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Beta-decay Spectroscopy of ^{20}Mg and the Implications for ^{15}O(α,γ)^{19}Ne Reaction

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Abstract: The breakout from the hot CNO cycle to the rapid proton capture process can occur via the ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na reaction sequence, and the β decay of ^{20}Mg can be used as an alternative method to characterize some specific resonances, which will provide detailed nuclear structure input for reaction rate calculations. The reliable information on the decay properties and structure of ^{20}Mg was obtained by measuring the emitted particles and γ-rays in the β decay with high efficiency and high resolution. Attempt was also made to search for the decay channels associated with the 4 033 keV resonance in ^{19}Ne. To test fundamental symmetries, the transitions in the mirror decays of ^{20}Mg and ^{20}O were compared. The precise experimental data presented here would be important to constrain the theoretical calculations. It is desirable to clarify the astrophysically relevant problem by further experiments with improved statistics on the basis of the present work.

Key words: β-delayed proton decay; rapid proton capture process; proton-γ-ray coincidence; mirror asymmetry

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1 Introduction

The CNO cycle and the rapid proton capture process (rp-process) may be linked by the breakout reaction sequence ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na[1]. The lowest resonance at 2 645 keV in ^{20}Na is situated in the Gamow-window of the ^{19}Ne(p,γ)^{20}Na reaction and is therefore decisive for its reaction rate in novae and x-ray bursters[2]. The spin and parity assignment of the 2 645 keV state is the most important controversial issue, which has lasted for 30 years. Very recently, reasonable agreement was achieved for the charge exchange reaction measurement[3], the direct measurement of ^{20}Ne(p,γ)^{20}Na reaction with radioactive ^{19}Ne beams[4], and the β-decay study of ^{20}Mg[5]. The spin and parity assignment of the 2 645 keV state was finally determined to be 3^+. Based on these properties, the ^{19}Ne(p,γ)^{20}Na reaction does not constitute a bottleneck in the break-out from the hot CNO cycle. For the ^{15}O(α,γ)^{19}Ne reaction, its resonant rate can be calculated from the radiative and α widths or equivalently the lifetimes and α-decay branching ratios for the relevant states. The resonance at 4 033 keV in ^{19}Ne is just above the α threshold as well as located

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in the Gamow window of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction and is therefore dominating the reaction rate. The lifetimes of the ^{19}Ne resonant states have been determined through Doppler-shift attenuation measurements[6–8]. Numerous measurements have been also performed to populate the excited states in ^{19}Ne via transfer reactions and measure the corresponding α-decay branching ratios[9–15]. However, due to the extremely small decay branching ratios for low-lying states, the α-decay branching ratio for the 4 033 keV state has been controversial[16]. Alternatively, the 4 033 keV state can be fed by the β-delayed proton emission of ^{20}Mg, so the α-decay branching ratio for the state can be measured directly via the β decay study of ^{20}Mg[17, 18]. In a similar case, the resonances in ^{30}S were studied via the β-delayed two-proton emission and β-delayed proton-γ emission of ^{31}Ar[19]. Besides, the search for cluster structure in ^{19}Ne is also of interest for nuclear structure study[20]. Apart from the knowledge of the resonances populated in the β decay of ^{20}Mg, another motivation is to investigate the isospin symmetry in comparison with the mirror decay and the mirror nucleus. The isospin-related problems have been active topics of both nuclear and particle physics research. The isospin symmetry relies on the similarity between a proton and a neutron with respect to the strong interaction. Hence, mirror transitions should have corresponding energies and strengths. However, the isospin symmetry is an approximate symmetry due to Coulomb interaction and other charge-dependent nuclear forces. This isospin-symmetry breaking has been shown to be a sensitive probe of nuclear structure effects and allows for stringent tests of the electroweak interaction described by the standard model[21, 22]. The β decay study of the lightest bound magnesium isotope, *i.e.*, ^{20}Mg has been performed with various experimental methods[5, 17, 18, 23–29]. In order to measure charged-particle in the decay with high detection efficiency and low detection threshold, we have developed a new detection system on the bases of our previous experiments with implantation method[30] and the experiments with complete-kinematics measurements[31–35].

