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A new high-spin level scheme for ^{149}Nd from a fusion-fission reaction

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Abstract. A new high-spin level scheme of ^{149}Nd has been identified, which is at variance with the one previously published. The states have been populated in the ^{12}C + ^{238}U fusion-fission reaction at 90 MeV bombarding energy and the emitted γ-transitions were detected using the Euroball III array. The yrast band is built on the $\nu i_{13/2}$ sub-shell as in the neighbouring isotones. Moreover, sign of octupole vibrations has been found in ^{149}Nd, as well as in ^{147}Ce, where several new states decaying to the yrast band have been newly observed.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Re Collective levels – 23.20.Lv Gamma transitions and level energies – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The $N = 89$ isotones belong to a transitional region where a change occurs from vibrational behaviour ($N \leq 88$) to rotational behaviour ($N \geq 90$). Their high-spin states have been the subject of extensive experimental studies for many years, those of the heavy isotones being populated by fusion-evaporation reactions (see, for instance, ^{153}Gd [1], and ^{151}Sm [2]), whereas those of the lighter isotones, ^{149}Nd [3], ^{147}Ce [4,5], and ^{145}Ba [6,7] have been produced from spontaneous fission of actinides. In all these isotones but one (^{149}Nd) the yrast band, a cascade of $E2$ transitions, is built on the $\nu i_{13/2}$ sub-shell, its orbits being located close to the neutron Fermi level for prolate-deformed shapes. As for ^{149}Nd, the authors of ref. [3] have proposed the beginning of a $\Delta = 1$ structure above a 493 keV level: This has been assigned to be the strongly coupled band built on the $11/2^-[505]$ orbital. The $(11/2^-)$ state is found to decay to a 352 keV level interpreted as a $(13/2^+)$ level. Surprisingly enough, they have not been able to identify the band built on this $(13/2^+)$ state even though it is located at lower energy than the $(11/2^-)$ state. Therefore one casts some doubts on these high-spin levels of ^{149}Nd.

In this paper, we report on a new high-spin level scheme of ^{149}Nd from a fusion-fission reaction experiment. The obtained level scheme is now very similar to the yrast structures observed in the other $N = 89$ isotones. The yrast band is built on the $(13/2^+)$ level located at 340 keV. It is worth pointing out that such a state was already known as it has been populated from several transfer reactions [8]. Moreover, the octupole vibrations, well known in this mass region, manifest themselves via a sequence of excited states decaying to the yrast states, as in ^{151}Sm [2] and ^{145}Ba [7]. The same side structure has been also newly observed in ^{147}Ce.

2 Experimental methods

The high-spin states in ^{149}Nd and ^{147}Ce have been populated using the fusion-fission reaction ^{12}C + ^{238}U at 90 MeV incident energy. The beam was provided by the Legnaro XTU tandem accelerator. The target of 47 mg/cm^2 ^{238}U was thick enough to stop the recoiling nuclei. The γ-rays were detected with the Euroball III [9]. The spectrometer contained 15 cluster germanium detectors placed in the backward hemisphere with respect to the beam, 26 clover germanium detectors located around 90°, and 30 tapered single-crystal germanium detectors located

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at forward angles. Each cluster detector consists of seven closely packed large-volume Ge crystals [10] and each clover detector consists of four smaller Ge crystals [11].

The data were recorded in an event-by-event mode with the requirement that a minimum of five unsuppressed Ge detectors fired in prompt coincidence and about 1.9×10^9 three- and higher-fold coincidence events were registered in the experiment. The data were sorted with the EURO14 software [12] and analysed using the Radware package [13].

In such experiments without any kinematical information, the Doppler shifts of the measured γ-rays cannot be corrected. Therefore, we only study the excited states having lifetimes longer than the stopping time of the fragments in the thick target (about 1 ps). The placement of the γ-ray transitions in the level scheme is based on γ-γ-γ coincidences and relative γ-ray intensities. The fact that prompt γ-rays emitted by the complementary fragments are detected in coincidence [14,15] has been used to identify the new transitions of ^{149}Nd. In this fusion-fission reaction, the main complementary fragments of ^{149}Nd are $^{92-94}$Sr.

