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Abstract

High-spin states of the nucleus ^{48}Cr have been studied via particle-γ-γ spectroscopy, following the ^{28}Si(^{28}Si,2α) reaction. A 44-element particle-detector array was used to isolate ^{48}Cr residues and to reduce γ-ray Doppler broadening. The collective band built upon the ground state has now been firmly established to spin 16^+, the highest possible in the isolated $f_{7/2}$ shell, and lifetimes of the four highest states have been measured from Doppler shifts. Although some of the ground-state band properties are well reproduced by recent *fp*-shell model calculations, a sharp reduction in E2 transition rates at the backbend is not.

PACS numbers:21.10.Re, 23.20.Lv, 27.40+z

The nucleus ${}^{48}_{24}\mathrm{Cr}_{24}$ has attracted attention recently in connection with the search for examples of strong deformation and its relation to the underlying particle behaviour. Situated halfway between the $Z, N = 20, 28$ "magic" numbers which define spherical limits, ^{48}Cr provides the conditions necessary for a valid description in terms of collective-model *and* spherical shell-model approaches within the same physical system. The number of valence particles, eight, is small enough to justify attempts to understand the independent-particle behaviour from a shell-model point of view, yet apparently large enough to cause collective effects such as strong deformation in the low-lying states of the nucleus.

Until recently, shell-model calculations for ^{48}Cr have perforce been limited either to the isolated $f_{7/2}$ shell [1] or to few-particle excitations to the $f_{5/2}p$ shell. New advances in shell-model calculations have made *full* fp-shell calculations possible in the mass-50 region [2]. A recent theoretical comparison between the shell model, which considers the role of independent particles in the laboratory frame, and the cranked Hartree-Fock-Bogoluybov (HFB) approach, which assumes a collective mean field in the intrinsic frame, has shown remarkable agreement [3].

The experimental situation has advanced similarly. Two decades ago, enhanced γ-ray transitions with rotor-like energies were identified among the low-lying states of ^{48}Cr and its neighbours ^{47}V and ^{49}Cr [4,5], signalling the appearance of collective states in the middle of the $f_{7/2}$ single shell. Until recently, studies of high-spin bound levels in such nuclei have been limited [6-9]. Light nuclei are resistant to many of the technologies which have proved successful in high-spin studies of heavier nuclei: their small radii restrict the angular momentum available in heavy-ion (HI) induced reactions; their low masses imply high recoil velocities, which, combined with the large transition energies following from small radii, lead to large Doppler effects; their low Z allows a large number of strongly-competing reaction channels. These effects combine unfavourably in the spectroscopy of mass-50 nuclei, and extraordinary measures are needed to produce γ-ray spectra of convincing intensity, resolution and purity. In the case of ^{48}Cr, only a few percent of HI reaction yields are in the channel of interest. Previous attempts to overcome these difficulties have used techniques such as neutron-γ coincidences following (HI,pnγ) reactions at energies near the Coulomb barrier [6,7], or recoil-ion identification of reaction residues [10]. These approaches offer neither the reasonable efficiency nor the high energy resolution necessary to extend γ-ray spectroscopy to high spin. Consequently, for states in ^{48}Cr above spin 8, unambiguous placement of excited levels was problematic, the determination of spin and parity quantum numbers difficult, and the measurement of lifetimes impossible.

