios, and reanalyzed measured neutron yield for each radioisotope measure-
Figure 3. Reanalyzed cross sections from radioisotope measurements of the $^9$Be$(\gamma, n)^8$Be cross section. Only the cross sections for the highest intensity photon energy of each radioisotope are shown, assuming that ratios to the cross sections at other photon energies equal the best fit ratios. The absolute yield of the measurements by Fujishiro et al. [19] are floated. The 2.7 MeV measurement by Snell et al. [15] of the $^{24}$Na/Be source yield was not included in the fit, but it is used to validate the contribution of higher energy resonances as measured by Arnold et al. [11].

| $J^\pi$ | $E_R$ (keV) | $\Gamma_\gamma$ (eV) | $\Gamma_\nu$ (keV) | $\beta_j$ to $^9$Be(g.s.) (%) |
|---------|------------|----------------------|-------------------|-----------------------------|
| 5/2$^-$ | 2431       | 0.098                | 0.77              | 6                           |
| 1/2$^+$ | 2880       | 1.8                  | 393               | 100                         |
| 5/2$^+$ | 3008       | 0.45                 | 168               | 70                          |
| 3/2$^+$ | 4704       | 7.8                  | 2419              | 38                          |
| 3/2$^-$ | 5590       | 15.7                 | 1477              | 38                          |

Table IV. Resonance parameters characterizing the contribution of high-energy resonances to the $^9$Be$(\gamma, n)$ cross section measured by Arnold et al. [11]. These resonances are subtracted from the radioisotope data in order to fit the parameters of the near threshold 1/2$^+$ state. Note that the table values are used as a parameterization, and may not be physical. In particular, the relatively narrow 3/2$^-$ and 3/2$^+$ resonances are being used to fit the cluster dipole resonance discussed in Section III. The widths of 3/2$^+$ and 3/2$^-$ resonances are multiplied by 1.57 from the values given by Arnold et al. in order to match their experimental data points. A 10% scale uncertainty on the summed cross section from these resonances is applied when fitting the parameters of the 1/2$^+$ state. The ground state branching ratios were selected to approximately match the observed ratio of thermal neutrons detected in two detector rings used by Arnold et al. Uncertainties in the ground state branching ratios are not provided and may be large.

III. COMPARISON TO PHOTON BEAM EXPERIMENTS

Figure [4] and Table [V] compare recent beamline measurements of the $^9$Be$(\gamma, n)$ reaction to the present reanalysis of radioisotope measurements. Except for the measurements of Fujishiro et al. [19] and the $^{28}$Al/Be and $^{206}$Bi/Be measurements of John and Prosser [15] all of the reanalyzed photoneutron measurements used homogeneous and isotropic neutron detectors with well modelled and slowly varying sensitivities for low-energy neutrons. Such detector designs are not suitable for use in a beamline environment.

Arnold et al. [11] and Utsunomiya et al. [2] detected neutrons using hollow cylindrical moderators with thermal neutron detectors positioned in concentric rings within the moderator. The ratio of the neutron detection rate in each ring allows the measurement of a weighted average neutron energy. Arnold et al. [63] calibrated their detector using several well known neutron production processes, and found a 4% discrepancy between the simulated and measured ratio of the count rate in the inner versus the outer ring, as shown in their Figure 13. Utsunomiya et al. claim to have measured a significant num-
Table V. Total neutron yields for reanalyzed and commercially available radioisotopes used in near threshold $^9$Be photoneutron sources. For each major photon energy, the branching ratio to the $^8$Be ground state assuming the resonance parameters given in Table IV and the energy of the outgoing neutron for that branch in the center of mass frame are given. The neutron yield is the product of the $^9$Be($\gamma,n$) cross section $\sigma_i$ and the photon branching fraction $\alpha_i$ for each photon energy $E_\gamma$. Photons yield, energies and half-lives, including those of decay chain daughter isotopes, are from [34, 47, 51, 60, 62]. Neutrons with other final states, such as $\alpha + \alpha + n$ or $^8$Be(3030 keV)+n will be produced at lower average energy and greater energy spread than those for the ground state transition. Neutron yield uncertainties are propagated from the fit to the $1/2^+$ state and from photon branching ratios.