2 Experimental techniques

The experiment was performed at the Heavy Ion Research Facility in Lanzhou (HIRFL)[36] in December 2014. More detailed descriptions can be found in Refs. [38–40], and here we give a brief introduction to the experiment. The ions in the secondary beam produced by the Radioactive Ion Beam Line in Lanzhou (RIBLL)[37] were identified by energy-loss (ΔE) and time-of-flight (ToF) with respect to two focus planes of the RIBLL given by silicon detectors and two scintillation detectors, respectively. The isotopes of interest were implanted into two double-sided silicon strip detectors (DSSD1 of 149 μm thickness and DSSD2 of 66 μm thickness), where the subsequently emitted β and protons were detected. During the experiment, a total number of 3×10^5 ^{20}Mg ions were implanted in the DSSDs. Besides, the silicon detectors were surrounded by five clover-type HPGe detectors, which were installed to measure the γ-rays emitted in the decay of the implanted nuclei. In order to achieve high detection efficiency and low detection threshold for the charged-particle emission, several technologies and solutions were conceived and implemented.

3 Analysis and results

The half-life of ^{20}Mg is determined to be 90.0 ± 0.6 ms by fitting the decay-time spectrum with a function composed of an exponential decay and a constant background. The uncertainty is deduced from the fitting program. The result is compared with the literature values in Fig. 1, and the half-life of ^{20}Mg is most precisely determined by the present work. The half-life of the nuclei along the rp-process pathway is one of the detailed nuclear structure inputs for quantitative descriptions of nucleosynthesis.

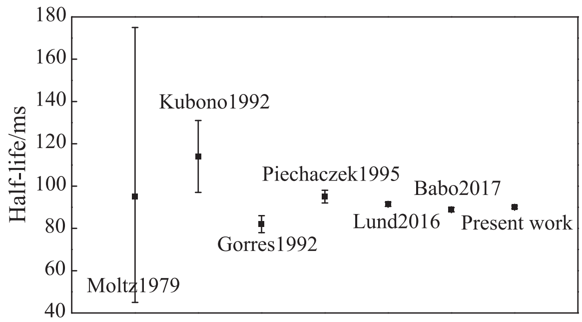

Fig. 1 Comparison between the half-lives of ^{20}Mg determined by the present work and those from literatures.

The β-delayed particle spectra from ^{20}Mg decay measured by the two DSSDs are shown in Fig. 2. More details on individual decay branches contained in each proton peak can be deduced through a proton-γ-ray coincidence analysis. Based on the γ-ray spectrum with coincidence gating condition on each proton peak, the decay branches from the excited states in ^{20}Mg feeding the ground state and excited states in ^{19}Ne can be assigned. The results are listed in Table 1, where the excitation energies of the states in ^{20}Na are determined by using the latest proton-separation energy value of ^{20}Na ($S_p(^{20}Na) = 2\,190.1(11)$ keV[43]). As shown in Fig. 3, the excitation energy of the Isobaric Analogue

Table 1 Decay branches contains in each proton peak and the corresponding initial states in ^{20}Na and the final states in ^{19}Ne.

E^*(^{20}Na)/keV	^{19}Ne g.s.	^{19}Ne 238 keV	^{19}Ne 275 keV	^{19}Ne 1508 keV	^{19}Ne 1536 keV
2998(13)	*p*1				
3863(14)	*p*4				
4130(22)	*p*5		*p*4		
4721(18)			*px*		
4801(32)	*p*7		*p*6		*p*2
5595(17)				*p*5	
6318(17)			*p*9		
6523(28)	*p*11	*p*10	*p*10		