Because of the asymmetry of the Euroball array comprising three types of Ge detectors, the statistics of our ^{149}Nd data was too low to perform γ-ray angular correlation analysis. Therefore, the spin assignments of the new high-spin states are based i) on the assumption that in the yrast decays spin values increase with excitation energy and ii) on the analogy with the level structure of the well-known neighbouring isotones.

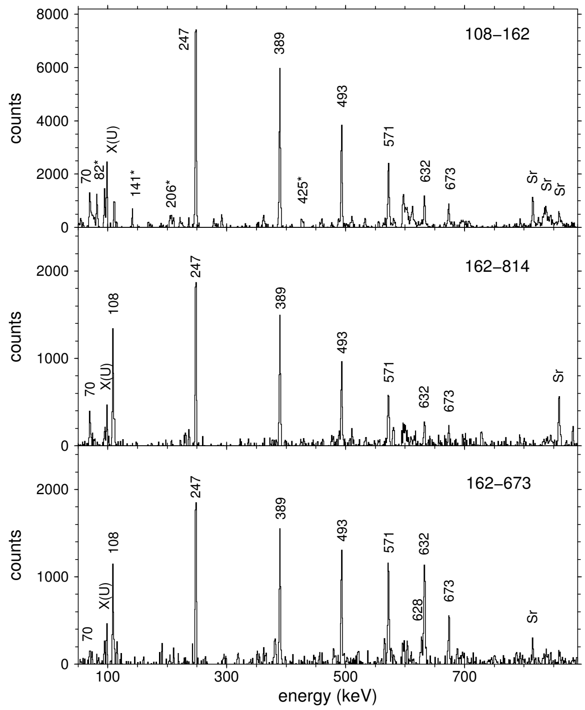

Fig. 1. Double-gated spectra built from the data obtained in the fusion-fission reaction ^{12}C + ^{238}U at 90 MeV beam energy. Top spectrum: gates set on two transitions of ^{149}Nd, 108 and 162 keV. Transitions emitted by the Sr complementary fragments are marked. Middle spectrum: gates set on one transition of ^{149}Nd (162 keV) and one transition of ^{92}Sr (814 keV). Bottom spectrum: gates set on two transitions of ^{149}Nd, 162 and 673 keV.

3 Experimental results

3.1 Study of ^{149}Nd

Few high-spin levels were known in ^{149}Nd prior to this work. From spontaneous fission of ^{252}Cf, the bottom of a $\Delta I = 1$ band based on a level located at 493 keV has been proposed in ref. [3]. This has been interpreted as the $11/2^-[505]$ structure, which is expected in this $N = 89$ isotone even though this is not the yrast band.

In our experiment, none of the γ-rays belonging to this structure or directly depopulating the 493 keV state has been observed in coincidence with the transitions emitted by $^{92-94}$Sr [16]. On the other hand, the 108 keV and 162 keV transitions corresponding to the decay of the known $(9/2^+)$ state at 270 keV [8] have been found to be correlated with the transitions emitted by the complementary fragments of ^{149}Nd. The double-gated spectrum set on these two transitions (see the top spectrum of fig. 1) also exhibits a new sequence of very strong lines, at 247, 389, 493, 571, 632 and 673 keV, which are proposed to be the yrast structure of ^{149}Nd. Moreover, the 70 keV transition, which can be clearly seen in this spectrum, is known to be located just above the $(9/2^+)$ state [8], meaning that the yrast band has to be built on the $(11/2, 13/2)^+$ level known at 340 keV excitation energy.

It is worth pointing out that all the transitions proposed by the authors of ref. [3] are weakly observed in coincidence with the 108 keV and the 162 keV transitions: 82, 141, 206, 222 and 425 keV lines. Nevertheless, being not correlated with the Sr transitions, they cannot belong to ^{149}Nd. This is illustrated in middle spectrum of fig. 1 where one of the two gates is set on the first transition of ^{92}Sr (814 keV). The 82 keV and 141 keV lines have completely disappeared whereas they have almost the same intensity as the 70 keV one in the top spectrum. In our experiment, the coincidence relationships of the 82, 108, 141, 162, 206, 222 and 425 keV transitions are very weak. Moreover, all of them are strongly contaminated by transitions emitted by other fragments. Therefore, the order of the γ-rays, previously proposed by the authors of ref. [3], cannot be confirmed and the identification of the emitting fragment is not possible from the data set of this experiment.