| Isotope | $t_{1/2}$ | $E_\gamma$ (keV) | $\alpha_i$ (%) | $E_n^{\text{cm}}$ to $^8$Be g.s. (keV) | Neutron yield ($\sum \alpha_i \sigma_i$) (mb) | $^8$Be g.s. branching (%) |
|---------|-----------|-----------------|---------------|-----------------------------|---------------------------------|---------------------------|
| $^{58}$Co | 70.86(6) d | 1674.73 | 0.517(10) | 9.05 | 0.00584(24) | 100.0 |
| $^{124}$Sb | 60.20(3) d | 1690.97 | 47.57(18) | 23.47 | 0.672(18) | 100.0 |
| | | 2090.93 | 5.49(3) | 378.68 | 0.0145(6) | 99.5 |
| | | Total | | | 0.00254(4) | 99.6 |
| | | Others | | | 0.687(18) | 100.0 |
| $^{105}$Ru | 4.44(2) h | 1698.17 | 0.0766(9) | 29.86 | 0.00109(3) | 100.0 |
| | | 1721.15 | 0.0299(3) | 50.27 | 3.93(14)$\times 10^{-4}$ | 100.0 |
| | | Total | | | 1.6(5)$\times 10^{-5}$ | 100.0 |
| | | Others | | | 0.00156(5) | 100.0 |
| | | Total | | | 0.424(16) | 100.0 |
| | | Others | | | 0.01062(26) | 99.9 |
| | | Total | | | 0.00580(22) | 99.4 |
| | | Others | | | 0.441(16) | 100.0 |
| $^{65}$Ni | 2.51719(26) h | 1724.92 | 0.399(12) | 53.62 | 0.00513(23) | 100.0 |
| | 2.245(2) min | 1778.99 | 100 | 101.64 | 0.909(19) | 100.0 |
| $^{28}$Al | 106.627(21) d | 1836.06 | 99.2(3) | 152.33 | 0.646(7) | 100.0 |
| | 2734.0 | 0.71(7) | 949.8 | 0.00425(5) | 95.3 |
| | 3219.7 | 0.0070(20) | 1381.1 | 3.6(11)$\times 10^{-5}$ | 81.5 |
| | Total | | | | 0.651(7) | 99.9 |
| | | Others | | | 0.102(5) | 99.0 |
| | | Total | | | 1.38(27)$\times 10^{-4}$ | 63.2 |
| | | Others | | | 0.192(6) | 97.0 |
| | | Total | | | 0.294(7) | 97.8 |
| $^{38}$Cl | 37.230(14) min | 2167.40 | 44.4(9) | 446.58 | 0.101(5) | 99.1 |
| | 72Ga | 14.10(1) h | 1862.00 | 5.410(18) | 175.36 | 0.0394(4) | 99.9 |
| | | 2201.59 | 26.87(12) | 476.95 | 0.0585(25) | 98.9 |
| | | 2491.03 | 7.73(3) | 734.00 | 0.0179(8) | 94.8 |
| | | 2507.72 | 13.33(6) | 748.82 | 0.0318(14) | 95.3 |
| | | Others | | | 0.033(4) | 97.7 |
| | | Total | | | 0.172(6) | 97.8 |
| | | Others | | | 0.060(4) | 97.8 |
| | | Total | | | 0.230(5) | 99.5 |
| | | Others | | | 0.0660(16) | 100.0 |
| | | Total | | | 0.336(12) | 100.0 |
| | | Others | | | 0.153(4) | 100.0 |
| | | Total | | | 0.0124(14) | 100.0 |
| | | Others | | | 0.0107(5) | 98.9 |
| | | Total | | | 0.0183(4) | 94.4 |
| | | Others | | | 0.0107(5) | 98.9 |
| | | Total | | | 0.0172(6) | 97.8 |

The number of neutrons from the $^9$Be($\gamma,n$) reaction at energies well below those expected from the $^9$Be($\gamma,n$)$^8$Be(g.s.) reaction channel. The calibration of their neutron energy scale depends on simulations that may have a similar discrepancy to that found by Arnold et al. Their claim likely would have been reported by Arnold et al. [1], and may also be inconsistent with the neutron energy spectrum measurements of $^{116}$In/Be and other photoneutron sources using proton recoil spectrometers [54]. These inconsistencies demonstrate the importance of the neutron yield measurements from well-modelled detectors used in the present analysis.

Table VI shows a comparison of the position, height, and width of the excitation function peak of the $1/2^+$ resonance for radioisotope, inverse Compton, and electron scattering experiments. The radioisotope experiments find a peak position that agrees well with the measurements of Arnold et al. and Utsunomiya et al. The different resonance parameters between these experiments is due to differences in the measured shape of the peak.
that may be caused by miscalibrated neutron detectors.

