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# Static Quadrupole Moment of the First Excited State of $^{28}$Si

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*Abstract*

The reorientation effect in Coulomb excitation has been used to measure the static quadrupole moment $Q_{2^+}$ and $B(\mathrm{E2}; 0^+ \to 2^+)$ for the $1 \cdot 779$ MeV first excited state of $^{28}$Si. The results obtained are $Q_{2^+} = +15 \cdot 5 \pm 3 \cdot 4$ $e\,\mathrm{fm}^2$ and $B(\mathrm{E2}; 0^+ \to 2^+) = 326 \pm 20$ $e^2\,\mathrm{fm}^4$. The value obtained for $Q_{2^+}$ confirms the results of other recent determinations using the reorientation effect, and the $B(\mathrm{E2}; 0^+ \to 2^+)$ value is in excellent agreement with the mean value deduced from previous lifetime determinations. Shell model and Hartree–Fock calculations of $Q_{2^+}$ both give a good account of the experimental result.

## Introduction

In studies of the variation of nuclear shape through the 2s–1d shell, the static quadrupole moment $Q_{2^+}$ of the first excited state of $^{28}$Si ($E_x = 1 \cdot 779$ MeV, $J^\pi = 2^+$; Endt and van der Leun 1978) is of particular significance. It has been widely accepted (see e.g. Nakai *et al.* 1970; Häusser *et al.* 1971; Christy and Häusser 1972) that the value of $Q_{2^+}$ is negative for even-$A$ nuclei in the first part of the shell, but is strongly positive for $^{28}$Si. If it is assumed that the corresponding nuclear charge distributions are axially symmetric, this indicates that the nuclear shape is prolate in the first part of the shell, but suddenly becomes oblate at $^{28}$Si.

In their 1972 review article, Christy and Häusser adopted a value of $Q_{2^+} = 16 \pm 4$ $e\,\mathrm{fm}^2$ for $^{28}$Si. There have now been at least seven determinations of $Q_{2^+}$; they are summarized in Table 1. At first sight there would seem to be little need for a further measurement. However, closer examination reveals substantial inadequacies in the available information. It was decided to make a new measurement for the following reasons:

(i) The experiments of Rebel *et al.* (1972) and Gale and Eck (1973) both involve coupled-channels analysis of scattering data, and are highly model dependent in that they both assume that the nucleus is a rigid rotator.

(ii) The other five experiments all use the reorientation effect in Coulomb excitation. The analyses are valid only to the extent that nuclear contributions to the excitation probability are negligible compared with the reorientation effect. Christy and Häusser (1972) comment that the bombarding energies used by Pelte *et al.* (1969) and Häusser *et al.* (1969) were both too high to safely exclude nuclear interference. Some of the data used by Nakai *et al.* (1970) correspond to a distance $s$ of closest approach between the nuclear surfaces of $4 \cdot 7$ fm (the values of $s$ quoted in the present paper are derived from equation (2) of Fewell *et al.* (1979*a*), assuming a nuclear radius of $1\cdot25A^{\frac{1}{3}}$ fm). It would be unwise to ignore the possibility of nuclear interference for an energy corresponding to $s = 4\cdot7$ fm unless it were demonstrated experimentally to be safe (see e.g. Spear *et al.* 1978). The experiment of Schwalm *et al.* (1972) involved the detection of de-excitation $\gamma$ rays at 0°; for the associated inelastically scattered projectiles, the value of $s$ could be as small as $5\cdot4$ fm. Again, it would be desirable to demonstrate experimentally that the bombarding energy used is safe. The work of Ball *et al.* (1979) has been reported in abstract only, and insufficient information is given to judge whether the energies used were safe. Thus, it is desirable to remeasure $Q_{2^+}$ under circumstances where the safety of the bombarding energies used has been demonstrated experimentally.

