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# $^{35}Cl(p,n)^{35}Ar$ threshold energy and its relation to the vanishing Cabibbo angle

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The threshold energy of the $^{35}Cl(p,n)^{35}Ar$ reaction has been measured to be 6942.2 ± 2.2 keV, clearly resolving the ambiguity arising from two previous conflicting values. The results are discussed in the context of the problems posed by a vanishing Cabibbo angle.

[NUCLEAR REACTIONS $^{27}Al(p,n)$ $E_p = 5770-5840$ keV, $^{35}Cl(p,n)$, $E_p = 6910-7000$ keV, measured $\beta^+$ yield; deduced reaction thresholds, Cabibbo angle in $^{35}Ar$.]

## I. INTRODUCTION

The vector coupling constant of weak interactions obtained from the $T = 1$ series of $0^+ \to 0^+$ superallowed transitions,[1] in conjunction with data from the decay of nuclei with $T = \frac{1}{2}$, may be used to deduce a value of the Cabibbo angle[2] for these nuclei. Hardy and Towner[3] have done this for the only three decays which can be analyzed in this way to date: those of the neutron, $^{19}Ne$, and $^{35}Ar$. Their results suggest that for $^{35}Ar$ the Cabibbo angle $\theta_C$ is consistent with zero while the values deduced for the other two cases agree with that obtained[4] from the hyperon $\beta$ decays: $\sin\theta_C = 0.232 \pm 0.003$.

It had been proposed[5] previously that, in analogy to superconductivity, symmetries which are normally broken at low temperatures could be reestablished, in macroscopic systems in thermodynamic equilibrium, above a certain critical temperature or in the presence of a high intensity vector field. In particular, Salam and Strathdee[6] had recently suggested that, if $CP$ is violated through a spontaneous breakdown mechanism, then the symmetry should be restored above some critical magnetic field, crudely estimated to be between $10^{11}-10^{14}$ G. Suranyi and Hedinger,[7] and more recently Lee and Khanna,[8] have estimated the nuclear magnetic field to be of an order of magnitude ($\sim 10^{16}$ G) sufficient[6] to restore the symmetry. At present, however, if $CP$ violation is a weak-interaction process (milliweak theory), the observable effects are too small to detect in nuclei.[9,10]

Salam and Strathdee had also pointed out that the Cabibbo angle should be turned off at fields of about $10^{16}$ G, if it has a spontaneous symmetry breakdown origin. Thus, the vanishing Cabibbo angle for $^{35}Ar$ could represent the first example of a nucleus where the electromagnetic field is high enough to turn off the Cabibbo angle and restore strangeness conservation in weak interactions. (Possible evidence from muon capture rate in $^{93}Nb$ has also been reported.[11]) An important consequence of a zero Cabibbo angle is that, in that case, the $\Lambda^0$-hyperon is stable. It would then be possible that, for some nuclei, the nuclear magnetic fields are so high that hypernuclei would become stable.[7]

Nevertheless, there is no *a priori* reason to expect the magnetic field in an $^{35}Ar$ nucleus to be larger than in $^{19}Ne$. In their calculations, Hardy and Towner have used the most recent value[12] of the $\beta$-decay end-point energy of $^{35}Ar$ ($E_0 = 4941.6 \pm 1.7$ keV) and a weighted average of the asymmetry parameter $A$ obtained from four measurements of the angular distribution of the positrons emitted by polarized nuclei. Recently, Szybisz and Rao[13] proposed a solution to the $^{35}Ar$ anomaly. They pointed out that if one adopts the largest value of $A$ as well as an older measurement[14] of $E_0 = 4968.5 \pm 3.5$ keV, which differs by 27 keV from the more recent value,[12] then the Cabibbo angle so obtained is consistent with the normal value.

In view of the importance of the existence of a zero Cabibbo angle and of the conflicting data, we have measured again the $\beta$-decay end-point energy of $^{35}Ar$. This was achieved, as in the previous two cases,[12,14] via a measurement of the $^{35}Cl(p,n)^{35}Ar$ threshold energy.