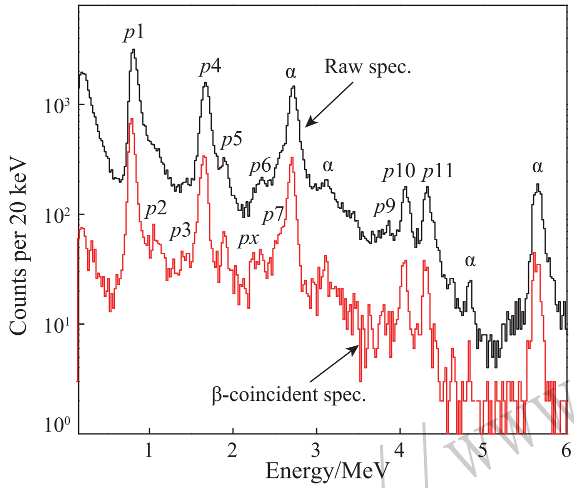

Fig. 2 (color online) β-delayed particle spectra from ^{20}Mg decay measured by the two DSSDs. The proton peaks from the β-delayed proton decay of ^{20}Mg are marked with "*p*+numbers" and the α peaks from the β-delayed α decay of ^{20}Na are marked with letters α.

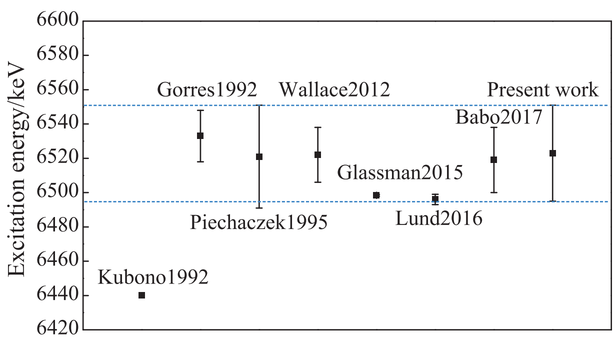

Fig. 3 Comparison between the excitation energies of the Isobaric Analogue State in ^{20}Na determined by the present work and those from literatures.

State in ^{20}Na was measured to be 6 523(28) keV, which is in nice agreement with the literature values of 6 533(15) keV[26], 6 521(30) keV[27], 6 522(16) keV[5], 6 498.4(5) keV[28], 6 496(3) keV[17], and 6 516(11) keV[29]. Attempt was also made to assign the new 2 256(18) keV proton peak labeled with *px* in Fig. 2 as the decay of the 4 721 keV state in ^{20}Na to the 275 keV state in ^{19}Ne, though the probability of *px* corresponding to 1 233 keV-275 keV cascading de-excitations from the 1 508 keV state in ^{19}Ne cannot be eliminated completely.

Based on the α-separation energy value of ^{19}Ne (S_α(^{19}Ne) = 3258.5(5) keV[44]), the resonance at 4 033 keV in ^{19}Ne can only be fed by the proton emission from the high-lying states in ^{20}Na. According to the compilation[41], the branching ratios for the γ-decay from the 4 033 keV state in ^{19}Ne to the 1536 keV state and the ground state of ^{19}Ne are (15±5)% and (80±15)%, respectively. A measurement of ^{19}F(^{3}He,t)^{19}Ne charge exchange reaction estimated the α-particle emission branching ratio of the 4 033 keV state in ^{19}Ne to be as low as $(2.9\pm2.1)\times10^{-4}$[11]. Therefore, it is more feasible to first search for the β-delayed proton-γ emission of ^{20}Mg rather than the β-delayed proton-α emission of ^{20}Mg. Fig. 4 shows the raw γ-ray spectrum around the energies of interest. In Fig. 4(a), the 2 614 keV γ ray comes from the natural ^{208}Tl decay[42] and no discernible peak around the expected energy of 2 497 keV can be observed in the spectrum. In Fig. 4(b), no discernible peak around the expected energy of 4 033 keV can be observed in the spectrum. The background-corrected number of counts around 4 033 keV is estimated to be 82(10), whereas the background-corrected number of counts around 2 497 keV is estimated to be negative. Hence, an upper limit of 7.5(19)% on the β-delayed proton emission branching ratio to the 4 033 keV state is estimated from the number of counts around 4 033 keV, the detection efficiency for the 4 033 keV γ ray, and the total numbers of the implanted ^{20}Mg ions. Another experiment with different method performed a few months after the present experiment set a more