**Table 1. Experimental determinations of $Q_{2^+}$ for $^{28}$Si**

| Reference | $Q_{2^+}$ ($e$ fm$^2$) | Method[A] | Details of method |
|---|---|---|---|
| Pelte *et al.* (1969) | $22\pm9$ | RECE | $^{32}$S on $^{28}$Si; singles $\gamma$-ray line shapes |
| Häusser *et al.* (1969) | $17\pm5$ | RECE | $^{28}$S on $^{62}$Ni; particle–$\gamma$ coincidence |
| Nakai *et al.* (1970) | $11\pm5$ | RECE | $^{28}$Si on $^{206}$Pb; particle–$\gamma$ coincidence |
| Schwalm *et al.* (1972) | $17\pm5$ | RECE | $^{34}$S on $^{28}$Si; singles $\gamma$-ray line shapes |
| Rebel *et al.* (1972) | $13\pm1$ | CCEIS | $^{4}$He on $^{28}$Si; angular distributions |
| Gale and Eck (1973) | $15\pm4$ | CCEIS | $^{16}$O on $^{28}$Si; angular distributions |
| Ball *et al.* (1979) | $17\pm3$ | RECE | $^{28}$Si on $^{208}$Pb; particle singles with Q3D |
| Present Work | $15\cdot5\pm3\cdot4$ | RECE | $^{28}$Si on $^{208}$Pb; Si s.b. detectors |

[A] Abbreviations: RECE, reorientation effect in Coulomb excitation; CCEIS, coupled channels analysis of elastic and inelastic scattering.

(iii) It is not clear from published information to what extent the various reorientation experiments have been corrected for effects such as electron screening, vacuum polarization, the use of the semiclassical approximation, M1 reorientation, E4 reorientation, mutual excitation and virtual excitation of states in the giant dipole resonance (GDR). For example, only Ball *et al.* (1979) and Schwalm *et al.* (1972) explicitly mention consideration of the GDR correction, and only Nakai *et al.* (1970) state explicitly that a correction was made for E4 reorientation.

(iv) Reorientation experiments are notoriously difficult, and it is desirable that any given quadrupole moment should be determined using as many different techniques as possible. In the present work, we have excited $^{28}$Si projectiles with a $^{208}$Pb target, and used silicon surface barrier detectors to measure directly the excitation probability of the first $2^+$ state at laboratory angles of 90° and 172·7°. This technique is substantially different from all of those used in previous reorientation studies of $^{28}$Si.

## Experimental Procedure

Principles of the experimental procedure, which used the reorientation effect in Coulomb excitation of $^{28}$Si projectiles, have been described in previous publications (Fewell *et al.* 1979*a*, 1979*b*). In order to determine both $Q_{2^+}$ and $B(\mathrm{E2};0^+\rightarrow2^+)$, two independent measurements of the excitation probability $P_{\mathrm{exp}}$ of the $2^+$ state are required. This was achieved by taking energy spectra at two different scattering angles. An annular silicon surface barrier detector was mounted at a distance of 51 mm from the target, corresponding to a mean laboratory scattering angle of 172·7°. Detectors were also placed on either side of the target to detect ions scattered through 90°, the mean scattering angle being known to $\pm 0\cdot 3°$, corresponding to an uncertainty of $\pm 0\cdot 6\%$ in the determination of $P_{exp}$. The precautions described by Fewell *et al.* (1979*a*, 1979*b*) were taken in order to minimize the effects of uncertainties in the trajectory of the incident beam and in the collinearity of the beam spot and the defining slits of the 90° detectors.