The third spectrum of fig. 1, which displays the complete yrast structure newly identified in ^{149}Nd, shows that the 673 keV transition is a doublet. Additional support to the assignment of all these new γ-rays comes from the coincidence spectra gated on the 37 keV X-ray of Nd and the new transitions. The analysis of all the coincidence relationships has led to the new level scheme drawn in fig. 2.

In the two neighbouring isotones, ^{147}Ce [4,5] and ^{151}Sm [2], the yrast band is built on the $9/2^+$ state lo-

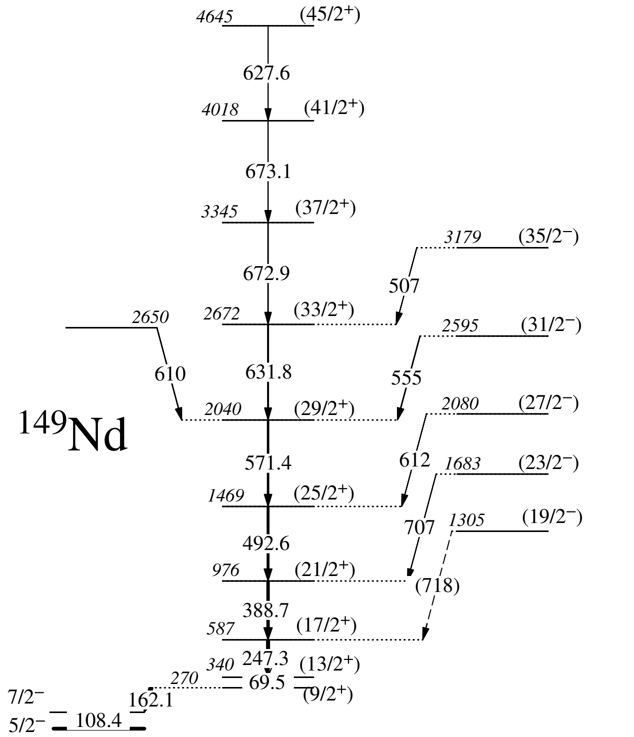

Fig. 2. New high-spin level scheme of $^{149}_{60}$Nd obtained in this work. The three first transitions (108, 162 and 70 keV) were already known [8].

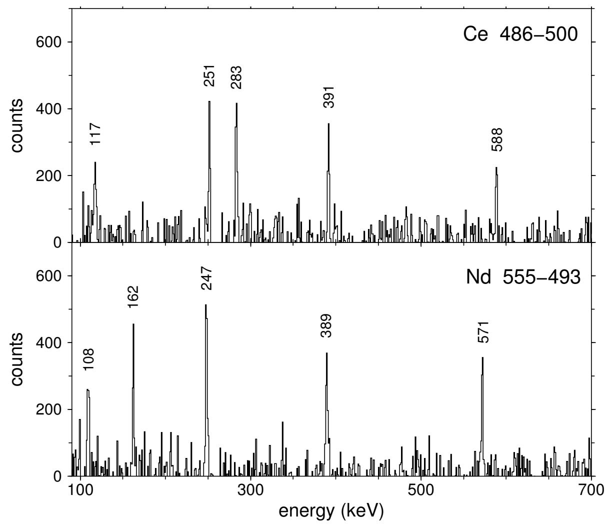

Fig. 3. Double-gated spectra built from the data obtained in the fusion-fission reaction ^{12}C + ^{238}U at 90 MeV beam energy. Bottom spectrum: gates set on two transitions of ^{149}Nd, 555 and 493 keV. Top spectrum: gates set on two transitions of ^{147}Ce, 486 and 500 keV.

cated at 400 keV and 92 keV, respectively, and its first transition ($13/2^+ \rightarrow 9/2^+$) has a very low energy (82 keV and 56 keV, respectively). The new yrast band built on the 270 keV level in ^{149}Nd is very similar to these ones and hence the same spin-parity assignment as for the corresponding levels in ^{147}Ce and ^{151}Sm has been adopted (reported in fig. 2).