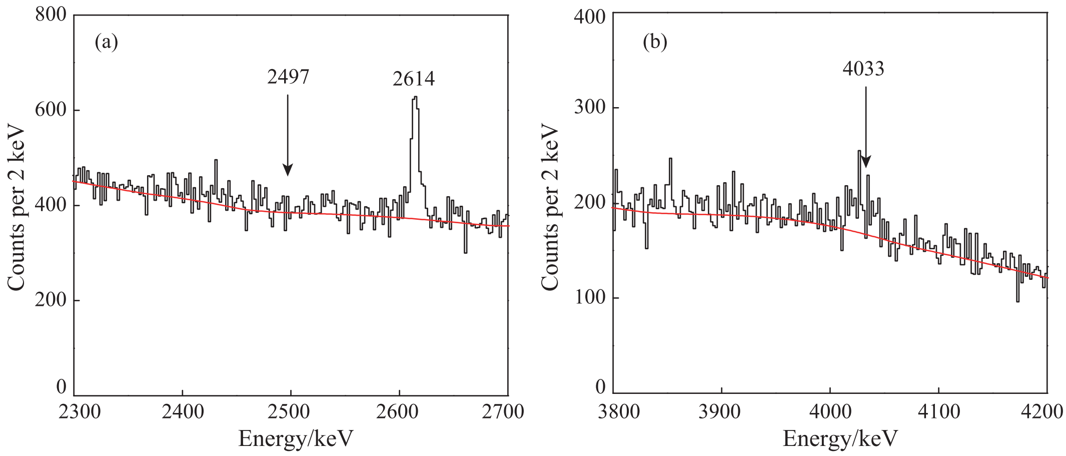

Fig. 4 (color online) γ-ray spectra measured by the clover-type HPGe detectors. (a) the γ-ray spectrum around the expected energy of 2 497 keV. (b) the γ-ray spectrum around the expected energy of 4 033 keV. The red curve represents a polynomial fit to the background.

stringent upper limit of 0.7%, owing to their higher statistics. Based on their upper limit of the branching ratio, less than one count would be observed in the present spectrum, *i.e.*, the decay channels associated with this state would not be observable with the present experimental sensitivity.

The partial decay scheme of ^{20}Mg reconstructed in the present experiment is shown in Fig. 5, in which the absolute β-decay branching ratios and the corresponding logft values for the ^{20}Na states are estimated by counting the efficiency and dead-time corrected β-delayed proton and γ-ray decay events. The results also provide opportunities to investigate the deviation from isospin symmetry, which can be reflected through the mirror asymmetry parameter $\delta = \dfrac{ft^+}{ft^-} - 1$, where the ft^+ and ft^- values are associated with the β^+ and β^- mirror decays, respectively[17, 27]. In this case, the δ parameters of the energetically accessible mirror transitions in the β decays of ^{20}O and ^{20}Mg are shown in Table 2. For the mirror decays involving particle-unbound states, the degree of isospin asymmetry is expected to be larger owing to the possible isospin mixing between nearby states[45, 46]. The breaking of the mirror symmetry is observed in the second mirror transitions, so the result reported by Ref. [27] is reproduced by the present measurement. However, up to now no satisfying theoretical explanation for the asymmetry has been found, therefore detailed calculations are needed to evaluate the contributions of the other effects that may induce mirror asymmetries[27].