This paper describes new measurements of the high-spin properties of ^{48}Cr, made possible by recent advances in high-efficiency, high-resolution particle-γ-γ spectrosocopy following energetic HI reactions. The ^{48}Cr nuclei were produced following the reaction ${}^{nat}\mathrm{Si}({}^{28}\mathrm{Si}, ypz\alpha\gamma)$ at the Tandem Accelerator SuperConducting Cyclotron (TASCC) facility at Chalk River Laboratories. The 8π spectrometer, with 20 Compton-suppressed Ge detectors and a 70-element bismuth germanate calorimeter, was used to detect γ rays emitted from the reaction residues. An array of charged-particle detectors [11], which in this experiment consisted of 44 CsI(Tl) detectors covering 94% of 4π, allowed the tagging of γ-γ events by their particle signatures. In addition, the momenta of the particles detected were used to reconstruct the reaction kinematics in each event, thus enabling a considerable reduction of the Doppler broadening of the peaks of the γ-ray spectra. Spin determinations were made using the directional correlations of nuclei oriented in the reactions (DCO). In addition to measurements made with self-supporting targets, spectra were collected with a gold-backed Si target, allowing measurements of lifetimes of the high-lying states by the Doppler-shift attenuation method (DSAM). As a result, energies, spins and parities and reduced transition matrix elements have been determined for excited states in the ground-state band up to spin 16^+, the highest spin available in the $f_{7/2}$ shell, and these quantities can now be compared to recent shell-model calculations.

During the experiment, targets of natural Si (92% ^{28}Si, 5% ^{29}Si, 3% ^{30}Si) were bombarded by a 125-MeV beam of ^{28}Si. The self-supporting target consisted of two 450 μg/cm^2 layers, while the backed target was 800 μg/cm^2 thick deposited on a 13 mg/cm^2 gold foil. In reactions leading to nuclei in this mass region, γ-ray energies are high and multiplicities are low. The hardware threshold γ-ray multiplicity requirement was therefore set at four - a Ge-Ge coincidence accompanied by at least two hits in the calorimeter. The total γ-ray spectrum obtained from the 8π spectrometer under those conditions is shown in Fig. 1(a). The charged-particle detector array was used to isolate the ^{48}Cr residues. It was important to do so cleanly and with reasonable efficiency, since the 2α channel represents only a few percent of the reaction yield. The most serious contamination in 2α-gated data arises from events associated with the 2αp and the 2α2p channels, leading to ^{47}V and ^{46}Ti, respectively. Both types of event are highly favoured over those associated with the 2α channel, and will be mistaken for "good" events if the protons escape detection due to geometrical, kinematic or detection-threshold losses. Taking into account the overall efficiencies obtained from yields of γ rays from ^{47}V, ^{46}Ti and ^{50}Cr in the 2αp-, 2α2p- and α2p-gated γ-γ matrices, an appropriate combination of these matrices was subtracted from the 2α-gated matrix, yielding a 'pure 2α' matrix. Spectra from this data set were dominated by ^{48}Cr γ rays, with weak lines of ^{49,50}Cr from the 2α exit channels involving ^{29,30}Si in the target. At the same time, the particle-detector array was used to reduce γ-ray Doppler broadening by reconstruction of the reaction kinematics. The reduction in linewidth, by a factor of approximately 2.5, allowed γ rays close in energy to be resolved (see below). The improvement which can be achieved by a combination of matrix subtraction and kinematic reconstruction is illustrated in Fig. 1(a) – (d).

In the present study, several important changes from earlier experiments arise through the higher intensity and better resolution available in the present work. Firstly, single gates could be set on each of the spectral lines, rather than a sum of gates. An example is shown in Fig. 1(e), where a gate set on the 1874-keV peak clearly reveals a second 1874-keV transition. Close inspection of the coincidence spectra reveals that this peak is indeed wider than others nearby and that it consists of two components, at 1872 and 1875 keV. Any acceptable division of the intensity into these two components places them respectively immediately above and below the 1347-keV transition, using descending intensity with increasing spin as the criterion. The energies, relative intensities and placement are further confirmed by the DSAM results.

Secondly, spin determinations from DCO ratio measurements could be made up to and including the top-most transition, using single gated spectra up to the $6^+ \rightarrow 4^+$ transition and summed spectra at gates on the lowest stretched-quadrupole transitions above this. In the case of the 1874-keV doublet, and for the weak side-band, it proved advantageous to use the backed-target data. In the case of the side band, this is necessitated by the long lifetime of the 3533-keV level (about 5 ns), during which time most of the nuclei recoiling from the self-supporting target escape from the region seen by the Ge detectors. In the case of the doublet, the division of intensity was found by comparing the stopped and Doppler-broadened components of the doublet (see below). The spectra using the gold-backed target were of poorer quality, since no reaction channel selection could be made, but were more intense so DCO ratios could be found for the lowest transitions of the side-band.