## II. MEASUREMENT AND ANALYSIS

The method of threshold measurement used in the present work has been described in detail elsewhere.[15] The results presented in this paper are based mainly on the observation of the $\beta^+$ radioactivity. Briefly, the technique makes use of a pneumatic beam chopper and associated software which controls the data acquisition. The beam charge falling on target was digitized and recorded during a beam-on period while, during the beam-off period, the positron activity, was detected in a NE102 plastic scintillator. To reduce background only pulses corresponding to $\beta^+$ having an energy greater than $\frac{1}{3}$ of the end-point energy were counted in a scaler. That scaler was connected to an analyzer whose channel number was incremented after each beam-on/beam-off cycle. At the same time, multiscaling of the $\beta^+$ was performed in order to separate, by half-life analysis, the desired activity from impurity products. A run consisted of about 200 cycles at each bombarding energy. Then, a counting period without beam served to determine the background after each run.

The analyzing magnet of the Université de Montréal tandem accelerator was calibrated by measuring the $^{27}Al(p,n)^{27}Si$ reaction threshold. It was found that, by saturating the analyzing magnet before the experiment, any effects due to differential hysteresis could be substantially attenuated. The threshold of the $^{27}Al(p,n)^{27}Si$ reaction could thus be reproduced within 1 keV, independently of the magnet history. Nevertheless, each measurement of the $^{35}Cl(p,n)^{35}Ar$ reaction threshold curve was preceded and followed by a similar measurement on the $^{27}Al(p,n)^{27}Si$ reaction to ascertain the correct value of the magnet constant in each case.

The proton beam was collimated through slits of 4.6 mm $\times$4.6 mm and 0.25 mm $\times$0.25 mm at the object and image points of the analyzing magnet, respectively. Since the radius of curvature is 0.88 m, the estimated beam energy spread, assuming no divergence is $\delta E/E = 2\delta R/R = \pm 0.014\%$. In fact, it is probably smaller.[16] The effect of this spread on the threshold determination is, however, certainly smaller because the yield curve fitting near threshold is obtained from several points. Nevertheless, because of magnet current instabilities and uncertainties in magnetic field reading, estimated to be of the same order of magnitude, this value is adopted. This estimate is confirmed by the reproducibility of the $^{27}Al(p,n)^{27}Si$ reaction threshold energy within 1 keV, when measured under different experimental conditions. If the $^{27}Al(p,n)^{27}Si$ and $^{35}Cl(p,n)^{35}Ar$ thresholds are analyzed in the same way near threshold, this source of error does not apply to each individual measurement but rather must be included once after the calculation of the average result.[17,18]

The Al target, placed at 45° to the beam direction, was evaporated onto a Ta backing. Its thickness, 0.30 mg/cm$^2$, was sufficient when inclined for the $\frac{3}{2}$ power law[19] to be valid as much as 22 keV above threshold. Figure 1 shows a typical yield curve obtained near threshold, and fitted with the function: yield = background + constant $x$ $(E_p - E_{th})^{3/2}$.

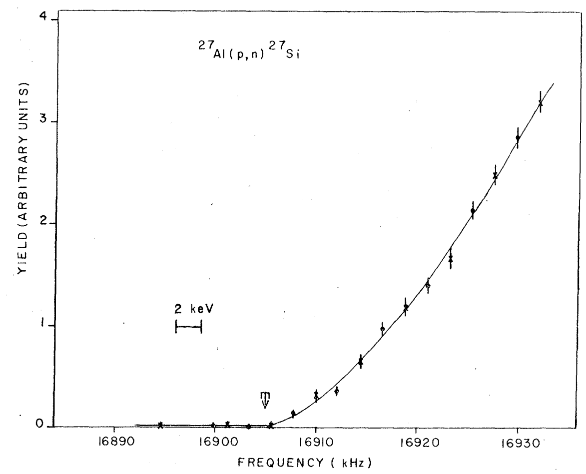


FIG. 1. Example of an $^{27}Al(p,n)^{27}Si$ threshold curve and its fit to a $\frac{3}{2}$-power function.