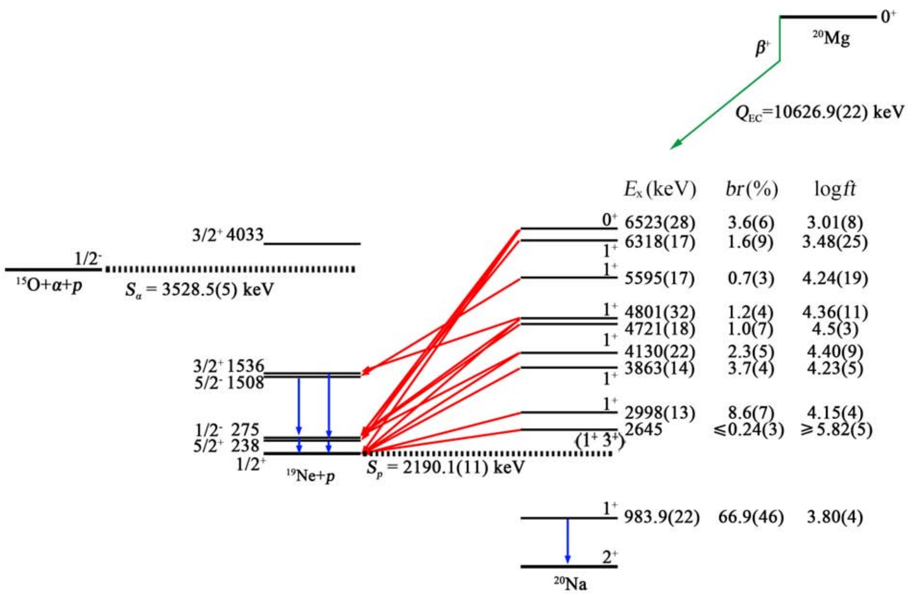

Fig. 5 (color online) Decay scheme of ^{20}Mg.

Table 2　Comparison between the transitions in the mirror β decays of ^{20}Mg and ^{20}O.

Transitions	logft	Ref.	δ
^{20}O→^{20}F 1 057 keV	3.740(6)	D. E. Alburger[47]	
^{20}Mg→^{20}Na 984.25(10) keV	3.83(2)	A. Piechaczek[27]	$0.230^{+0.076}_{-0.071}$
^{20}Mg→^{20}Na 984.10(25) keV	3.78(3)	M. V. Lund[17]	0.096±0.077
^{20}Mg→^{20}Na 983.9(22) keV	3.80(4)	Present work	0.148±0.107
^{20}O→^{20}F 3488 keV	3.65(6)	D. E. Alburger[47]	
^{20}Mg→^{20}Na 3001(2) keV	4.08(6)	A. Piechaczek[27]	$1.69^{+0.86}_{-0.65}$
^{20}Mg→^{20}Na 2970(8) keV	4.07(3)	M. V. Lund[17]	1.63±0.41
^{20}Mg→^{20}Na 2998(13) keV	4.15(4)	Present work	2.16±0.53

4 Conclusion

A detailed β decay spectroscopic study of ^{20}Mg was performed at RIBLL by a continuous-implantation method. The spectroscopic information including the half-life of ^{20}Mg, the excitation energies, the branching ratios, and the logft values for the states in ^{20}Na populated in the β decay of ^{20}Mg was extracted from the present measurement, with particular emphasis on the the level structure of ^{19}Ne. We resorted to indirect methods such as β-delayed proton-α emission or β-delayed proton-γ-ray decay of ^{20}Mg to extract information about the key resonance in ^{19}Ne. However, no conclusive result of the critical 4 033 keV state in ^{19}Ne can be obtained with the present data, only the upper limit of its branching ratio is estimated to be 7.5(19)% via the γ-ray spectrum. Similarly, no evidence was observed for the 4 033 keV state in ^{19}Ne in another measurement with a different method[17]. Despite the extremely weak transitions, these two measurements opened a way to the search for the 4 033 keV state in ^{19}Ne through β-delayed proton-γ emission and β-delayed proton-α emission of ^{20}Mg. It is apparent that further experiments are needed to solve the problems of astrophysical interest on the basis of the present works[48]. The large isospin asymmetry for the mirror decays of ^{20}Mg and ^{20}O was also well reproduced, providing more experimental data on nuclei with large isospin asymmetries, and the theoretical analysis should be explored in the future to shed more light on the mechanism behind the isospin symmetry breaking effects.