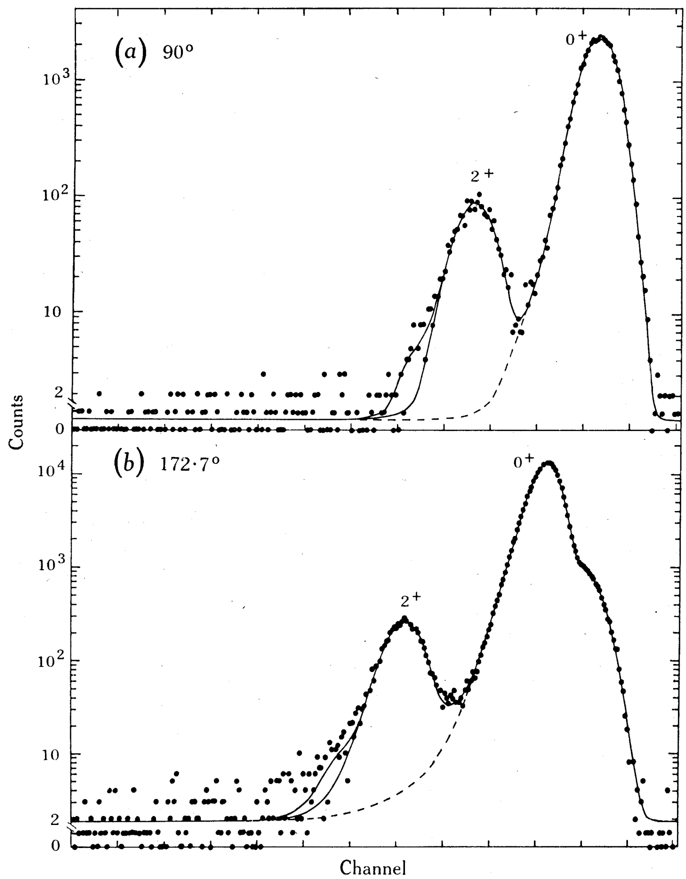


**Fig. 1.** Typical spectra obtained at (*a*) 90° (119·84 MeV) and (*b*) 172·7° (104·86 MeV) for $^{28}Si$ ions scattered from $^{208}Pb$. The full curves are fits to the data obtained as described in the text; the dashed curves show the tail of the $0^+$ peak. The structure on the high energy side of the $0^+$ peak in (*b*) is characteristic of the line shape obtained for mono-energetic $^{28}Si$ ions with this particular detector.

Beams of $^{28}Si^{8,9+}$ ions were obtained from the ANU 14UD pelletron accelerator. The beam energy was known to better than $0\cdot 1\%$ (Spear *et al.* 1977). The targets consisted of $^{208}PbS$ evaporated onto thin carbon foils. The isotopic enrichment of $^{208}Pb$ was $99\cdot 14\%$, and the partial thickness of $^{208}Pb$ was approximately 4 and 8 $\mu g\,cm^{-2}$ for the two targets used in the course of the experiment. A thin layer of carbon (approximately $1\,\mu g\,cm^{-2}$) was evaporated onto the targets to reduce deterioration under bombardment. Beam currents ranged up to about 350 nA. With the target surface perpendicular to the beam direction, spectra were obtained at 172·7° for $^{28}$Si bombarding energies from 94·88 to 104·86 MeV. With the target at 45° to the beam, spectra were obtained at 90° and 172·7° for energies from 109·85 to 139·81 MeV.

## Analysis and Results

Typical spectra obtained at 90° (119·84 MeV) and 172·7° (104·86 MeV) are shown in Fig. 1. Procedures used for unfolding the elastic ($0^+$) and inelastic ($2^+$) groups, and hence determining the excitation probability $P_{\rm exp}$ of the $2^+$ state ($P_{\rm exp} = d\sigma_{2^+}/(d\sigma_{0^+}+d\sigma_{2^+})$), were essentially as described previously (Esat *et al.* 1976; Fewell *et al.* 1979*a*, 1979*b*). The peak due to excitation of the 2·61 MeV $3^-$ state of $^{208}$Pb is imperfectly resolved from the $^{28}$Si $2^+$ peak. It was included in the fit by calculating its intensity from the known values (Joye *et al.* 1977) of $B(E3;0^+\to3^-)$ and $Q_{3^-}$, assuming a pure Coulomb interaction. The consequent uncertainties in $P_{\rm exp}$ are negligible compared with statistical uncertainties. The full curves of Fig. 1 show the fits to the data; in each case the difference between the two full curves indicates the calculated contribution from target excitation of the $3^-$ state in $^{208}$Pb. The dashed curve shows the tail of the $0^+$ peak deduced from the analysis. The errors assigned to $P_{\rm exp}$ include, in addition to statistical uncertainties, a 15% uncertainty in estimating the background under the inelastic peak.

Elastic scattering from target impurities in the mass range $A$ = 193–198 and 196–202 could contribute peaks to the spectrum in the region of the inelastic peak at 90° and 172·7° respectively. This possibility was investigated by examining a spectrum obtained at 55·93 MeV in the 172·7° detector. Taking a two standard deviation uncertainty in the background, upper limits of 0·6% and 2·7% were placed on such contributions to the excitation probability at 90° and 172·7° respectively. Similar considerations apply to the possibility that contaminant peaks in regions adjacent to that of the inelastic peak might significantly affect the determination of the excitation probability.

