

Mass of ^{27}P and ^{31}Cl *

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ABSTRACT

The Q-values for the ($^3\text{He}, ^8\text{Li}$) reaction on ^{32}S and ^{36}Ar have been measured. The resulting masses for the new nuclei ^{27}P and ^{31}Cl are compared to the predictions of various models. The lowest $T=3/2$ state in ^{27}Si was also observed in the $^{29}\text{Si}(p,t)^{27}\text{Si}$ reaction, and its excitation energy and mass excess were determined.

I. Introduction

Measurements of the mass of the previously unobserved nuclei ^{27}P and ^{31}Cl complete the series of $T_z=-3/2$ ground state masses in the s,d shell. The ($^3\text{He}, ^8\text{Li}$) reaction has been shown to be a useful reaction for reaching nuclei of this type,¹ but these two cases were made difficult by target problems. In the case of ^{27}P , the ^{32}S target which is required evaporates easily in the beam, and therefore beam currents had to be reduced to much lower values than used previously. For ^{31}Cl , an ^{36}Ar gas target was required at relatively high pressures because of the very low cross section (10 nb/sr).

The ground state masses of these two nuclei, particularly ^{27}P , are of special interest because various models give quite different predictions. The ^{27}P ground state configuration is expected to have a large $s_{1/2}$ proton component, and is only bound by about 870 keV against proton decay. This has a marked effect on the Coulomb energy, an effect which is not properly accounted for in a Garvey-Kelson mass formula.² It is also the most severe test of the isobaric multiplet mass equation³ that one could hope for in a mass quartet. The nucleus ^{31}Cl is only bound against proton emission by about 300 keV, a fact that should also be reflected in the Coulomb energy.

II. Experimental

The general experimental equipment which was used has been described previously.⁴ In this experiment extensive use of off-line analysis of event-by-event tapes was made to minimize the

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background. The focal plane detector consisted of the double proportional counter plus thin plastic scintillator combination.

II.1 The $^{32}\text{S}(^3\text{He}, ^8\text{Li})^{27}\text{P}$ reaction.

The problems of using a elemental sulfur target are well known. It is difficult to produce a uniform target of reasonable areal density, and, in addition, a small amount of beam can easily re-evaporate it. These problems are exacerbated by the requirements for an accurate Q-value measurement using a low-cross section reaction. Although beam currents of 2-3 uA on a beam spot of 1 mm^2 are available, they could not be used, in the present case, even though the target was covered on both surfaces with 20 ug/cm^2 carbon foils. The target could not withstand currents greater than 100 nA with a spot defocused to $3\text{-}4\text{ mm}^2$. Thus the runs were very long with these low beam current, and only three runs were taken at angles of 7° , 9° and 11° .

Another problem, target graininess, was reduced by exposing the target to a high beam current for a short time. In a test ($^3\text{He}, ^7\text{Be}$) run this was found to improve the resolution by about a factor of two without appreciably reducing the yield. The calibration reaction for the mass measurement was $^{32}\text{S}(^3\text{He}, ^7\text{Be})$, and this was taken both before and after the approximately one day long runs on ($^3\text{He}, ^8\text{Li}$). The specific ionization of the ^7Be -ions is very close to that of the ^8Li -ions, so an accurate target thickness measurement, which would have been quite difficult, was not required. The target thickness was approximately 200 ug/cm^2 as determined from the width of the $^{32}\text{S}(^3\text{He}, ^7\text{Be})^{28}\text{Si}$ ground state peak. The spectrum

from the $^{32}\text{S}(^3\text{He}, ^8\text{Li})^{27}\text{P}$ reaction at 7° is given in Fig.

1. The ^{27}P ground state peak is clearly evident although not at all strong. The cross section was about 100 nb/sr at 7° and dropped off with angle. The 9° and 11° runs show a peak at the same Q-value to well within the errors but with a centroid which is not as well defined. These runs were taken as a corroboration that the kinematics were correct for the $^{32}\text{S}(^3\text{He}, ^8\text{Li})^{27}\text{P}$ reaction, but the Q-value comes primarily from the 7° data. An excited state was observed at $E_x = 1.66 \pm 0.04\text{ MeV}$ at all three angles.

The overall error on the ^{27}P mass determination reflects mainly the uncertainties in the centroids of the peak (25 keV), but there were also contributions from target thickness (10 keV) and beam energy uncertainty (15 keV). The final Q-value determination gives $-31,277 \pm 35\text{ keV}$, which corresponds to a mass excess of $-753 \pm 35\text{ keV}$ for ^{27}P .