For the $^{35}Cl(p,n)^{35}Ar$ reaction, the choice of target material presented some difficulties because of the high volatility of most Cl compounds. Cramer and Mangelson[14] have used a polyvinyl compound, while Freeman, Robinson, and Wick[12] used KCl. In our case, we carefully evaporated natural AgCl onto a Au backing for good thermal conductivity, and cooled the target ladder with running water. Both thick targets (4 mg/cm$^2$ or 220 keV effective thickness when inclined) and thin targets (310 $\mu$g/cm$^2$ or 17 keV effective thickness when inclined), were used, the thin ones being necessary to verify the presence of a resonance very near threshold, as reported in Ref. 12. Before each series of irradiations at a given energy, the target was positioned so that a fresh area would be exposed to the beam. Figure 2 represents typical data obtained with a thick and a thin target. The presence of the resonance just above threshold at around 18525 kHz is confirmed in the case of the thin target, as can be seen in Fig. 2(b). Because of the proximity of this resonance to the threshold energy, only the first few data points above threshold were used in the fit to the $\frac{3}{2}$ power function. Two or three different ranges of yield points were used in the fitting program, both from data obtained from the decay curve of the multiscaling and from the direct scaler counts. The results of the fit differred mostly in the slope, but the threshold value was not generally affected by more than 0.8 keV. The adopted error includes this effect. The nature of the resonance is unknown. It could correspond to a resonance in the compound nucleus at 15.26 MeV excitation, but we estimated that a fit to an expression incorporating a Breit-Wigner resonance, as is generally done for the $^7Li(p,n)^7Be$ threshold,[20] would only introduce additional param-

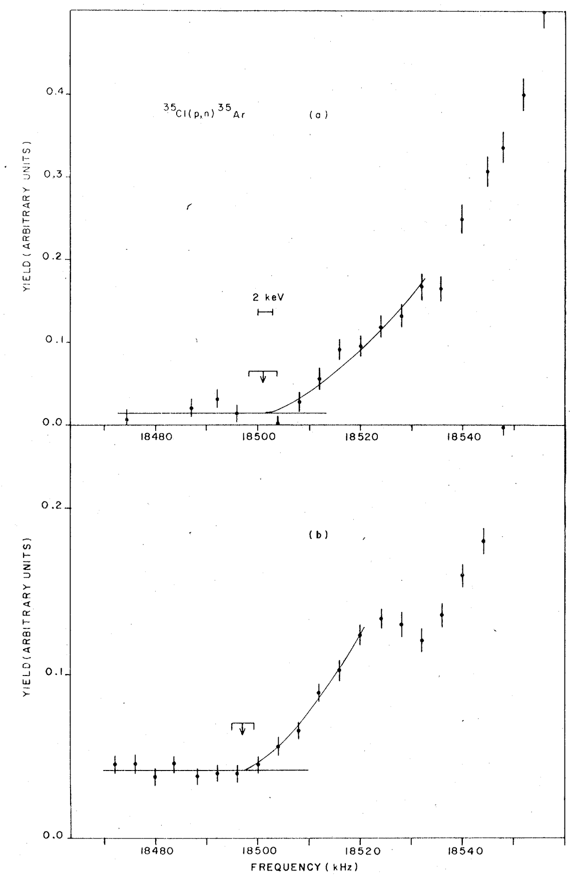


FIG. 2. Examples of $^{35}$Cl$(p,n)^{35}$Ar threshold curves and fits to a $\frac{3}{2}$-power function: (a) thick target, (b) thin target. The smooth curves shown extend only through the points used in the fitting procedure.

eters without substantially affecting the threshold result.

Our final result based on the weighted average of eight measurements is $E_{th} = 6942.2 \pm 1.2$ keV. If we take into account the finite resolution of the beam estimated above and the uncertainty in the $^{27}$Al$(p,n)^{27}$Si reaction threshold calibration energy[17] (the largest source of error), then the error is increased to 2.2 keV.