The possibility that transfer reactions might contribute peaks under the inelastic peak was also investigated. The only single-nucleon transfer reaction which can contribute peaks in the appropriate region is the neutron pickup reaction $^{208}$Pb($^{28}$Si, $^{29}$Si)$^{207}$Pb ($Q$ = 1·107 MeV). Peaks from single-nucleon transfer reactions were clearly visible in the 172·7° spectra at the higher bombarding energies. However, they rapidly became less prominent with decreasing bombarding energy, and at 119·84 MeV no transfer peaks could be observed. Upper limits for possible effects on the determination of $P_{\rm exp}$ were estimated by examining the 104·86 MeV backscattering spectrum. (For reasons given below, no 172·7° data obtained at energies above 105 MeV were considered in calculating $Q_{2^+}$ and $B(E2;0^+\to2^+)$.) Two different approaches were used. Firstly, the spectral region corresponding to the most prominent neutron transfer peak observed at higher energies was considered. This peak occurred about 2 MeV below the $2^+$ peak. If it is assumed that a peak in the $2^+$ region would have the same intensity, then, at the level of two standard deviations of the background in the appropriate part of the spectrum, its effects on $P_{\rm exp}$ may be estimated at less than 0·3%. Secondly, the spectral region corresponding to the proton transfer reaction $^{208}Pb(^{28}Si, ^{27}Al)^{209}Bi$ ($Q = -7\cdot788$ MeV) was examined. The systematics of single-nucleon transfer reactions near the Coulomb barrier (Buttle and Goldfarb 1971) suggest that this reaction should occur with comparable intensity to the neutron pickup reaction. With the assumption of equal intensities, the corresponding contribution to $P_{exp}$ may be set at less than $0\cdot2\%$. Consistent with the well-known backward peaking of transfer reactions near the Coulomb barrier (e.g. Franey *et al.* 1979), no indication of transfer reactions was observed in any of the 90° spectra.

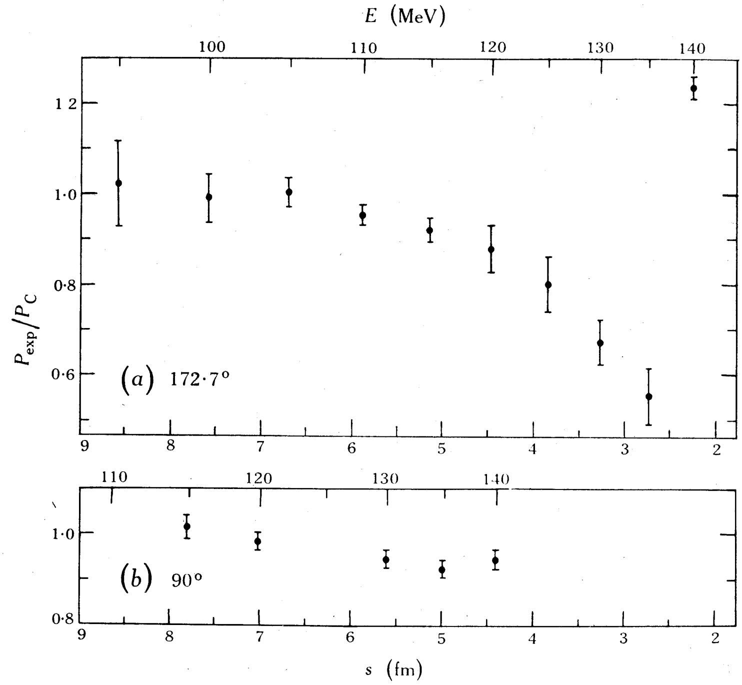


**Fig. 2.** Plots of the double ratio $P_{exp}/P_C$ against beam energy $E$ and the distance $s$ of closest approach of the nuclear surfaces.

Fig. 2 shows the energy dependence of the ratio $P_{exp}/P_C$, where $P_C$ is the excitation probability of the $2^+$ state calculated on the assumption of a pure Coulomb interaction. It appears that nuclear interference becomes significant at about 110 MeV at 172·7°; consequently, only data obtained at 94·88, 99·87 and 104·86 MeV were used in the calculation of $Q_{2^+}$ and $B(E2; 0^+ \to 2^+)$. Interference effects are less clearly marked at 90°; however, only the 114·85 and 119·84 MeV data were used in the analysis. Thus, at both angles, all data used to determine $Q_{2^+}$ and $B(E2; 0^+ \to 2^+)$ corresponded to distances $s$ of closest approach greater than 6·5 fm.