II.2 The $^{29}\text{Si}(p, t)^{27}\text{Si}(T=3/2)$ reaction

Since the analog of the ^{27}P ground state in ^{27}Si was unknown, a search for this state was made using the $^{29}\text{Si}(p, t)^{27}\text{Si}$ reaction at 40.2 MeV . Spectra were taken at angles of 6° , 18° and 24° with an energy resolution of $\sim 10\text{ keV}$. The 6° spectrum is shown in Fig. 2. As is usual in these cases, the $T=3/2$ state shows up as a very strong transition and in this case is forward peaked because of the $L=0$ angular momentum transfer. The calibration reaction was $^{12}\text{C}(p, t)^{10}\text{C}\text{ g.s.}$, which falls very close to the peak of interest. The data obtained at the three angles agree to within 4 keV , and the resultant Q-value is $-23,798\text{ keV}$ which corresponds to a mass excess of -5757 keV and an excitation

energy of 6,628 keV. The error assigned to each of these numbers is 5 keV and stems from a number of sources particularly angle and beam energy uncertainty.

II.3 The $^{36}\text{Ar}(^3\text{He}, ^8\text{Li}) ^{31}\text{Cl}$ reaction

The gas cell arrangement used in this experiment was the same as described in a paper⁵ on $^{36}\text{Ar}(^3\text{He}, ^6\text{He}) ^{33}\text{Ar}$, but in the case of $(^3\text{He}, ^8\text{Li})$ the energy loss of the outgoing particles is much larger. Two runs were taken, one at 260 Torr pressure and one at 160 Torr pressure. These are shown in figs. 3 and 4 in which one can see the effect of gas pressure on resolution clearly.

The measured Q-values in these two runs agreed to within 20 keV, but possible systematic errors due to the large energy losses of both the incident and outgoing particles prevent a very accurate determination. These losses were of the order of 200 keV and 1 MeV respectively. The effect of these corrections on the Q-value determination was minimized by comparison to other reactions on gas targets. These were $^{36}\text{Ar}(^3\text{He}, ^7\text{Be}) ^{32}\text{S}$, $^{14}\text{N}(^3\text{He}, ^7\text{Be}) ^{10}\text{B}$, and $^{14}\text{N}(^3\text{He}, ^8\text{Li}) ^9\text{C}$. The intercomparison of these reaction revealed no inconsistencies in the energy loss corrections which would have changed the final Q-value by more than 30 keV. Another difficulty in the experiment stemmed from the very low cross section (10 nb/sr). Even with the relatively high gas pressures, it was difficult to get enough counts for an accurate centroid determination. The final value for the Q-value of $^{36}\text{Ar}(^3\text{He}, ^8\text{Li}) ^{31}\text{Cl}$ was $29,180 \pm 50$ keV which corresponds to a mass excess of -7070 ± 50 keV.

III. Discussion of Results

Table I gives a summary of the presently measured ground state masses and the predictions of various theoretical models mainly taken from a recent publication.⁶ This discussion will focus on the isobaric multiplet mass equation (IMME) and the Garvey-Kelson transverse relation³ (as recalculated by Janecke).⁶ The agreement with the other predictions is typical for each particular method, and the physical basis of each method is well described in ref. 6.

A comparison of the experimental results for the now complete A=27 and 31 quartets is given in Table II. The mass excesses for the other members of the quartets are taken from compilations⁷ except for the T=3/2 state in ^{31}S , which was measured in a $^{33}\text{S}(p,t)^{31}\text{S}$ experiment at 40 MeV by Nann, et al.⁸ The state of the other quartets is summarized in a recent paper.⁹ The agreement with the Isobaric Multiplet Mass equation is excellent throughout the s,d shell, and it is clear that the interest should now be in understanding why this is so even for the case in which the proton-rich member is barely bound.

A simple single particle calculation was made to investigate the effect of a barely bound $s_{1/2}$ proton on the IMME. The $s_{1/2}$ proton well has no centrifugal barrier, and therefore one expects a greater expansion of the wave function as compared for example to a $d_{5/2}$ proton with the same binding. Using a Wood-Saxon well, one can show that the effect of the expansion of the wave function near the top of the well gives a reduction of about 110 keV in the Coulomb energy of the $T_z = -3/2$ member

of the $A=27$ multiplet but does not produce a d coefficient in the IMME. The binding energies for allowed proton decay of ^{27}P , and of its analogs in ^{27}Si and ^{27}Al are 0.87, 1.07 and 1.45 MeV respectively. Thus each of these levels reflect to some extent the reduction of Coulomb energy due to the increased radial extent of a $s_{1/2}$ proton near the top of a well. Using a simple shell model wave function (pure $s_{1/2}$ neutron for ^{27}Mg) one finds decreased Coulomb energies as compared to a $d_{5/2}$ neutron with the same binding of 110, 62 and 26 keV respectively. This leads to a vanishing d -coefficient and shows that even relatively large radial wave function differences between members do not necessarily lead to a significant violation of the IMME. Conversely, one can not use the success of the IMME to show that the wave functions of all four members are identical.