Thirdly, from the measurements with the backed target, lifetimes of states in the range 0.05 to 1 ps could be obtained from the γ-ray Doppler-shift attenuation method (DSAM). Early methods of extraction of level lifetimes in this mass region, well suited to states populated in light-ion reactions, assumed prompt feeding of states followed by exponential decay. In heavy-ion reactions, it is necessary to take account of the time-dependent feeding of each state through its precursors, both known and unknown.

Centroids were found for each of the four polar angles of the Ge array by gating on fully-stopped transitions low in the level scheme. The Doppler shift derived from the differences in these centroids, attenuated from its full value by a factor F, was compared to calculated values which use a standard treatment of the recoil-ion stopping process [12,13], taking into account decay through higher observed levels and allowing for unobserved top- and side-feeding. The fact that no unaccounted γ rays are seen in coincidence with the known yrast transitions suggests that any top- and side-feeding transitions are of high energy ($E_\gamma > 4.1$ MeV, the upper detection limit) and therefore rapid.

In the DSAM measurements it was possible to set gates on the lowest four yrast transitions, all of which show a stopped fraction close to 100%. The 1874-keV peak, which shows both broad and narrow components, was examined with a gate set on the narrow component, at 1875 keV. The coincident spectra showed no stopped component, and the fit to the Doppler-shifted peak with angle results in a transition energy of 1872 keV, consistent with the fitting of the particle-gated spectra obtained with the self-supporting target.

The level scheme obtained from the present work is shown in Fig. 2. The centroid shifts of the four highest transitions of the yrast band, as found in spectra from detectors in the four rings, are shown in the inset. Lifetimes deduced from the Doppler shifts, as well as earlier measurements for the states are indicated beside each level. The diagram contains either new or revised information for levels above spin $J = 6$. For example, the use of single gates has made it possible to assign the 2023-keV and 2214-keV transitions to the sideband, rather than the previously-suggested placement in the yrast band. The side band, to which two new levels have been added, has been the subject of some disagreement regarding the spin and parity of the band-head level at 3533 keV. DCO ratios obtained from the present work are consistent with spins 5 and 6 for the 3533- and 4064-keV levels, in agreement with the assignments given in Ref. [10]. It has been suggested that a band commencing with 5^- would be analogous to those arising from $d^{-1}f$ excitations in other nuclei, such as ^{46}Ti, and that considerable collectivity might be expected [9]. The enhancement of the $8 \rightarrow 6$ 2214-keV $E2$ transition found in the present work (7.2 $W.u.$) is consistent with this. However, no similar $7 \rightarrow 5$ transition was found.

The main structure in Fig. 2, the band of positive-parity yrast states, now reaches $J^\pi = 16^+$, the highest spin possible in the isolated $f_{7/2}$ shell. Fig. 3 shows the relation between rotational frequency, taken to be half the transition energy as in the cranked shell-model approach, and spin $J = (J_i + J_f)/2$ in the band. The onset of 'back-bending' at a frequency $\hbar\omega \simeq 0.9$ MeV was already known (*e.g.*, [10]), and has been attributed to the spin alignment of a pair of $f_{7/2}$ nucleons. Fig. 3 also includes the results of $f_{7/2}$ shell-model [1] and fp shell-model [2,3] calculations. The agreement between theory and experiment is striking and shows that the the full-fp shell model is capable of describing the energies of the yrast levels extremely well, from the collective rotor-like spacings at low spin through the back-bending region up to and including the state of the highest spin possible in the ground-state configuration.