IV. ASTROPHYSICAL PRODUCTION

The $^{8}\text{Be}(\gamma, n)^{9}\text{Be}$ cross section may be used to calculate the dominant two step contribution to the astrophysical production rate of the $\alpha(\alpha n, \gamma)^{9}\text{Be}$ reaction. The reaction proceeds via

$$\alpha + \alpha \rightarrow ^{8}\text{Be}$$

$$^{8}\text{Be} + n \rightarrow ^{9}\text{Be}$$

with both $^{8}\text{Be}$ and $^{9}\text{Be}$ in their ground state. A direct three-body reaction is possible and may dominate the reaction rate at low temperatures [8], but high-sensitivity searches for this process have not demonstrated its existence [65]. The thermal production rate by the two-step process is a double integral over the energy of two Maxwell-Boltzman distributed collision velocities, the cross sections for the two subprocesses, and the mean lifetime of the $^{8}\text{Be}$ nucleus, where the $^{8}\text{Be}$ nucleus may be produced off-shell [46].

The $^{8}\text{Be}(n, \gamma)^{9}\text{Be}$ reaction is related by the reciprocity theorem to the $^{9}\text{Be}(\gamma, n)^{8}\text{Be}$ cross section, as described by Arnold et al. [1]. The cross section for elastic $\alpha + \alpha$ scattering via the $^{8}\text{Be}$ compound state is taken from [66], with resonance width $\Gamma_{\alpha\alpha} = 5.57 \pm 0.25$ eV and resonant energy $E_{r} = 92.03$ keV.

Table VII shows the adopted $^{9}\text{Be}$ astrophysical production rate while Figure 5 shows this rate in comparison with the calculations of NACRE [46] and Arnold et al. [1]. At low temperatures, the rate follows that of Arnold et al. The low temperature rate differs from that of NACRE by a factor of $\sqrt{E/92.03}$ keV in the integrand, where $E$ is the center of mass energy of the $\alpha$ particles in the first reaction step. At astrophysically relevant temperatures of 1 GK to 5 GK, the new rate lies largely between those from NACRE and Arnold et al. At high energies, the contribution from higher energy resonances is increased compared to that calculated by Arnold et al. because of increases to the resonance widths (see Table IV caption).

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Table VI. The $^{9}\text{Be}(\gamma, n)$ excitation function peak energy, cross section, and width near the $1/2 +$ resonance, and the resonance energy for recent experiments. Note that the position of the excitation function peak and the resonance position are not simply related for this near threshold resonance. Charged particle scattering experiments including Burda et al. [29] fail to accurately reproduce the cross section measured by direct experiments. The peak positions and areas measured by inverse Compton scatter photon beam experiments [1, 2] match the present analysis, while the peak widths and heights differ significantly.

| Reference                | $E_{R}$ (keV) | $E_{\gamma,\text{max}}$ (keV) | $\sigma_{\text{max}}$ (mb) | FWHM (keV) |
|--------------------------|--------------|-------------------------------|----------------------------|------------|
| Present                  | 1736.8(18)   | 1696.8                        | 1.43                       | 152        |
| Arnold et al. [1]        | 1731(2)      | 1698.3                        | 1.64                       | 138        |
| Utsunomiya et al. [29]   | 1728(1)      | 1694.3                        | 1.35                       | 161        |
| Burda et al. [29]        | 1748(6)      | 1705.9                        | 1.03                       | 177        |

Figure 4. Comparison of the fitted $^{8}\text{Be}(\gamma, n)^{8}\text{Be}$ cross section to recent inverse Compton scattered photon beam [1, 2] and electron scattering [29] measurements (see text).

Figure 5. Calculated rate from the two step $^{4}\text{He}(\alpha n, \gamma)^{9}\text{Be}$ fusion reaction compared to previous evaluations [1, 46]. Bands show $\pm 1\sigma$ uncertainties.
Table VII. Calculated rate from the two step $^4$He$(\alpha,n)^9$Be fusion reaction versus temperature. By convention, rates are in units of $(\text{mol/cm}^3)^{-2}\text{s}^{-1}$\cite{10}.

V. SUMMARY

Radioisotope source yield measurements of the near threshold $1/2^+$ state of the $^9$Be($\gamma,n)^{10}$Be reaction cross section have been reanalyzed. After reanalysis, these measurements are self-consistent and provide precise experimental bounds of the Breit-Wigner parameters, with absolute cross section uncertainties under 2%. Twenty percent level inconsistencies between the results of Arnold et al.\cite{1}, Utsunomiya et al.\cite{2}, and this reanalysis are likely due to systematic errors in the low-energy neutron absolute detection efficiency of the two beamline experiments. The best fit to the cross section indicates that the 1/2+ state is a resonance.

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