A very different situation exists for the Garvey-Kelson symmetric relation.² The mass of ^{27}P is related to the ground state masses of nearby nuclei by the relation

$$^{27}\text{P} = ^{27}\text{Mg} + ^{25}\text{Al} - ^{25}\text{Mg} + ^{27}\text{S} - ^{27}\text{Al} + ^{29}\text{P} - ^{29}\text{Si}.$$

The $s_{1/2}$ Coulomb energy is accounted for here by the $^{29}\text{P} - ^{29}\text{Si}$ ground state mass difference. However, the proton binding energy in ^{29}P is 2.75 MeV, considerably greater than the 0.87 MeV in ^{27}P , and therefore this relation should predict a mass excess approximately 110 keV too large. As can be seen in Table I, the data does seem to reflect this simple effect. The Garvey-Kelson transverse relation works much better for ^{31}Cl , an agreement which is

typical for this relation. The shell model calculations of De Meijer, et al.¹⁰ are the most successful of all the predictions. They used the specific microscopic shell model wave function appropriate to each level and evaluated many contributions to the Coulomb energy difference between the $T_z = -3/2$ and $T_z = -1/2$ members of the quartet.

Continuation of the mass measurements of $T_z = -3/2$ nuclei is possible above $A=37$ (the present limit) using heavy ion transfer reactions, and work has already begun on ^{39}Sc using the $(^{14}\text{N}, ^{15}\text{C})$ reaction at 110 MeV.

REFERENCES

1. W. Benenson, A. Guichard, E. Kashy, H. Nann and L.W. Robinson, Phys. Letters 58B,46(1975).
2. G.T. Garvey, W.J. Gerace, R.C. Jaffe, I. Talmi and I. Kelson, Rev. Mod. Phys. 41,51(1969).
3. E.P. Wigner, in Proceedings of the Robert A. Welch Foundation Conferences on Chemical Research, Houston, Texas 1957, edited by A. Milligam (Robert A. Welch Foundation, Houston, Texas, 1957). The Structure of the Nucleus, p. 67.
4. W. Benenson, E. Kashy, I.D. Proctor and B.M. Freedman, Phys. Lett. 43B,117(1973).
5. H. Nann, W. Benenson, E. Kashy, and P. Turek, Phys. Rev. C9,1848(1974).
6. Atomic and Nuclear Data Tables, S. Maripuu ed., 17,1 (1976).
7. P.M. Endt and C. Van der Leun, Nucl. Phys. A105,1(1967).
8. H. Nann, A. Saha and B.H. Wildenthal to be published.
9. W. Benenson, E. Kashy, D. Mueller and H. Nann. Proceedings of 3rd International Conference on Nuclei Far from Stability. R. Klapisch, ed., CERN 76-13(1976).
10. R.J. de Meijer, H.F.J. Van Royen and P.J. Brussaard, Nucl. Phys. A164,11(1974).

TABLE I.--Comparison of the experimentally determined mass excess to theoretical predictions (kev).

	^{27}P	^{31}Cl
Experiment	-753±35	-7070±50
IMME	-716±16	-7066±60
Myers ^a	-4270	-9630
Groote, Hilfe & Takahashi ^a	-560	-7150
Liran & Zeldes ^a	-340	-6850
Beinor, Lombard & Mas ^a	-600	-6200
Janecke, Garvey & Kelson ^a	-550	-7030
De Meijer et al. ^b	-766	-7068

^aFrom ref. 6.

^bref. 10.

FIGURE CAPTIONS

- Fig. 1.--Spectrum from the $^{32}\text{S}(^3\text{He}, ^8\text{Li})^{27}\text{P}$ reaction at 76 Mev and 7° . An excited state of ^{27}P is shown at $E_x=1.66$ Mev. One channel corresponds to 17 kev of excitation energy.
- Fig. 2.--Spectrum from the $^{29}\text{Si}(p,t)^{27}\text{Si}$ reaction in the region of the lowest $T=3/2$ state.
- Fig. 3.--Spectrum from the $^{36}\text{Ar}(^3\text{He}, ^8\text{Li})^{31}\text{Cl}$ reaction at 74 Mev and a target pressure of 260 torr. One channel corresponds to 34 kev in excitation energy.
- Fig. 4.--Spectrum from the $^{36}\text{Ar}(^3\text{He}, ^8\text{Li})^{31}\text{Cl}$ reaction at 76 Mev and 160 torr pressure. One channel corresponds to 17 kev of excitation energy.

TABLE II.--Comparison to the IMME.

A	a	b	c	d	χ^2
27	-8118±4	-4625±6	200±9	6.2±6.4	-
27	-8121±2	-4620±5	207±3	-	0.97
31	-1546±12	-5294±22	201±14	0.5±13	-
31	-15463±5	-5292±13	200±7	-	0.64