A more sensitive comparison with theory is offered by the reduced transition matrix elements, which are shown in Fig. 4. The new measurements extend the $B(E2)$ values, previously known to $J = 8$ [9], through the backbend to the highest-spin state. On the one hand, the general pattern of values of enhanced values at low spin ($\simeq 30W.u.$), falling as the maximum possible spin of $J = 16$ is approached, is reproduced by theory. On the other hand, neither calculation finds the irregular behaviour in $B(E2)$ values found in experiment at the backbend. This phenomenon in the transition rates appears to be in keeping with a band crossing in which strong interference, or a forbidden selection rule can occur. In principle, this is possible in the case of a spin alignment. However, neither SM nor cranked-HFB calculations predict such effects in ^{48}Cr, although both predict the occurence of a back-bend, and the SM predicts the energetics extremely well.

In summary, new γ-ray spectroscopic measurements have been made of high-spin states in the $N = Z$ nucleus ^{48}Cr. It has been demonstrated that the capabilities of an efficient multi-element charged-particle detector array, when combined with a large γ-ray spectrometer, are particularly well suited to the study of such light nuclei. The collective band built upon the ^{48}Cr ground state has now been determined to $J = 16$, the highest spin possible in the isolated $f_{7/2}$ shell, and lifetimes of all the states have been measured from Doppler shifts. Some of the collective properties of the ground-state band are well reproduced by recent fp-shell model calculations, namely, the average $E2$ transition rates at low spin and the energies of the complete set of excited states. However, the sharp irregularity in measured transition rates at the backbend is not seen in the calculations. Further work may be required to understand the nature of spin alignments in such a light nucleus, since it appears that the measured transition rates reflect a process more complicated than the smooth change which is expected both in the shell-model and in the collective-model approach.

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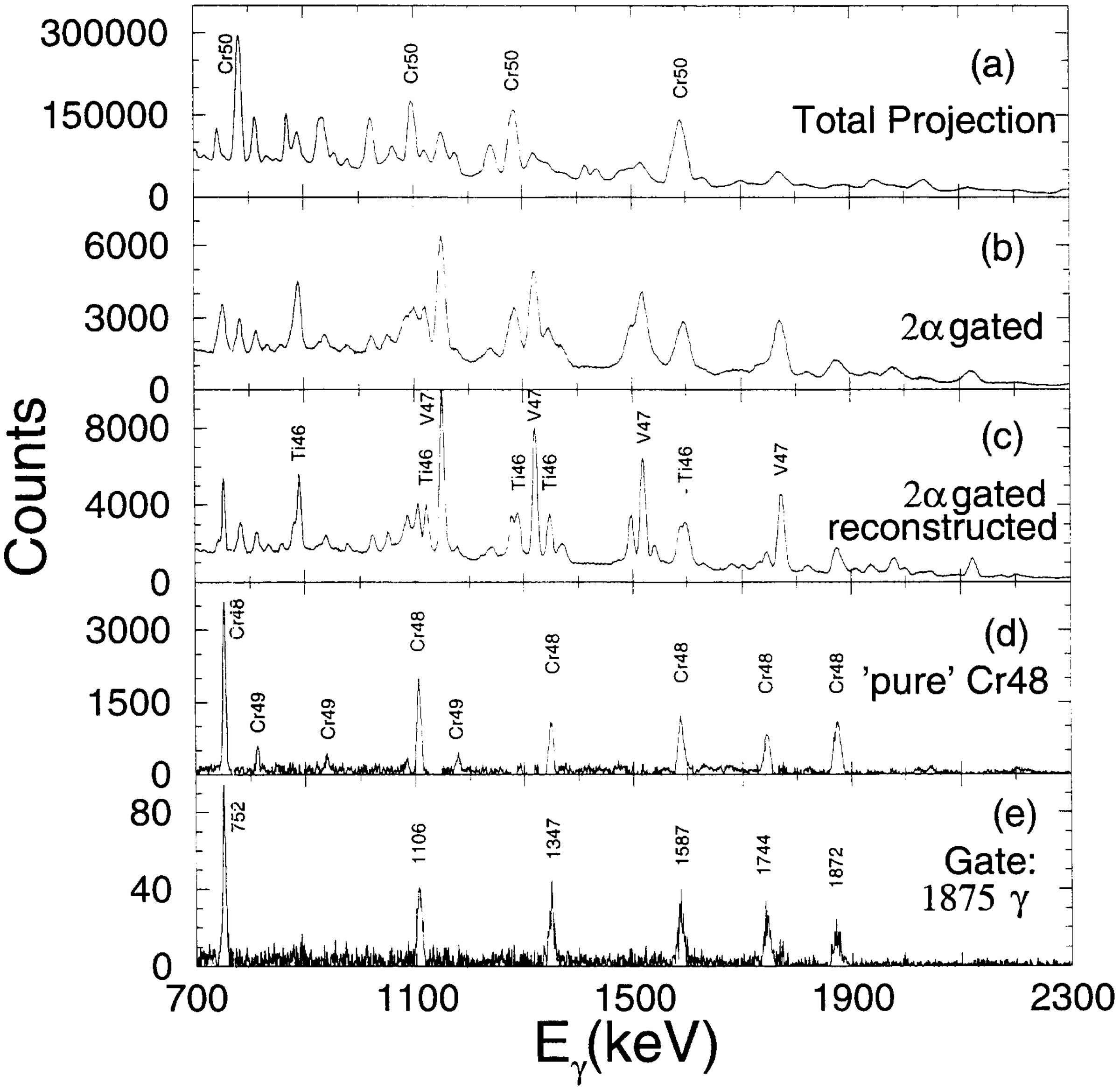
Figure 1. Gamma-ray coincidence spectra from the reaction ^{28}Si-on-^{nat}Si at 125 MeV; (a) total projection, BGO-ball multiplicity $K \geq 2$, (b) gated on 2-α events (c) gated on 2-α events with kinematic reconstruction, (d) 'pure' ^{48}Cr (see text), and (e) gated on $E_\gamma = 1875$ keV. Peaks corresponding to the most strongly favoured reaction channels are marked (see also text).