References:

[1] WIESCHER M, GÖRRES J, SCHATZ H. J Phys G: Nucl Part Phys, 1999, **25**: R133.
[2] KUBONO S. Nucl Phys A, 1995, **588**: 305c.
[3] BELARGE J, KUVIN S A, BABY L T, *et al.* Phys Rev Lett, 2016, **117**: 182701.
[4] LOTAY G. private communication.
[5] WALLACE J P, WOODS P J, LOTAY G, *et al.* Phys Lett B, 2012, **712**: 59.
[6] TAN W P, GÖRRES J, DALY J, *et al.* Phys Rev C, 2005, **72**: 041302(R).
[7] KANUNGO R, ALEXANDER T K, ANDREYEV A N, *et al.* Phys Rev C, 2006, **74**: 045803.
[8] MYTHILI S, DAVIDS B, ALEXANDER T K, *et al.* Phys Rev C, 2008, **77**: 035803.
[9] MAGNUS P V, SMITH M S, HOWARD A J, *et al.* Nucl Phys A, 1990, **506**: 332.
[10] VISSER D W, CAGGIANO J A, LEWIS R, *et al.* Phys Rev C, 2004, **69**: 048801.
[11] TAN W P, FISKER J L, GÖRRES J, *et al.* Phys Rev Lett, 2007, **98**: 242503.
[12] TAN W P, GÖRRES J, BEARD M, *et al.* Phys Rev C, 2009, **79**: 055805.
[13] REHM K E, WUOSMAA A H, JIANG C L *et al.* Phys Rev C, 2003, **67**: 065809.
[14] DAVIDS B, VAN DEN BERG A M, DENDOOVEN P, *et al.* Phys Rev C, 2003, **67**: 012801(R).
[15] DAVIDS B, VAN DEN BERG A M, DENDOOVEN P, *et al.* Phys Rev C, 2003, **67**: 065808.
[16] DAVIDS B, CYBURT R H, JOSE J, *et al.* Astrophys J, 2011, **735**: 40.
[17] LUND M V, ANDREYEV A, BORGE M J G, *et al.* Eur Phys J A, 2016, **52**: 304.
[18] LUND M V. A Search for Exotic Decay Modes on the Proton Drip-line - the Cases of ^{20,21}Mg[D]. Aarhus University, 2016.
[19] KOLDSTE G T, BLANK B, BORGE M J G, Phys Rev C, 2013, **87**: 055808.
[20] TORRESI D, WHELDON C, KOKALOVA1 T, *et al.* J Phys: Conf Ser, 2017, **876**: 012021.
[21] LAM Y H, SMIRNOVA N A, CAURIER E. Phys Rev C, 2013, **87**: 054304.
[22] SMIRNOVA N A, BLANK B, BROWN B A, *et al.* Phys Rev C, 2017, **95**: 054301.
[23] MOLTZ D M, ÄYSTÖ J, CABLE M D, *et al.* Phys Rev Lett, 1979, **42**: 43.
[24] KUBONO S, FUNATSU, Y, IKEDA N, *et al.* Nucl Instr Meth B, 1992, **70**: 583.
[25] KUBONO S, IKEDA N, FUNATSU Y,*et al.* Phys Rev C, 1992, **46**: 361.
[26] GÖRRES J, WIESCHER M, SCHELLER K, *et al.* Phys Rev C, 1992, **46**: R833.