The analysis was performed using the multiple Coulomb-excitation program of A. Winther and J. de Boer (reprinted in the text by Alder and Winther 1966). Matrix elements connecting the states at excitation energies $E_x = 0\ (0^+)$, $1\cdot779\ (2^+)$, $4\cdot617\ (4^+)$ and $4\cdot979\ (0^+)$ MeV were computed from data given by Endt and van der Leun (1978); only the E2 matrix elements between the ground and $2^+$ states and between the $2^+$ and $4^+$ states were found to be significant. The value of $B(E4; 0^+ \to 4^+)$

for the transition between the ground state and the 4·617 MeV state given by Nakada and Torizuka (1972) (namely $1 \cdot 78 \times 10^4$ $e^2\,\text{fm}^8$) changes $|Q_{2^+}|$ by 0·19 $e\,\text{fm}^2$ and $|B(\text{E2}; 0^+ \rightarrow 2^+)|$ by 1·3 $e^2\,\text{fm}^4$. The sign of the matrix element, and hence the sign of the change, is not known; however, the magnitude of the correction is negligible compared with other experimental uncertainties. Effects of other states up to $E_x = 7 \cdot 4$ MeV, including the second $2^+$ state at 7·38 MeV, were investigated and found to be negligible. Since neither the 4·617 nor the 4·979 MeV states has any significant coupling to the ground state, the ambiguity in the value of $Q_{2^+}$, which often occurs in reorientation experiments because of uncertainty concerning the sign of the interference term involving higher states, does not occur in the present case.

Corrections were applied for the effects of target thickness, electron screening (Saladin *et al.* 1969), vacuum polarization (Fewell 1978), nuclear polarization (Beck and Kleber 1971), the use of the semiclassical approximation (Alder *et al.* 1972), mutual excitation (Häusser and Cusson 1970) and M1 and E4 reorientation (Fewell 1978). The magnitudes of these corrections are summarized in Table 2.

**Table 2. Changes in $Q_{2^+}$ and $B(\text{E2}; 0^+ \rightarrow 2^+)$ produced by corrections for various effects**

| Effect | $\Delta Q$ ($e\,\text{fm}^2$) | $\Delta B(\text{E2}; 0^+ \rightarrow 2^+)$ ($e^2\,\text{fm}^4$) |
|---|---|---|
| Target thickness, electron screening, vacuum polarization, nuclear polarization | −0·6 | 0 |
| Semiclassical approximation | −0·2 | −1 |
| Mutual excitation | −0·2 | −21 |
| M1 reorientation | −0·9 | −4 |
| E4 reorientation[A] | +0·2 | 0 |

[A] It is assumed that $H_{2^+}$, the hexadecupole moment of the $2^+$ state, is 9 $e\,\text{fm}^4$. This value was calculated assuming $\beta_2 = -0 \cdot 35$, $\beta_4 = +0 \cdot 14$ (Gale and Eck 1973) and $\langle r^4 \rangle = 121$ fm$^4$ (Nakada and Torizuka 1972).

Allowance has also been made for the effect of the GDR, on the assumption that $k = 1$, where $k = \sigma_{-2}/3 \cdot 5 A^{5/3}$ ($\sigma_{-2}$ is the minus-two moment of the total photo-absorption cross section, the hydrodynamic-model estimate of this quantity being $3 \cdot 5 A^{5/3}$; Häusser *et al.* 1973). The GDR correction increases $Q_{2^+}$ by 1·8 $e\,\text{fm}^2$, which is about one half of a standard deviation in the final result, and increases $|B(\text{E2}; 0^+ \rightarrow 2^+)|$ by 19·5 $e^2\,\text{fm}^4$, which is approximately equal to one standard deviation.