Figure 2. Level scheme for ^{48}Cr obtained from this experiment. Energies of the levels and γ-ray transitions are given in keV, with the mean lifetimes given beside each level. Lifetime data up to spin $J = 8$ in the yrast band and up to spin $J = 6$ in the side band are taken from Refs. [7] and [9]. The widths of the arrows are proportional to the observed γ-ray intensities. Inset: Relative centroid shifts for the top four transitions in the yrast band.

Figure 3. Spin, J, *vs.* rotational frequency, $\hbar\omega = (E_i - E_f)/2)$. The theoretical results are taken from Ref. [1] ($f_{7/2}$ shell model) and Ref. [2] (fp shell model).

Figure 4. Reduced transition matrix elements, $B(E2; J \rightarrow J-2)$, for the ground-state band in ^{48}Cr. Details as in Fig. 3. The data above spin $J = 8$ are taken from the present work. For $J = 6, 8$ and 10 the experimental limits are indicated.



Counts
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150000
0
6000
3000
0
8000
4000
0
3000
1500
0
80
40
0
(a)
Total Projection
Cr50
Cr50
Cr50
Cr50
(b)
2α gated
(c)
2α gated
reconstructed
Ti46
V47
Ti46
V47
Ti46
Ti46
V47
Ti46
V47
(d)
'pure' Cr48
Cr48
Cr49
Cr49
Cr48
Cr49
Cr48
Cr48
Cr48
Cr48
(e)
Gate:
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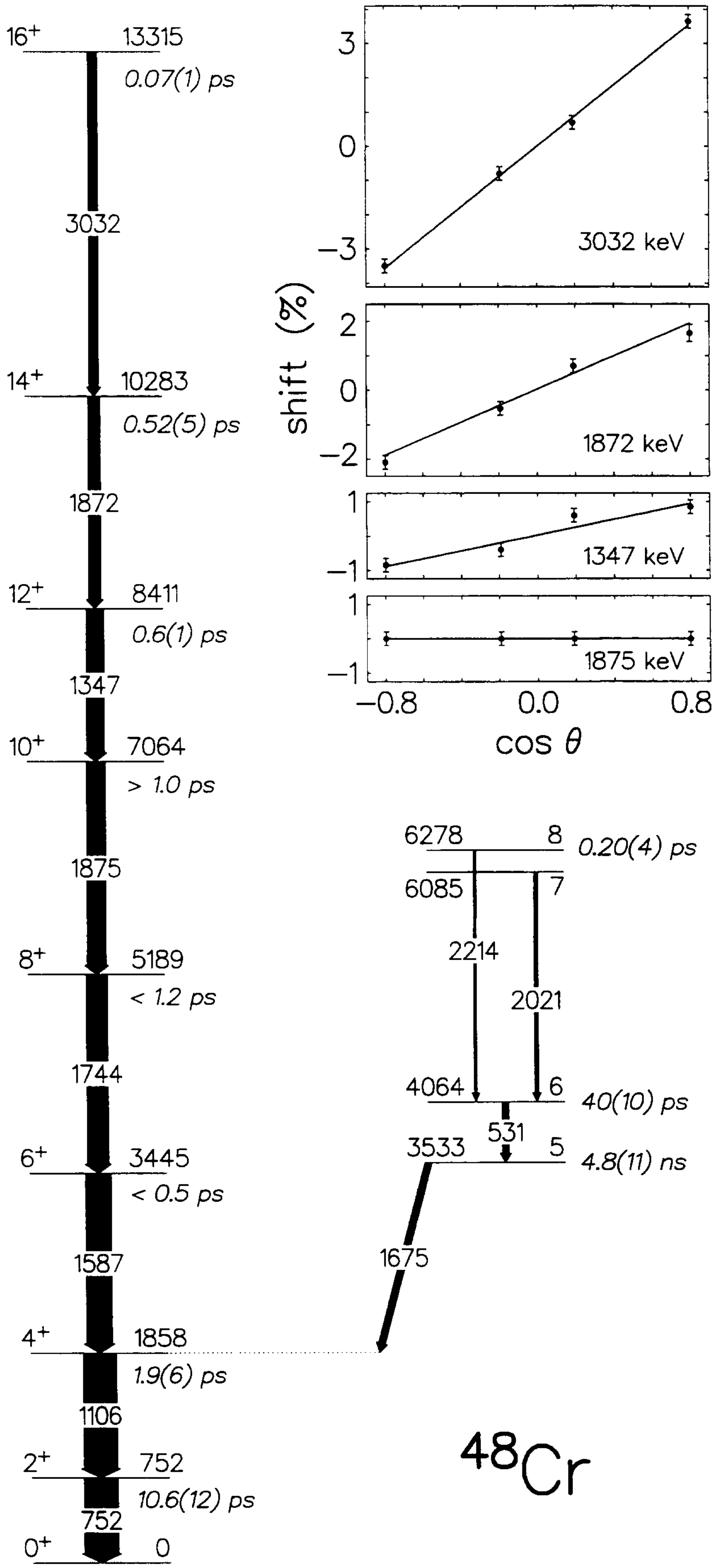
752
1106
1347
1587
1744
1872
700
1100
1500
1900
2300
E_γ(keV)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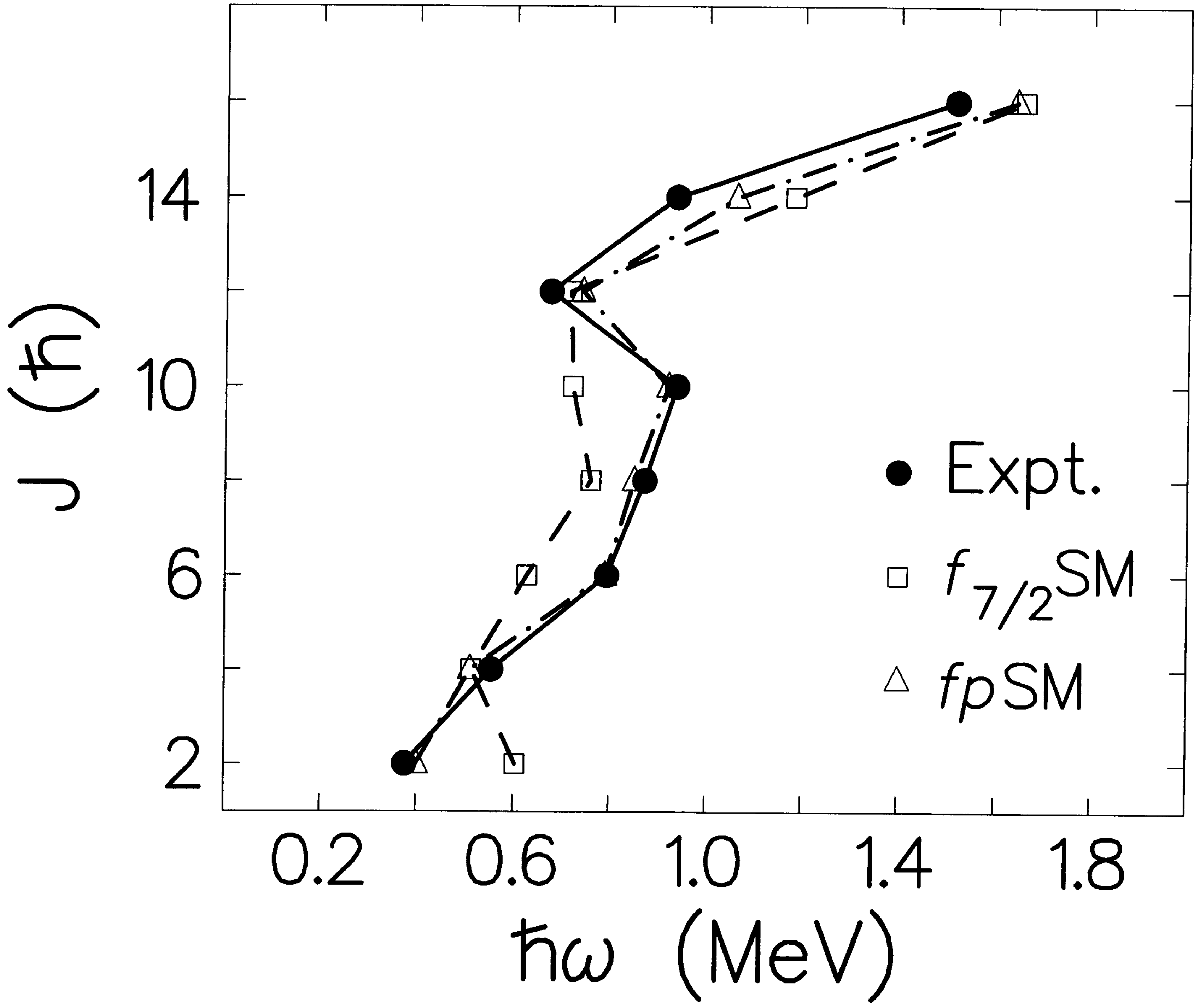
3032
14+ 10283
0.52(5) ps
1872
12+ 8411
0.6(1) ps
1347
10+ 7064
> 1.0 ps
1875
8+ 5189
< 1.2 ps
1744
6+ 3445
< 0.5 ps
1587
4+ 1858
1.9(6) ps
1106
2+ 752
10.6(12) ps
752
0+ 0
6278 8 0.20(4) ps
6085 7
2214
2021
4064 6 40(10) ps
531
3533 5 4.8(11) ns
1675
48Cr
shift (%)
3
0
−3
3032 keV
2
0
−2
1872 keV
1
−1
1347 keV
1
−1
1875 keV
−0.8
0.0
0.8
cos θ