In addition, the level scheme of ^{149}Nd comprises several weakly populated levels, each of them decays to one state of the yrast band. An example of double-gated spectrum involving one of the transitions depopulating such levels is shown in fig. 3 (bottom spectrum). These new states, which can be arranged as members of a side band, have very similar behaviour (excitation energy and decay) as those of side bands with negative parity which have been observed in the neighbouring isotones, ^{145}Ba [7] and ^{151}Sm [2]. Once more, the same spin-parity assignments have been adopted.

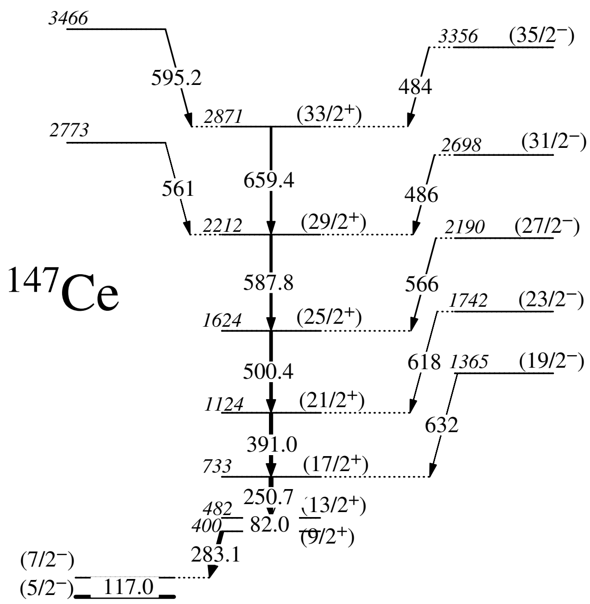

Fig. 4. Level scheme of $^{147}_{58}$Ce obtained in this work.

3.2 Study of ^{147}Ce

Previously, the yrast states of ^{147}Ce had been studied from the spontaneous fission of ^{248}Cm [4]. Later on, several new side bands had been identified from another experiment using a ^{252}Cf source [5]. In the present work, we could not confirm any of these new side bands. The part directly built on the first ($7/2^-$) state could be too weakly populated in our experiment to be observed, this is expected if the corresponding states have low-spin values. On the other hand, we could expect to see some negative-parity states strongly linked to the positive-parity yrast states, as mentioned above for ^{149}Nd.

Among the four transitions proposed by the authors of ref. [5], only one (566 keV) has been confirmed by our analysis. However, several other new transitions have been found to populate the yrast states, they are shown in fig. 4 and an example of a double-gated spectrum involving one of these new transitions is given in fig. 3 (top spectrum).

4 Discussion

The previous high-spin studies of the heavy $N = 89$ isotones using fusion-evaporation reactions had revealed a lot of rotational sequences built of the numerous individual states located close to the neutron Fermi levels. Their properties are well described in the framework of either the cranked shell model (see, for instance, the case of ^{153}Gd [1]) or particle-rotor model (see, for instance, the case of ^{151}Sm [2]). In all the heavy $N = 89$ isotones, the $\Delta I = 2$ decoupled band built on the $13/2^+$ state is much more populated than the other structures (about an order of magnitude). Since only the yrast states can be observed in the fusion-fission experiment, the high-spin level schemes of ^{147}Ce and ^{149}Nd obtained in the present work exhibit mostly the decoupled band corresponding to the $\nu i_{13/2}$ subshell.

It is worth noting that contrary to the well-known decoupled band [17], the first state of the positive-parity structure has not the maximum spin value, $I = j = 13/2$, but a lower spin value, $I = j - 2 = 9/2$. Moreover, the $13/2^+$ and $9/2^+$ states get closer and closer in energy when the proton number increases (from 82 keV in $_{58}$Ce to 22 keV in $_{66}$Dy). This is due to the fact that the neutron Fermi level is not located below the entire $\nu i_{13/2}$ set of orbits. In addition, the position of the neutron Fermi level is expected to fluctuate within the first $\nu i_{13/2}$ orbits because of the deformation changes of the $N = 89$ isotones and of the large number of negative-parity orbits lying close in energy (confirmed by the change of the ground-state spin which is $5/2^-$ in ^{145}Ba-^{151}Sm and $3/2^-$ in ^{153}Gd). Its migration among the $\nu i_{13/2}$ orbits leads to the changes observed in the bottom of the yrast bands, mentioned above.