The value obtained for $Q_{2^+}$ is $15 \cdot 5 \pm 3 \cdot 4$ $e\,\text{fm}^2$, and that for $B(\text{E2}; 0^+ \rightarrow 2^+)$ is $326 \pm 20$ $e^2\,\text{fm}^4$. The estimated uncertainties take account of uncertainties in the spectrum analysis, beam energy and scattering angle at 90°, and of the ambiguity in the sign of $\langle 4^+ \| M(\text{E4}) \| 0^+ \rangle$ for the 4·617 MeV state. In fact, the last three uncertainties make contributions which are negligible compared with those due to uncertainties inherent in spectrum analysis.

## Discussion

Endt and van der Leun (1978) list the results of 19 determinations of $\tau_m$, the mean lifetime of the 1·779 MeV state of $^{28}$Si. These results were obtained using a wide variety of experimental techniques, including Doppler-shift attenuation, resonance fluorescence, inelastic electron scattering and Coulomb excitation. From all these, Endt and van der Leun adopt a value of $\tau_m = 700 \pm 20$ fs, which corresponds to $B(E2;0^+ \to 2^+) = 327 \pm 10\ e^2\,fm^4$. The present result of $B(E2;0^+ \to 2^+) = 326 \pm 20\ e^2\,fm^4$ is in remarkably good agreement with this value. It may be significant that if no GDR correction were applied in the present analysis, the result obtained for $B(E2;0^+ \to 2^+)$ would be noticeably smaller, i.e. $307 \pm 20\ e^2\,fm^4$. Recently Davies *et al.* (1979) have reported a preliminary value of $\tau_m = 667 \pm 35$ fs, that is, $B(E2;0^+ \to 2^+) = 343 \pm 18\ e^2\,fm^4$, from a high velocity Doppler-shift attenuation measurement.

It is interesting that the present result for $Q_{2^+}$ agrees very well with the arithmetic mean of all previous results listed in Table 1, namely $16\cdot0\ e\,fm^2$. As indicated in the Introduction, some early measurements are either model dependent or may have been inadequately corrected for nuclear interference or other effects whose significance has since been appreciated. It is most encouraging that the three most recent, and presumably most reliable, reorientation measurements are in excellent agreement with each other, i.e. $17 \pm 5\ e\,fm^2$ (Schwalm *et al.* 1972), $17 \pm 3\ e\,fm^2$ (Ball *et al.* 1979) and $15\cdot5 \pm 3\cdot4\ e\,fm^2$ (present work).

**Table 3. Calculated values of $Q_{2^+}$ for $^{28}$Si**

| Shell model calculations | | Hartree–Fock calculations | |
|---|---|---|---|
| Reference | $Q_{2^+}$ ($e\,fm^2$) | Reference | $Q_{2^+}$ ($e\,fm^2$) |
| Singhal *et al.* (1979) | +17·6 | Khadkikar and Kulkarni (1974) | +20·5 |
| Wong and Lougheed (1978) | +15·1 or +17·4 | Schmid *et al.* (1974) | −21·8 to −23·5 or +18·5 to +22·8 |
| Van Hienen *et al.* (1974) | +16·2 | | |
| Soyeur and Zuker (1972) | +18·6 | Goeke *et al.* (1972) | +12·1 |
| de Voigt *et al.* (1972) | +15 | Lee and Cusson (1972) | +17·4 |
| Wildenthal *et al.* (1971) | +14·3 | Abgrall *et al.* (1972) | +23 |
| McGrory and Wildenthal (1971) | +16 | Ford *et al.* (1971) | +17·7 |

There have been numerous calculations of $Q_{2^+}$ for $^{28}$Si. Results obtained from various versions of shell model and Hartree–Fock calculations are listed in Table 3. Only work published since 1970 is included. The shell model calculations show little scatter and are in excellent agreement with experiment. The Hartree–Fock results show a greater dispersion and, on the whole, tend to be slightly larger than the experimental value. It is noteworthy that the rotational-model relationship between $Q_{2^+}$ and $B(E2;0^+ \to 2^+)$ (see Christy and Häusser 1972) is obeyed within the experimental uncertainties. This is also the case for $^{24}$Mg (Fewell *et al.* 1979*b*) and $^{26}$Mg (Christy and Häusser 1972).

In conclusion it may be said that the value of $Q_{2^+}$ for $^{28}$Si is well established, and that both shell model and Hartree–Fock calculations give a good account of the experimental result, with the shell model calculations being in slightly better agreement.

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