## III. DISCUSSION AND CONCLUSIONS

Our value for the $^{35}$Cl$(p,n)^{35}$Ar reaction threshold is clearly in agreement with that obtained by Freeman *et al.*[12] ($E_{th} = 6941.2 \pm 1.7$ keV), when we use the $^{27}$Al$(p,n)^{27}$Si reaction threshold calibration energy ($E_1 = 5800.1 \pm 1.5$ keV) worked out by Freeman,[17] as an average of several independent measurements. If on the other hand, we use a more recent calibration energy value ($E_2 = 5803.3 \pm 0.3$ keV) measured by Naylor and White,[21] we obtain for the $^{35}$Cl$(p,n)^{35}$Ar reaction threshold, $E_{th} = 6946.0 \pm 1.8$ keV, in slight disagreement with Freeman *et al.*[12] Nevertheless, in both cases, our work clearly rules out the threshold value ($E_{th} = 6968.9 \pm 3.5$ keV) measured by Cramer and Mangelson.[14] Our work also confirms the presence of a resonance near threshold. The break in the yield curve due to the resonant effect occurs at an energy which would correspond to the threshold value measured by this last group. They measured the $\beta^+$ yield in terms of coincidences between the positron counts and the annihilation quanta from the positrons. Thus, they could have missed the true threshold because of the resulting reduction in detection efficiency.

We have decided to base the following discussion on the threshold value deduced from $E_1$ rather than $E_2$ since the latter energy appears to be in conflict with the recently published[22] masses of $^{27}$Al and $^{27}$Si. However, our conclusions are not affected by this choice. The weighted average of our threshold value and that of Freeman *et al.*[12] is then $E_{th} = 6941.6 \pm 1.4$ keV. The corresponding $Q$ value is $-6746.4 \pm 1.4$ keV and the $^{35}$Ar positron end-point energy is $4941.9 \pm 1.4$ keV, taking the magnitude[22] of $(m_n - m_H)c^2$ to be $782.40 \pm 0.05$ keV.

Then, using the present data and recent precision measurements[23,24] of the half-life and branching ratios of the $^{35}$Ar decay, the $Ft$ value, incorporating the model independent radiative corrections up to second order and a charge-dependent correction (evaluated to be $(0.6 \pm 0.3)\%$ by inspection of the $T=1$ $0^+ \to 0^+$ superallowed series[1]) is calculated to be $5675 \pm 21$ sec from the parametrization of Wilkinson and Macefield.[25] Repeating the analysis of Hardy and Towner[3] on the basis of the average of the asymmetry parameter measurements ($A = 0.22 \pm 0.03$) yields a Cabibbo angle of $\sin\theta_C = 0.0$ with a maximum uncertainty of 0.10, a value inconsistent with the "normal" value $\sin\theta_C = 0.232 \pm 0.003$. If we use the largest value of $A(0.33 \pm 0.06)$, as was done by Szybisz and Rao,[13] we obtain $\sin\theta_C = 0.115^{+0.085}_{-0.115}$, which is still more than one standard deviation from the accepted value. Even then, there does not seem to be any experimental evidence to justify the selection of this particular $A$ value.

Thus, the $^{35}$Ar case remains an anomaly, as compared to the neutron and $^{19}$Ne, the Cabibbo angle values obtained from hyperon $\beta$ decays and the data of the $T=1$ series of $0^+ \to 0^+$ superallowed transitions, at least up to the $f$ orbit. If the restoration of symmetry is due to the presence of a high nuclear magnetic field,[6] then, to explain the results, one would require the field in $^{35}$Ar to be very different from other systems. However, Lee and Khanna[8] have shown recently that the magnetic field intensity for a valence nucleon in a nucleus is a function of its orbital angular momentum but is "independent of the mass, charge, spin, deformation and evenness or oddness of the nucleus" and could be of the order of magnitude of the critical strengths estimated by Salam and Strathdee. The $^{35}$Ar anomaly is therefore unlikely to be attributable to this mechanism and it remains to be resolved.

After submission of the present paper we learned of a very recent measurement of the $^{35}Cl(p,n)^{35}Ar$ reaction threshold by White and Naylor.[26] Their result ($E_{th} = 6943.0 \pm 1.0$ keV) agrees with ours and that of Freeman *et al.*

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