As the ^{149}Nd level scheme has been identified up to spin $(45/2^+)$, its yrast band structure can be analyzed in a large range of rotational frequency and compared to the one of the neighbouring isotope, ^{150}Nd. The angular momentum alignments have been calculated following the procedure described in ref. [18], with the following Harris parameters: $\Im_0 = 26\,\hbar^2\text{MeV}^{-1}$ and $\Im_1 = 80\,\hbar^4\text{MeV}^{-3}$. They have been obtained in such a way that the initial alignment values of the even-even isotope are close to 0 and the values of the odd-N one remain almost constant up to 0.25 MeV rotational frequency. The results are presented in fig. 5, showing also the results of the ^{147,148}Ce isotopes. One can observe that the initial alignment of ^{149}Nd and ^{147}Ce is around $5\hbar$, that is less than the maximum value ($6.5\hbar$) expected from a $\nu i_{13/2}$ shell, in agreement with the location of the neutron Fermi level close to the second or third orbit of the $\nu i_{13/2}$ shell. The backbending observed around the rotational frequency of 0.28–0.30 MeV in the even-even nuclei plots is due to the breaking of a $\nu i_{13/2}$ pair. It is also observed in ^{149}Nd, although slighlty delayed because of the blocking of one neutron state.

In several nuclei of this mass region alternating-parity sequences connected by strong electric dipole transitions have been measured, in agreement with theoretical predictions of an island of *stable* octupole deformed nuclei around $Z = 56$ and $N = 90$ [20]. Although the $N = 89$ isotones do not exhibit such alternating-parity sequences, many observed structures are connected through strong $E1$ transitions which are interpreted as due to octupole *vibrations*. In particular the coupling of the octupole vibration of the core to the $i_{13/2}$ neutron gives states with $I^\pi \geq 19/2^-$. The evolution of the energies of the octupole phonon in the $N = 89$ isotones and in the neighbouring even-even nuclei as a function of the proton number (see fig. 6) shows that the odd-N behaviour is close to

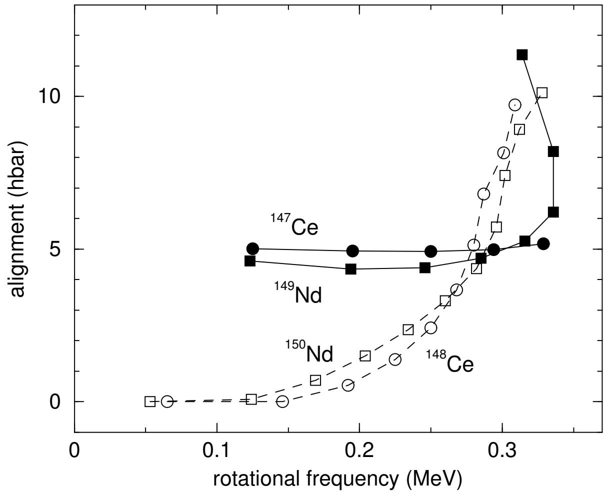

Fig. 5. Experimental alignments for the yrast band of ^{149}Nd (filled squares) and ^{147}Ce (filled circles), as compared to those of the ground-state band of ^{150}Nd (empty squares) [16,19] and ^{148}Ce (empty circles) [16]. The values of Harris parameters are $\Im_0 = 22\,\hbar^2\text{MeV}^{-1}$, $\Im_1 = 100\,\hbar^4\text{MeV}^{-3}$ for ^{147,148}Ce and $\Im_0 = 26\,\hbar^2\text{MeV}^{-1}$, $\Im_1 = 80\,\hbar^4\text{MeV}^{-3}$ for ^{149,150}Nd.