[27] PIECHACZEK A, MOHAR M F, ANNE R, *et al.* Nucl Phys A, 1995, **584**: 509.
[28] GLASSMAN B E, PÉREZ-LOUREIRO D, WREDE C, *et al.* Phys Rev C, 2015, **92**: 042501(R).
[29] BABO M. β-delayed Charged Particle Decays of Neutron-deficient Nuclei ^{20}Mg and ^{22,23}Si[D]. University of Caen Normandy, 2017.
[30] SUN L J, LIN C J, XU X X, *et al.* Chin Phys Lett, 2015, **32**: 012301.
[31] LIN C J, XU X X, JIA H M, *et al.* Phys Rev C, 2009, **80**: 014310.
[32] XU X X, LIN C J, JIA H M, *et al.* Phys Rev C, 2010, **81**, 054317 (2010).
[33] XU X X, LIN C J, JIA H M, *et al.* Phys Rev C, 2010, **82**: 064316.
[34] XU X X, LIN C J, JIA H M, *et al.* Phys Lett B, 2013, **727**: 126.
[35] LIN C J, XU X X, WANG J S, *et al.*, Nucl Phys Rev, 2016, **33**: 160. doi: 10.11804/NuclPhysRev.33.02.160. (in Chinese) (林承键, 徐新星, 王建松, 等. 原子核物理评论, 2016, **33**(02): 160.)
[36] ZHAN W L, XIA J W, ZHAO H W, *et al.* Nucl Phys A, 2008, **805**: 533c.
[37] SUN Z Y, ZHAN W L, GUO Z Y, *et al.* Nucl Instr Meth A, 2003, **503**: 496.
[38] SUN L J, XU X X, LIN C J, *et al.* Nucl Instr Meth A, 2015, **804**: 1.
[39] SUN L J, XU X X, LIN C J, *et al.* Nucl Phys Rev, 2016, **33**: 230.
[40] SUN L J, XU X X, FANG D Q, *et al.*, Phys Rev C, 2017, **95**: 014314.
[41] TILLEY D R. Nucl Phys A, 1995, **595**: 1.
[42] MARTIN M J. Nucl Data Sheets, 2007, **108**: 1583.
[43] WREDE C, CLARK J A, DEIBEL C M, *et al.* Phys Rev C, 2010, **81**: 055503.
[44] WANG M, AUDI G, KONDEV F G *et al.* Chin Phys C, 2017, **41**: 030003.
[45] BORGE M J G, DEDING J, HANSEN P G, *et al.* Phys Lett B, 1993, **317**: 25.
[46] PÉREZ-LOUREIRO D, WREDE C, BENNETT M B, *et al.* Phys Rev C, 2016, **93**: 064320.
[47] ALBURGER D E, WANG G, WARBURTON E K, *et al.* Phys Rev C, 1987, **35**: 1479.
[48] WREDE C, GLASSMAN B E, PÉREZ-LOUREIRO D, *et al.* submitted.

^{20}Mg β 衰变谱学与 ^{15}O$(\alpha,\gamma)^{19}$Ne 反应

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摘要: ^{15}O$(\alpha,\gamma)^{19}$Ne$(p,\gamma)^{20}$Na 反应链是高温CNO循环向快速质子俘获过程突破的一条关键路径，相关的反应率输入量可通过 ^{20}Mg 的 β 衰变可布居 ^{19}Ne 共振态并测量其衰变性质来获得。通过高效率高精度地测量 ^{20}Mg β 衰变中产生的质子与 γ 射线得到了 ^{20}Mg 衰变的详细信息，并构建了完整的衰变纲图，还进行了 ^{19}Ne 4 033 keV 共振态衰变性质的探索，获得了该态在 ^{20}Mg β 衰变中被布居的分支比上限。通过比 ^{20}Mg 和 ^{20}O 镜像能级跃迁的结果确认了同位旋非对称性，为检验相关理论模型提供了精确的实验数据。对于突破路径中有重要影响的 ^{19}Ne 4 033 keV 共振态的性质，有待更高统计的实验进一步研究。

关键词: β 缓发质子衰变；快速质子俘获过程；质子-γ 符合；镜像非对称性

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