J (ħ)
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10
6
2
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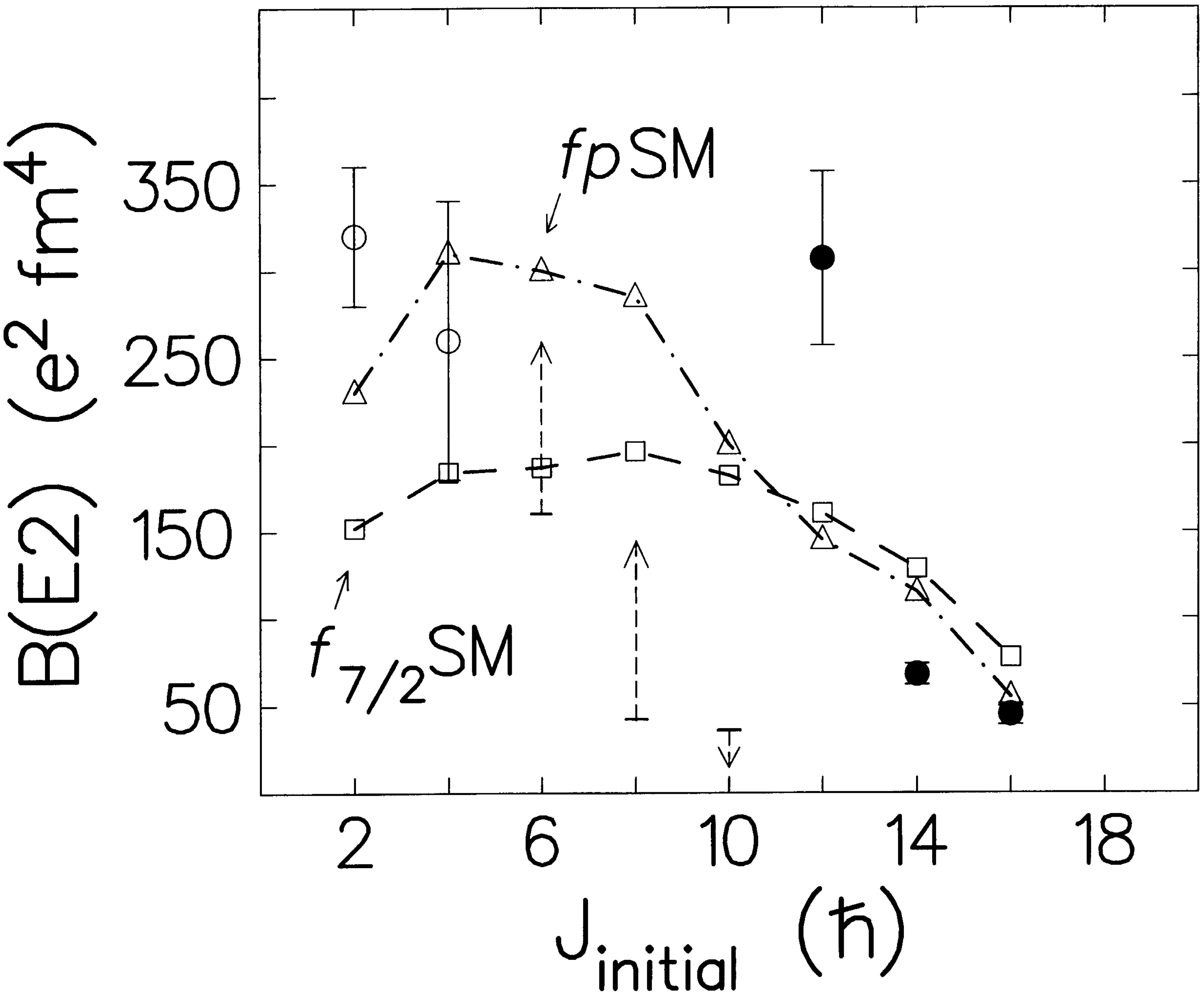
0.6
1.0
1.4
1.8
ħω (MeV)
● Expt.
□ $f_{7/2}$SM
△ fpSM


B(E2) (e^2 fm^4)
350
250
150
50
2
6
10
14
18
J$_{initial}$ (ħ)
fpSM
$f_{7/2}$SM