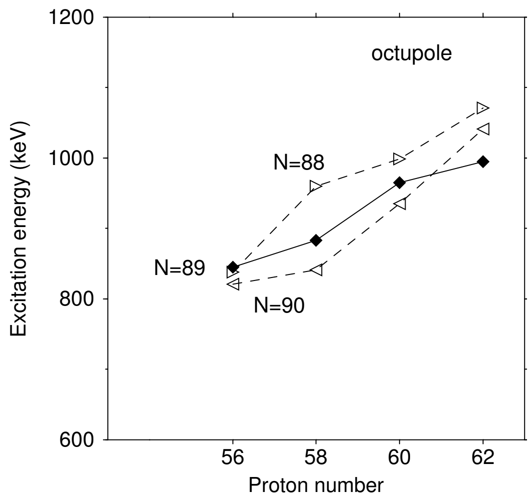

Fig. 6. Excitation energy of the octupole mode in the $N = 88$, 89, 90 isotones as a function of the proton number, from $_{56}$Ba to $_{62}$Sm. The energies of the 3^- states of the $N = 88$ isotones (triangle right) and of the $N = 90$ isotones (triangle left) are compared to the excitation energies of the $19/2^-$ states relative to the $13/2^+$ states of the $N = 89$ isotones (filled diamond).

the even-N ones. In $^{151}_{62}$Sm, the $19/2^-$ state built on the $\nu h_{9/2}$ configuration is expected in the same energy range as the one from $\nu i_{13/2} \otimes 3^-$, their mixing explains the lower energy quoted for $Z = 62$.

5 Conclusion

In the present work, we could not confirm any of the high-spin levels (with $I \geq 11/2$) previously assigned to ^{149}Nd in ref. [3] and reported in the last compilation [8]: The proposed γ-transitions are not detected in coincidence with those emitted by the Sr isotopes which are the complementary fragments of ^{149}Nd in our experiment. On the other hand, new high-spin states in ^{149}Nd have been identified up to spin value (45/2) and excitation energy around 4.6 MeV. The yrast band has been assigned to be based on the $\nu i_{13/2}$ orbital, as the corresponding bands in the other $N = 89$ isotones. The backbending observed at a rotational frequency of $\hbar\omega \approx 0.33$ MeV is slightly delayed as compared to the one observed in ^{150}Nd, because of the blocking of one $\nu\, i_{13/2}$ orbit. In ^{149}Nd as well in ^{147}Ce, several states, lying between 1.3 and 3.3 MeV excitation energy, mostly decay to the yrast states, as observed in the other isotones. This is the only manifestation of octupole correlations in these $N = 89$ isotones, which are located at the border of the mass region showing reflection-asymmetric shapes.

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References

1. T.B. Brown *et al.*, Phys. Rev. C **66**, 064320 (2002).
2. M.K. Khan *et al.*, Nucl. Phys. A **567**, 495 (1994).
3. J.K. Hwang *et al.*, Int. J. Mod. Phys. E **6**, 331 (1997).
4. F. Hoellinger *et al.*, Phys. Rev. C **56**, 1296 (1997).
5. M. Sakhaee *et al.*, Phys. Rev. C **60**, 067303 (1999).
6. M.A. Jones *et al.*, Nucl. Phys. A **605**, 133 (1996).
7. S.J. Zhu *et al.*, Phys. Rev. C **60**, 051304 (1999).
8. B. Singh, Nucl. Data Sheets **102**, 1 (2004).
9. J. Simpson, Z. Phys. A **358**, 139 (1997); F.A. Beck, Prog. Part. Nucl. Phys. A **28**, 443 (1992).
10. J. Eberth *et al.*, Nucl. Instrum. Methods A **369**, 135 (1996).
11. G. Duchêne *et al.*, Nucl. Instrum. Methods A **432**, 90 (1999).
12. Ch. Theisen, Euro14 sorting package, unpublished.
13. D. Radford, Nucl. Instrum. Methods A **361**, 297 and 306 (1995).
14. M.A.C. Hotchkis *et al.*, Nucl. Phys. A **530**, 111 (1991).
15. M.G. Porquet *et al.*, Acta Phys. Pol. B **27**, 179 (1996).
16. ENSDF database, `http://www.nndc.bnl.gov/ensdf/`.
17. F.S. Stephens, Rev. Mod. Phys. **47**, 43 (1975).
18. R. Bengtsson, S. Frauendorf, Nucl. Phys. A **327**, 139 (1979).
19. Ts. Venkova *et al.*, in preparation.
20. I. Ahmad, W.R. Phillips, Rep. Prog. Phys. **58**, 1415 (1995).